Recently Learned Foreign Abstract and Concrete Nouns Are Represented in Distinct Cortical Networks Similar to the Native Language

Katja M. Mayer,[1,2]* **Manuela Macedonia**,[1,3] and **Katharina von Kriegstein**[1,4]

[1]*MPRG Neural Mechanisms of Human Communication, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany*
[2]*Institute for Psychology, Department of Psychology, University of Münster, Münster, Germany*
[3]*Institute for Information Engineering, Johannes-Kepler-University Linz, Linz, Austria*
[4]*Department of Psychology, Humboldt University of Berlin, Berlin, Germany*

Abstract: In the native language, abstract and concrete nouns are represented in distinct areas of the cerebral cortex. Currently, it is unknown whether this is also the case for abstract and concrete nouns of a foreign language. Here, we taught adult native speakers of German 45 abstract and 45 concrete nouns of a foreign language. After learning the nouns for 5 days, participants performed a vocabulary translation task during functional magnetic resonance imaging. Translating abstract nouns in contrast to concrete nouns elicited responses in regions that are also responsive to abstract nouns in the native language: the left inferior frontal gyrus and the left middle and superior temporal gyri. Concrete nouns elicited larger responses in the angular gyri bilaterally and the left parahippocampal gyrus than abstract nouns. The cluster in the left angular gyrus showed psychophysiological interaction (PPI) with the left lingual gyrus. The left parahippocampal gyrus showed PPI with the posterior cingulate cortex. Similar regions have been previously found for concrete nouns in the native language. The results reveal similarities in the cortical representation of foreign language nouns with the representation of native language nouns that already occur after 5 days of vocabulary learning. Furthermore, we showed that verbal and enriched learning methods were equally suitable to teach foreign abstract and concrete nouns. *Hum Brain Mapp 38:4398–4412, 2017.* © 2017 Wiley Periodicals, Inc.

Key words: foreign vocabulary; functional magnetic resonance imaging; language network; memory; learning; enrichment

INTRODUCTION

Learning and speaking a foreign language is important for many aspects in modern societies, such as trade, science, and politics. Understanding how the human brain learns foreign languages can help to adapt teaching strategies for better learning outcome. A critical aspect of learning a foreign language is the acquisition of vocabulary. From the native language, we know that different word types such as verbs and nouns [e.g., Khader et al., 2010; Liljestrom et al., 2008; Soros et al., 2003], or abstract and

*Correspondence to: Katja M. Mayer, Institute for Psychology, University of Münster, Fliednerstr. 21, 48149 Münster, Germany. E-mail: katja.m.mayer@gmail.com

Received for publication 1 November 2016; Revised 14 April 2017; Accepted 17 May 2017.

DOI: 10.1002/hbm.23668

Published online 5 June 2017 in Wiley Online Library (wileyonlinelibrary.com).

concrete nouns [e.g., Binder et al., 2005] are represented in different regions of the brain [see Kemmerer, 2014, for a review]. Whether this is also the case for different word types in a foreign language is unknown.

One study with proficient bilinguals provided evidence for a common representation for nouns in both the native and the foreign language [Halsband et al., 2002]. The study showed similar areas for word representation when late bilinguals (foreign language acquisition after the age of 10 years) encoded and retrieved word pairs in the native and the foreign language. In addition, Francis and Goldmann [2011] found between-language priming when bilinguals (mean age of foreign language acquisition was 7 years) performed abstract-concrete decision tasks on nouns of the native and the foreign language. Whether a foreign language and the native language have similar representation in the brain seems to depend on several factors such as the level of proficiency in the foreign language, the level of exposure to both languages, and the age of acquisition of the foreign language [see Abutalebi, 2008; Abutalebi and Green, 2007; Halsband, 2006, for reviews]. Halsband et al.'s [2002] and Francis and Goldmann's [2011] studies contained abstract and concrete nouns. However, the analyses were pooled over both word types, that is, the potentially distinct representations for abstract and concrete nouns in the foreign language were not directly compared with each other. Mestres-Misse et al. [2009] investigated the representation of abstract and concrete words during learning. Participants conducted a sentence completion task. They derived the meaning of abstract and concrete novel words from the linguistic context of sentences in which they were embedded. By means of functional magnetic resonance imaging (fMRI), the study revealed that novel words referring to concrete concepts elicited larger responses in the left fusiform gyrus in contrast to novel words that referred to abstract concepts. Novel words referring to abstract concepts did not elicit larger responses in contrast to concrete novel words. There were no responses in the fusiform gyrus for native words. This indicates a difference in the representation of novel concrete words during learning and the representation of concrete words in the native language. It is therefore an open question whether the representation of foreign concrete and abstract nouns is similar to the representation of native concrete and abstract nouns only in proficient bilinguals or early in the learning process.

The main aim of the present study was to test how recently learned foreign abstract and concrete nouns are represented in the human brain. To do this, we directly compared the representation of recently learned foreign abstract and concrete nouns and related them to previous results for abstract and concrete nouns in the native language.

At a grammatical level, concrete nouns are words that refer to something that can be perceived with the sensory system [e.g., Paivio et al., 1968]. Concrete nouns refer to objects such as "house," "street," or "ball," which can be seen or touched for example. In contrast, abstract nouns refer to words like "theory," "view," or "synthesis," which cannot be perceived by any sensory modality. Several neuroimaging studies have shown that for the native language abstract and concrete nouns have partially different representations in the brain [e.g., Hoffman et al., 2015; Huang et al., 2010; Klostermann et al., 2008; Lehmann et al., 2010; Wang et al., 2010; Weiss and Rappelsberger, 1996; Zhang et al., 2006]. Such dissociation between representations of abstract and concrete nouns is also supported by findings in patients with brain lesions [Cousins et al., 2016; Martensson et al., 2011; see Shallice and Cooper, 2013, for a review] and in healthy participants [Fernandino et al., 2016; Shibahara and Wagoner, 2002; Vigliocco et al., 2014]. This dissociation was also found in a transcranial magnetic stimulation (TMS) study [Papagno et al., 2009]. A meta-analysis [Wang et al., 2010] including 19 neuroimaging studies showed that abstract nouns in contrast to concrete nouns elicited larger responses in the left inferior frontal gyrus, the left middle temporal gyrus, and the left superior temporal gyrus. Figure 1A shows the anatomical locations of these areas. In contrast, concrete nouns elicited larger responses in the precuneus, the fusiform gyrus, posterior cingulate cortex, and the parahippocampal gyrus [Wang et al., 2010] (Fig. 1B). Additionally, there was evidence that the left angular gyrus, the left culmen, and the left superior occipital gyrus might also be involved in processing concrete nouns [Wang et al., 2010]. A further consistent finding for concrete nouns is that, depending on the meaning, processing concrete nouns can lead to responses in specialized sensory cortices such as olfactory [Gonzalez et al., 2006] or gustatory areas [Barros-Loscertales et al., 2012].

With respect to understanding general mechanisms of language acquisition, previous research brought forward a neurophysiological model that explains how learners use contextual cues to infer meaning for novel words [Rodriguez-Fornells et al., 2009]. In the model, core processes of language acquisition such as meaning integration and item consolidation are modeled in networks of brain areas that are involved during the process. As a general language acquisition model, Rodriguez-Fornells et al.'s [2009] neurophysiological model does not specify whether different word types elicit distinct response patterns within the network. Differential involvement of sub-networks with respect to different word types is likely to occur, however. Due to differences in availability of knowledge on abstract and concrete concepts [Mestres-Misse et al., 2014], the different noun types might elicit distinct response patterns within the network. To investigate the representation of recently learned abstract and concrete nouns, we performed two fMRI experiments. In each experiment, we taught a group of adults in abstract and concrete nouns in the artificial language Vimmi [Macedonia et al., 2011]. We used Vimmi because it allowed us to control for differences in word length, prosody, etymology, and affixation between abstract and concrete words that can occur in natural languages [Reilly and Kean, 2007]. After learning, participants

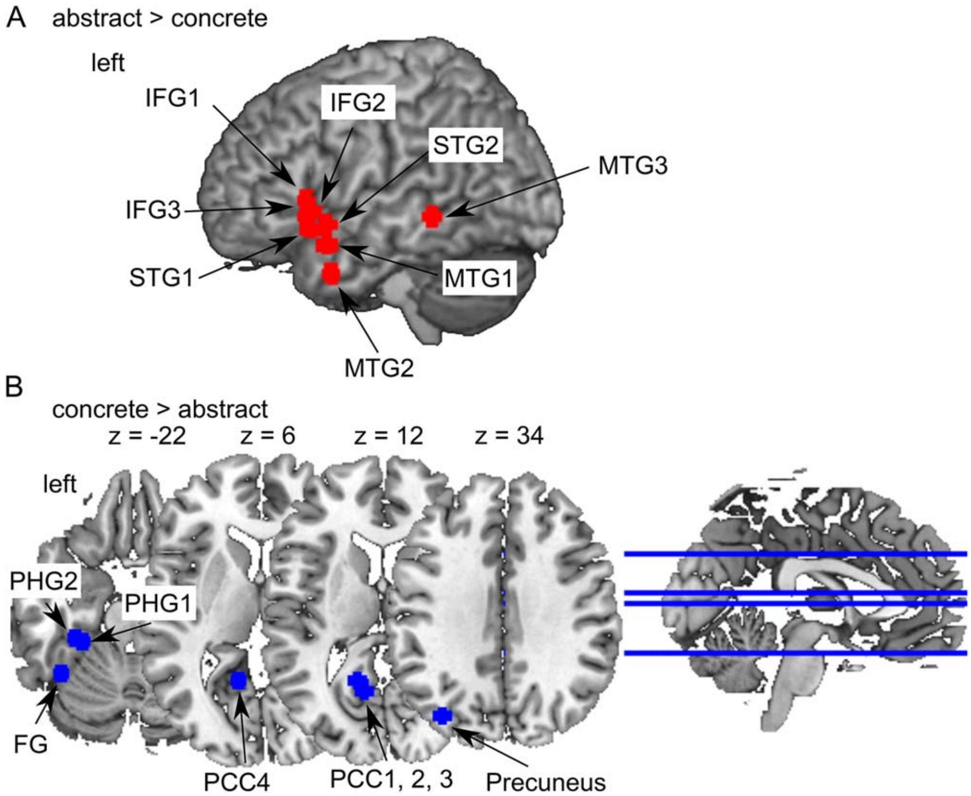

Figure 1.

Brain regions involved in processing of abstract and concrete nouns in the native language. The colored regions are based on coordinates found in a meta-analysis of 19 neuroimaging studies [Wang et al., 2010]. In the present study, these areas were used as regions of interest consisting of spheres with a 5 mm radius. (**A**) Regions involved in processing abstract nouns to a larger extend than in processing concrete nouns were the inferior frontal gyrus (IFG), the superior temporal gyrus (STG), and the middle temporal gyrus (MTG). IFG1: the most superior cluster in the IFG; IFG2: the cluster in the IFG which is more inferior compared to IFG1; IFG3: most inferior cluster in the IFG; MTG1: most superior cluster in the MTG; MTG2: inferior cluster in the MTG; MTG3: most posterior cluster in the MTG; STG1: anterior STG cluster; STG2: posterior STG cluster. (**B**) Regions that were involved in processing concrete nouns to a larger extend than in processing abstract nouns were the fusiform gyrus (FG), the parahippocampal gyrus (PHG), the precuneus, and the posterior cingulate cortex (PCC). PHG1: medial PHG cluster; PHG2: lateral PHG cluster; PCC1, 2, 3: partly overlapping more superior clusters in the PCC; PCC4: most inferior cluster in the PCC. Additionally, Wang et al. [2010] report evidence for the involvement of the left superior occipital gyrus, the left angular gyrus and the left culmen which, however, showed less robust significance levels in their meta-analysis. [Color figure can be viewed at wileyonlinelibrary.com]

performed a vocabulary test during fMRI. We tested for differences in the blood oxygen level dependent (BOLD) response magnitudes during translation of foreign abstract or concrete nouns. We had the following hypotheses. If foreign nouns are represented in a similar way to native language nouns, larger BOLD responses in inferior frontal and temporal areas should occur during the translation of abstract words in contrast to concrete nouns [Wang et al., 2010] (Fig. 1A). For the translation of concrete nouns in contrast to abstract nouns, the precuneus, the posterior cingulate cortex, the fusiform gyrus, the parahippocampal gyrus, and lateral parietal areas as well as the culmen and superior occipital areas should respond more strongly [Wang et al., 2010] (Fig. 1B). In the two experiments of our study, participants learned words under different conditions. Vocabulary was either presented auditorily only or it was enriched with gestures, or pictures. The experimental design therefore allowed us to additionally test whether the representations of foreign concrete and abstract nouns in the cortex depend on the learning condition.

MATERIALS AND METHODS

Participants

In total, the sample for the two fMRI experiments comprised 43 adults (Experiment 1: 9 males, 13 females; mean age = 24.6 years, SD = 2.1 years, range 21 to 26 years;

Experiment 2: 11 males, 11 females, mean age = 26.14 years, SD = 3.6 years, range 21 to 34 years; 1 left-handed participant). Participants had normal hearing and normal or corrected-to-normal vision. They did not suffer from any neurological or psychiatric illness and did not take medication. Originally, 48 participants were recruited for the two experiments but in each experiment two participants dropped out before the learning phase was completed. Due to a technical fault, the fMRI dataset of one participant had to be excluded. The experiments were run in accordance with the Declaration of Helsinki and approved by the ethics committee of the University of Leipzig. Participants were informed that the experiments were conducted to investigate the effectiveness of different teaching methods on foreign vocabulary learning in adulthood but naïve to specific hypotheses. Participants gave informed consent prior to the experiments.

Design

Each experiment was set up as a 2(word type: concrete nouns, abstract nouns) × 3(learning conditions: gesture enrichment, picture enrichment, no enrichment) design with repeated measures of both factors. The two experiments differed in whether the learning conditions involved motor responses of the participants or not (see section Procedure: Vocabulary Learning). We collapsed the data across both experiments and across learning conditions to address the main aim of the present study, that is, investigating whether recently learned foreign language nouns have similar representations in the brain as reported for native language nouns. To investigate the effects of the different learning conditions on the representation of abstract and concrete foreign language nouns, we analyzed the complete 2 × 3 design for both experiments separately and also collapsed across experiments.

Stimuli

The 90 foreign language words used for the study were part of the artificial language corpus Vimmi [Macedonia et al., 2011; Macedonia and Knosche, 2011]. Forty-five Vimmi words were assigned to concrete German nouns and 45 Vimmi words were assigned to abstract German nouns. Following previous work [e.g., Binder et al., 2005; Mellet et al., 1998], we defined abstract nouns as words that cannot be perceived with any sensory modality. As concrete nouns, we chose words that refer to objects that can be perceived visually. This implies that the concrete words reach high levels of concreteness and imagery. Learners might thus create a mental image of the object the word referred to [Paivio et al., 1968]. For each word, we recorded a German and a Vimmi audio file in a sound-attenuated chamber using a Rode NT55 microphone (Rode Microphones, Silverwater, Australia). Audio files were 1 s long. In addition, for the gesture enrichment learning condition, we recorded for each word a gesture symbolizing the word meaning using a Canon Legria HF S10 camcorder (Canon, Tokyo, Japan). White fader settings were used for appropriate color display. A gesture was considered to symbolize the meaning of a word when two of the authors (KMM, MM) and one student assistant agreed that the gesture symbolized the meaning. Each video lasted 4 s. For the picture enrichment learning condition, we obtained line drawings depicting the word meaning from a professional cartoonist (http://www.klaus-pitter.com/).

Wiemer-Hastings and Xu [2005] showed that the individual experience with concrete concepts is often related to objects while the individual experience with abstract concepts is often related to social situations [see also Mestres-Misse et al., 2014]. This may lead to differences with respect to which gestures and pictures are suitable as symbols for the word meaning. For gestures, we approached this issue by keeping the complexity of the gestures similar across abstract and concrete nouns (i.e., all gestures involved simple movements of the body and the limbs but no simulated social interactions). The variation across the two word types for pictures was larger. Pictures for concrete nouns displayed both single objects and objects embedded in scenes whereas pictures for abstract nouns displayed scenes describing the word meaning.

PROCEDURE

Vocabulary Learning

In each of the two experiments, participants learned foreign language vocabulary during a 5-day learning week (Monday to Friday; Fig. 2A). During the learning week, each learning day consisted of two learning sessions that included the same conditions. In each session, each learning condition (gesture enrichment, picture enrichment, no enrichment) was presented once. Participants learned 30 Vimmi words in each learning condition, including 15 concrete and 15 abstract nouns in a randomized order. Within one condition, the 30 Vimmi words were presented 4 times. Thus, over the 5 learning days participants heard every Vimmi word 40 times. The order of the conditions was counterbalanced across the learning days. On the Monday following the learning week, participants were presented with an fMRI experiment in which they performed a vocabulary test. Before the learning week, participants were instructed and familiarized with the experimental procedure and the MR safety protocols individually during an appointment with the experimenter.

Both experiments involved the same stimuli. In the no enrichment condition, participants sat still, fixated on a black screen, and listened to the Vimmi words and their German translations. One learning trial consisted of an auditory presentation of the Vimmi word (200 ms after trial onset), followed by a presentation of the auditory German translation (4,200 ms after trial onset), which was followed by the second presentation of the Vimmi word (5,900 ms after trial onset). An example of a no enrichment learning trial is displayed in Figure 2B. In the learning condition with gesture enrichment, participants saw a video. It showed an actress performing a gesture representing the word meaning each time they heard the Vimmi word (first presentation at trial onset, second presentation 5,700 ms after trial onset). In the picture enrichment learning condition, participants saw pictures representing the word's meaning each time they heard the Vimmi word (first presentation at trial onset, second presentation 5,700 ms after trial onset). Each picture was shown for 4,000 ms. In both experiments, we instructed participants to learn as many Vimmi words as possible.

In Experiment 1, during the learning condition with gesture enrichment, we asked participants to first listen to the auditory Vimmi word, to watch the gesture, and thereafter to listen to the German translation. Participants were instructed to perform the gesture when the Vimmi word and the video were displayed the second time. Similarly, in the learning condition with picture enrichment, we asked the participants to copy the outline of the picture with the right index finger in the air when the picture was presented for the second time during the trial (Fig. 2B). Participants could choose the line they wanted to copy themselves but they had to copy the same line consistently throughout learning. In Experiment 2, participants were instructed to only listen to the Vimmi words and to the translations while watching the screen. Thus, participants neither performed the gesture nor copied the picture. The specific nature of the learning condition was chosen to assess the influence of gestures and pictures on foreign language learning as previously reported [Mayer et al., 2015]. Participants completed the learning phase in small groups of 7 to 8 adults (3 groups per experiment).

Learning progress was monitored with vocabulary tests. They took place before the learning sessions on days 2, 3, 4, and 5. Learning and test phases lasted between 3 and 4 h per day including breaks. On day 8, a vocabulary test was taken during fMRI. Note that there was no learning on days 6, 7, and 8. Further behavioral vocabulary tests were performed after the fMRI on day 8 and 2 and 6 months after the first day of the learning week.

fMRI Procedure

Before the fMRI data acquisition, participants were instructed outside of the MR scanner. In the MR scanner, a few practice trials were presented to ensure that auditory stimuli appeared equally loud to both ears and that participants could see the whole screen. Participants lay

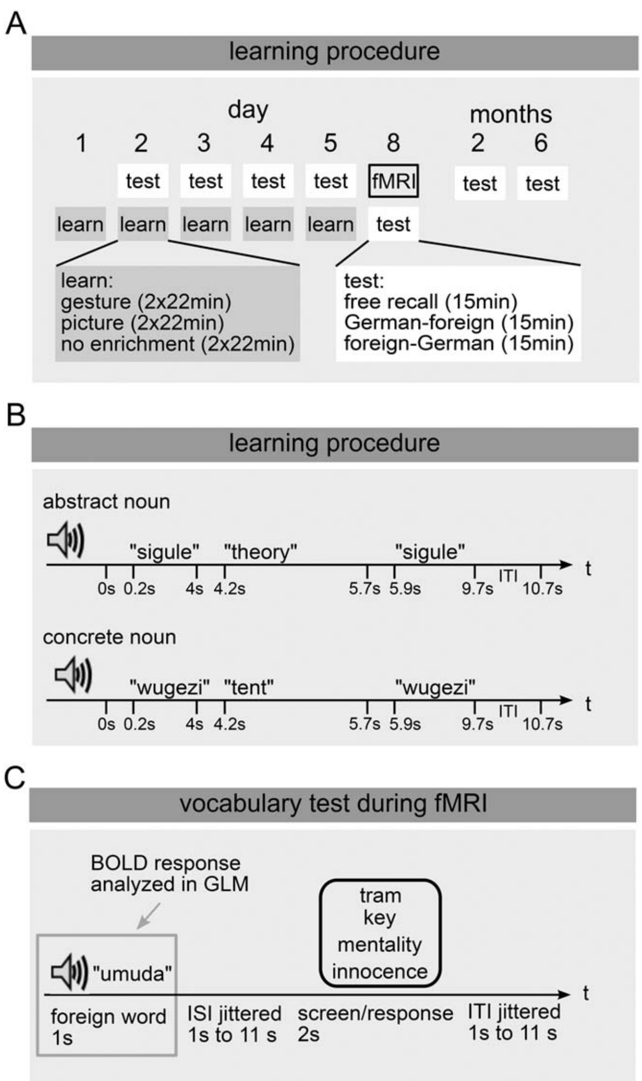

Figure 2.

Experimental Procedure. (**A**) Learning procedure. Participants learned the Vimmi words on 5 consecutive days. Starting on day 2, learning progress was monitored with vocabulary tests. On day 8, the vocabulary test was preceded by a vocabulary test with fMRI. (**B**) Example trials of the no enrichment learning condition. Participants heard a Vimmi word, followed by the German translation and, again the Vimmi word. In the gesture and the picture condition, foreign words were accompanied by videos of gestures symbolic to the word meaning and pictures displaying the word meaning, respectively. When learning with gestures participants performed the gestures in Experiment 1 and viewed them in Experiment 2. When learning with pictures in Experiment 1, participants copied a part of the picture projected on the wall with the right index finger in the air. In Experiment 2, participants only viewed the pictures. (**C**) Vocabulary test during fMRI. fMRI: functional magnetic resonance imaging; ITI: inter-trial interval; ISI: inter-stimulus interval; BOLD: blood oxygenation level dependent; GLM: general linear model; sigule/wugezi/umuda: foreign words of the artificial language "Vimmi." Translations written in English in the figure were presented in German in the study.

supine and held an MR-compatible response box with four buttons in the right hand. Via a mirror mounted on the headcoil participants could view a screen. Visual stimuli were projected onto the screen using a projector. Participants' ears were protected with earplugs and MR-compatible headphones (Mark II, MR confon, Magdeburg, Germany) that were also used to present the auditory stimuli. fMRI scanning started with the written instruction "waiting for trigger…." Triggering was used to ensure synchrony between the experiment and the MR scanner. After 2 dummy fMRI volume acquisitions, the experiment started. Each trial began with a Vimmi word presented auditorily (see Fig. 2C for an example trial). After an interstimulus interval (ISI) consisting of a black screen with jittered duration (min = 1 s, max = 11 s, $M = 2$ s, SD = 1.94 s), a response screen appeared. On the response screen, a list with four German translations was presented with one of them being the correct one. The response screen was presented for 2 s. Participants indicated the correct translation with a button press while the response screen was present. They used the right index finger to indicate the word on top of the list, the right middle finger to indicate the second word, the ring finger to indicate the third word, and the little finger to indicate the bottom word of the list. No feedback was provided. We chose a translation task to ensure that only those trials were analyzed for which participants knew the word's meaning. In between trials, an intertrial interval (ITI) with jittered duration (min = 1 s, max = 11 s, $M = 2$ s, SD = 1.94 s) was added. An ITI consisted of a black screen. After the ITI, the next trial started. During one run, each of the 90 Vimmi words was presented once. In addition, 27 null-events [Friston et al., 1999] were included in a randomized order in the experiment. The order of the Vimmi words was randomized across participants and runs. One run lasted approximately 10 min. There were 2 runs in total.

In addition to the two runs of the vocabulary tests, we also acquired two functional localizers. These were not relevant for the research question of the present report and details on them were reported previously [Mayer et al., 2015].

fMRI Scanning Parameters

We used a Siemens Tim Trio 3T MR scanner (Siemens, Erlangen, Germany). Scanning sessions started with the acquisition of a T2*-weighted scan to localize the head and a B0 fieldmap to characterize geometric distortions of the magnetic field. Next, we presented two runs of the vocabulary test. For each vocabulary test, 392 T2*-weighted echo planar images (EPIs) were acquired. The EPIs (42 transversal slices with 1 mm gaps in between; slice thickness: 2 mm; field-of-view: 192 mm × 192 mm; in-plane resolution: 3 mm × 3 mm, 64 × 64 matrix; TR = 2.79 s; TE = 30 ms) were aligned to the anterior commissure-posterior commissure line. The first two TRs of every run were discarded to allow for T1 equilibrium. At the end of the scanning session, we acquired a T1-weighted 3D MP-RAGE (magnetization-prepared rapid gradient echo) [Mugler and Brookeman, 1990] sequence with selective water excitation and linear phase encoding.

fMRI Analysis

BOLD responses were analyzed with the general linear model (GLM) approach implemented in SPM8 (http://www.fil.ion.ucl.ac.uk/spm/). We used the B0 fieldmap to correct geometric distortions. We removed low-frequency drifts in the signal with a cut-off of 100 s. Preprocessing involved realignment to the first image of the first run, unwarp, normalization to the T1 standard brain implemented in SPM8, and smoothing with an 8 mm full-width half-maximum Gaussian kernel.

Our experiment was an event-related design. We modeled the onset times of the conditions as stick functions and convolved them with the hemodynamic response function. For each participant's dataset, we built a design matrix in which we included a regressor for each experimental condition (abstract-gesture, abstract-picture, abstract-no enrichment, concrete-gesture, concrete-picture, concrete-no enrichment), for trials on which participants gave the wrong or no response, and for the six movement parameters acquired during realignment. Also, we included a constant term for each run.

To investigate differences in the representation of abstract and concrete nouns, we averaged across the three enrichment conditions and set up our contrasts as follows. We identified brain areas that show larger responses to concrete nouns than to abstract nouns by coding the regressors for the three concrete conditions with 1 and the three abstract conditions with −1 and vice versa to identify brain areas with larger responses to abstract than to concrete nouns. Any other regressor was coded with 0 as regressor of no interest. Each participant's dataset was analyzed individually with a fixed-effects model. The individual statistical parametric maps were submitted to a random-effects model to obtain t-statistics at the group level.

Statistical inference was made on the basis of one-sample t-tests. To specifically compare our results to those reported for the native language, we conducted region of interest (ROI) analyses. They were based on the coordinates reported by Wang et al. [2010]. ROIs were spheres centered on Wang et al.'s [2010] coordinates with a radius of 5 mm. For regions with larger BOLD responses to abstract in comparison to concrete nouns, these included three clusters in the left inferior frontal gyrus (which we labeled IFG1, 2, 3 in Fig. 1A), two clusters in the superior temporal gyrus (which we labeled STG1 and STG2 in Fig. 1A), and three clusters in the middle temporal gyrus (which we labeled MTG1, 2, 3 in Fig. 1A). For regions with larger BOLD responses to concrete in comparison to abstract nouns, these included four clusters in the posterior cingulate cortex (which we labeled PCC1, 2, 3, 4 in Fig. 1B), two clusters in the parahippocampal gyrus (which we labeled PHG1 and PHG2 in Fig. 1B), one cluster in the

TABLE I. Behavioral accuracy on the vocabulary test during functional magnetic resonance imaging

	Abstract nouns		Concrete nouns	
Learning condition	Mean (%)	SE (%)	Mean (%)	SE (%)
Experiment 1 (motor tasks)				
No enrichment	87.14	0.82	90.16	0.71
Picture	86.67	0.73	89.21	0.71
Gesture	86.83	0.85	91.59	0.49
Experiment 2 (no motor tasks)				
No enrichment	88.84	0.62	91.21	0.50
Picture	89.85	0.56	89.85	0.51
Gesture	86.21	0.59	88.33	0.62

Note. Participants were presented with 15 Vimmi words in each condition. Experiment 1: $N = 21$, Experiment 2: $N = 22$. M: mean, SE: standard error of the mean.

fusiform gyrus (which we labeled FG in Fig. 1B), and one cluster in the precuneus (Fig. 1B). For the concrete nouns, we also explored regions that were found at a less robust significance level in Wang et al.'s [2010] study, namely the left superior occipital gyrus, the left angular gyrus, and the left culmen. For these regions, we used an anatomical map (WFU pickatlas) [Maldjian et al., 2003] because Wang et al. [2010] did not report coordinates for these clusters. As a recent study into the representation of concrete nouns in the native language found evidence for bilateral responses in the angular gyri [Roxbury et al., 2014], we also included the right angular gyrus in our analyses using the WFU pickatlas map. For the ROI analyses, we accepted clusters as significant when $P_{FWE} < 0.05$, corrected at the peak level for the ROI. For clusters for which we did not have an a priori hypothesis, we set a significance threshold of $P_{FWE} < 0.05$ corrected at the cluster level for the whole brain with an extended cluster size of $k = 10$. Coordinates are reported in the Montreal Neurological Institute (MNI) space.

Furthermore, we conducted psychophysiological interaction (PPI) analyses using the standard PPI analysis implemented in SPM8 to explore further clusters that might be involved in processing concrete nouns. As seed regions, we used clusters identified by our GLM analysis (see Results: fMRI Results). We used spheres with 5 mm radius centered on the peak voxels found for the concrete noun > abstract noun contrast. As the psychological regressor, we coded whether an abstract or a concrete foreign word was presented. We coded any learning condition that contained a concrete noun with 1 and any learning condition that contained an abstract noun with -1.

RESULTS

Behavioral Results

We performed a 2(word type: concrete nouns, abstract nouns) × 3(learning conditions: gesture enrichment, picture enrichment, no enrichment) repeated measures ANOVA collapsed across the two experiments on translation performance during fMRI with the following results. Participants translated significantly more concrete nouns correctly than abstract nouns (Table I). This was reflected in a main effect of word type ($F(1, 42) = 4.31$, $P = 0.04$). No other main effect or interaction reached significance (Ps > 0.30). There were no main effects or interactions for response times (Ps > 0.63).

fMRI Results

Contrasting BOLD responses for abstract versus concrete nouns

The contrast abstract > concrete revealed significant effects in all three ROIs (Fig. 3A, Table II) of the left inferior frontal gyrus (IFG1, 2, 3 in Fig. 1A) and in the posterior middle temporal gyrus (MTG3 in Fig. 1A). For the superior temporal gyrus, the more anterior of the two clusters (STG1 in Fig. 1A) reached significance. An additional whole-brain analysis revealed that clusters in the inferior frontal and the posterior middle temporal gyrus were also significant when no ROI analysis was conducted ($P_{FWE} < 0.01$, corrected at the cluster level for the whole brain, Fig. 3A, Table II). To control for the difference in behavioral accuracy between the translation of abstract and concrete nouns, we entered the behavioral difference as a covariate in the design matrix of the GLM. The results stayed qualitatively the same (Table III).

Contrasting BOLD responses and functional connectivity for concrete versus abstract nouns

Using the ROI analysis for the concrete > abstract contrast, we found that two clusters in the left parahippocampal gyrus (PHG1 and PHG2 in Fig. 1B) showed significant responses (Fig. 3B, Table IV). Furthermore, for the regions Wang et al. [2010] reported as less robust in terms of the significance level in their meta-study (left angular gyrus, left culmen, left superior occipital gyrus), we found that the left angular gyrus and the left superior occipital gyrus had significant responses. The peak voxels of the two ROIs were located in one joint cluster expanding from the parietal to the occipital lobe (Fig. 3B). Following Roxbury et al. [2014], we also included the right angular gyrus in our ROI analysis. We found that this area was significant, too (Fig. 3B, Table IV). As for abstract nouns, the results stayed qualitatively the same when we entered the behavioral difference between abstract and concrete nouns as a covariate in the design matrix of the GLM (Table V).

Several regions previously reported by Wang et al. [2010] did not reach significance in our ROI analyses (i.e., left precuneus, posterior cingulate cortex, fusiform gyrus, and culmen) when testing for regions involved in the translation of concrete nouns. This finding might indicate that the concrete nouns in a foreign language recruit a smaller network than found previously for the native language. We explored whether the regions found here for the concrete nouns in the foreign language would

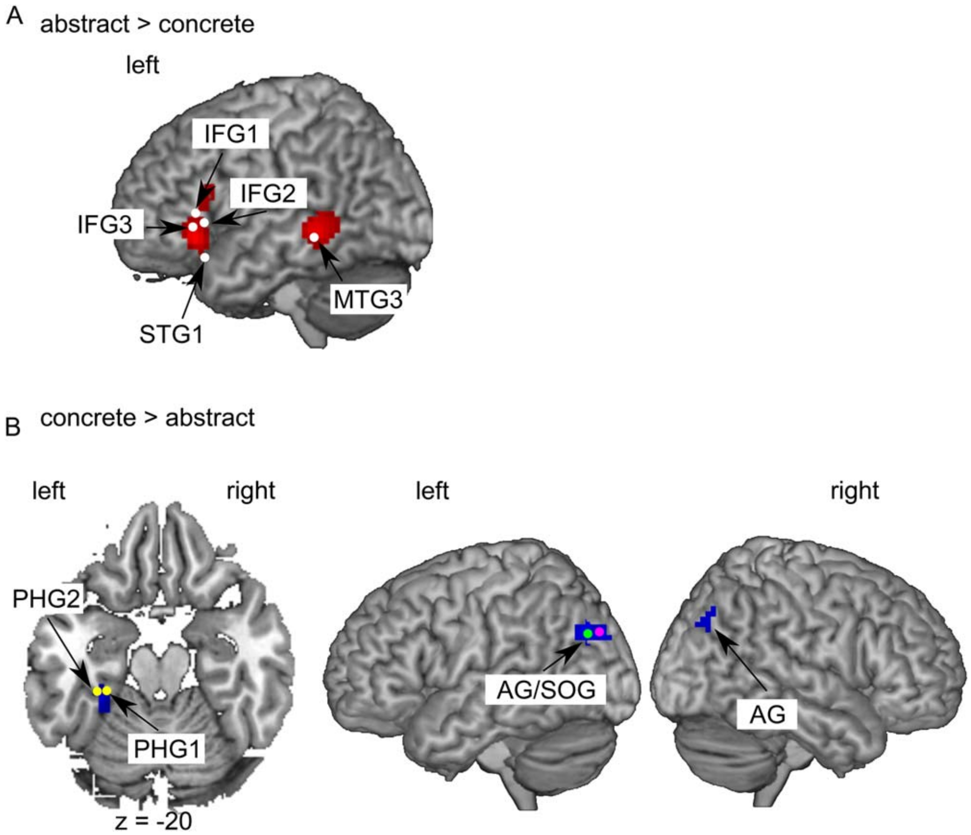

Figure 3.

Results of the functional magnetic resonance imaging study. $N = 43$. (**A**) Red clusters: higher BOLD response when translating abstract nouns in comparison to translating concrete nouns of a foreign language. White dots: centers of the IFG, STG, and MTG ROIs as reported by Wang et al. [2010]. (**B**) Blue clusters: higher BOLD response when translating concrete nouns in comparison to translating abstract nouns of a foreign language. In the left hemisphere, a joint cluster responded that expanded from the AG to the SOG. Yellow dots: centers of the PHG ROIs as reported by Wang et al. [2010]. Green dot: peak voxel when the AG mask of the WFU pickatlas was used as a ROI. Pink dot: peak voxel when the SOG mask of the WFU pickatlas was used as a ROI. IFG: inferior frontal gyrus, STG: superior temporal gyrus, MTG: middle temporal gyrus, AG: angular gyrus, PHG: parahippocampal gyrus, SOG: superior occipital gyrus, ROI: region of interest, BOLD: blood oxygenation level dependent. [Color figure can be viewed at wileyonlinelibrary.com]

functionally interact with regions found previously in the native language. We performed functional connectivity analyses (PPI) on the regions that were responsive in the contrast concrete > abstract nouns (left and right angular gyri, both parahippocampal gyrus clusters, superior occipital gyrus). The psychological variable coded the word category, that is, abstract or concrete word. We entered the time course of the regions identified by the ROI analyses as the physiological regressor in the PPI analysis.

The left angular gyrus showed significant PPI with the posterior part of the left lingual gyrus (MNI coordinates of the peak voxel: $x = -12$, $y = -91$, $z = -5$, $k = 91$, $Z = 3.68$, $P_{FWE} < 0.05$, corrected at the cluster level for the whole brain, Fig. 4A). The lateral parahippocampal gyrus ROI (labeled PHG2 in Fig. 3B) showed significant PPI with a cluster in the posterior cingulate cortex (MNI coordinates of the peak voxel: $x = -12$, $y = -46$, $z = 4$, $k = 113$, $Z = 4.14$, $P_{FWE} < 0.05$, corrected at the cluster level for the whole brain, Fig. 4B) that expanded into both hemispheres. The cluster corresponded to the most inferior one of Wang et al.'s [2010] clusters in the left posterior cingulate cortex (PCC4 in Fig. 1B). There were no significant PPIs when the right angular gyrus, the medial parahippocampal gyrus (labeled PHG1 in Fig. 3B), and the superior occipital gyrus were the seed regions.

Testing interactions between word type and learning condition

The participants learned the foreign nouns under three different learning conditions. Therefore, we also tested for interactions between word type and learning condition. The

TABLE II. Results of the functional magnetic resonance imaging analysis for the contrast abstract > concrete

Brain area	MNI (mm) x	y	z	k	Z
Whole-brain approach					
MTG	−57	−40	−2	148	4.97*
IFG	−48	26	−5	111	4.88*
Wang et al.'s [2010] coordinates used as ROIs					
IFG1#	−51	23	1		3.82**
IFG2#	−48	20	−5		3.39**
IFG3#	−45	23	−5		4.13**
STG1#	−48	20	−8		3.54**
MTG3#	−57	−40	−2		4.97**

Note. $^{**}P_{FWE} < 0.05$, corrected at the peak level, small-volume-corrected for the ROI; $^{*}P_{FWE} < 0.01$, corrected at the cluster level, $k > 10$. ROIs in the IFG, STG, and MTG were 5 mm spheres centered on the coordinates reported by Wang et al. [2010]. #Numbering refers to Figure 1A. MTG: middle temporal gyrus, STG: superior temporal gyrus, IFG: inferior frontal gyrus, ROI: region of interest.

2(word type) × 3(learning condition) repeated measures design was analyzed with an F-test using the full factorial function implemented in SPM8. No cluster reached significance when each experiment was analyzed separately and when we collapsed across the two experiments even at a lenient statistical threshold of $P < 0.001$, uncorrected (except for one cluster in the anterior cingulate for Experiment 2: $x = 3$, $y = 2$, $z = -5$, $k = 4$, $Z = 3.42$, $P < 0.001$ uncorrected. This cluster did not remain significant when FWE-correction was applied and was therefore not interpreted). This indicated that the different learning conditions did not affect the factor of word type.

TABLE III. Results of the functional magnetic resonance imaging control analysis for the contrast abstract > concrete

Brain area	MNI (mm) x	y	z	k	Z
Whole-brain approach					
IFG	−48	26	−5	109	4.82*
MTG	−57	−40	−2	144	4.92*
Wang et al.'s [2010] coordinates used as ROIs					
IFG1#	−51	23	1		3.79**
IFG2#	−48	20	−5		3.36**
IFG3#	−45	23	−5		4.08**
STG1#	−48	20	−8		3.51**
MTG3#	−57	−40	−2		4.92**

Note. $^{**}P_{FWE} < 0.05$, corrected at the peak level, small-volume-corrected for the ROI; $^{*}P_{FWE} < 0.01$, corrected at the cluster level, $k > 10$. ROIs in the IFG, STG, and MTG were 5 mm spheres centered on the coordinates reported by Wang et al. [2010]. #Numbering refers to Figure 1A. MTG: middle temporal gyrus, STG: superior temporal gyrus, IFG: inferior frontal gyrus, ROI: region of interest. The behavioral difference in accuracy between abstract and concrete nouns was included in the design matrix as a covariate.

TABLE IV. Results of the functional magnetic resonance imaging analysis for the contrast concrete > abstract

Brain area	MNI (mm) x	y	z	Z
Whole-brain approach: n.s.				
Wang et al.'s [2010] coordinates used as ROIs				
PHG1+,#	−30	−34	−17	3.25**
PHG2+,#	−33	−34	−17	2.87**
Anatomical masks used as ROIs (WFU pickatlas)				
AG+	−48	−76	31	3.89**
AG+	48	−73	34	3.37**
SOG+	−36	−85	31	3.75**

Note. $^{**}P_{FWE} < 0.05$, corrected at the peak level, small-volume-corrected for the ROI. ROIs in the PHG were 5 mm spheres centered on the coordinates reported by Wang et al. [2010]. +seed regions for the PPI analyses were 5 mm spheres. #Numbering refers to Figure 1B. AG: angular gyrus, PHG: parahippocampal gyrus, SOG: superior occipital gyrus, ROI: region of interest, PPI: psychophysiological interaction.

DISCUSSION

In this study, we investigated the neural representation of abstract and concrete nouns in a foreign language during a translation task. We tested whether both kinds of words are represented in distinct brain areas as shown in studies on abstract and concrete nouns in the native language [Roxbury et al., 2014; Wang et al., 2010]. We found

TABLE V. Results of the functional magnetic resonance imaging control analysis for the contrast concrete > abstract

Brain area	MNI (mm) x	y	z	Z
Whole-brain approach: n.s.				
Wang et al.'s [2010] coordinates used as ROIs				
PHG1#	−30	−34	−17	3.22**
PHG2#	−30	−31	−17	2.86**
Anatomical masks used as ROIs (WFU pickatlas)				
AG	−48	−76	31	3.88**
AG	48	−73	34	3.45**
SOG	−36	−85	31	3.73**

Note. $^{**}P_{FWE} < 0.05$, corrected at the peak level, small-volume-corrected for the ROI. ROIs in the PHG were 5 mm spheres centered on the PHG coordinates reported by Wang et al. [2010]. #Numbering refers to Figure 1B. AG: angular gyrus, PHG: parahippocampal gyrus, SOG: superior occipital gyrus, ROI: region of interest. The behavioral difference in accuracy between abstract and concrete nouns was included in the design matrix as a covariate.

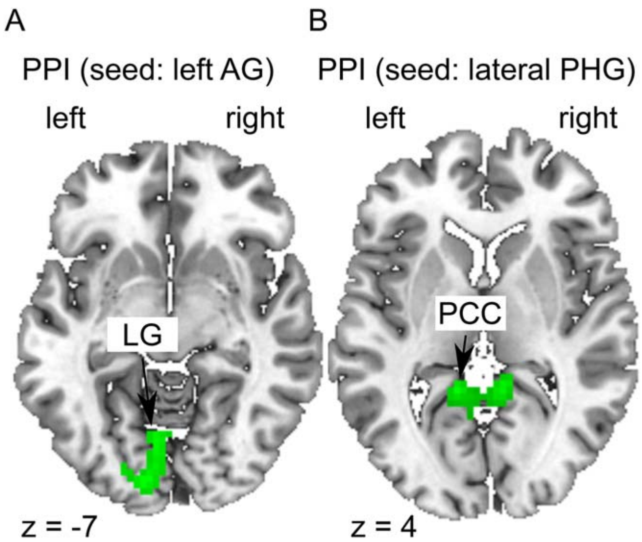

Figure 4.

Result of the PPI analyses. (**A**) The left angular gyrus (AG) was used as a seed region. The left lingual gyurs (LG) had higher functional connectivity with the left AG for concrete in comparison to abstract nouns. (**B**) The left lateral parahippocampal gyrus (labeled PHG2 in Fig. 3B) was used as a seed region. The posterior cingulate cortex (PCC) had higher functional connectivity with the PHG for concrete in comparison to abstract nouns. [Color figure can be viewed at wileyonlinelibrary.com]

that abstract nouns elicited larger responses in contrast to concrete nouns in areas that have been previously implicated in processing abstract nouns in the native language: the left inferior frontal and the left superior and middle temporal gyrus. Concrete nouns elicited larger responses in contrast to abstract nouns in the left parahippocampal gyrus, the left superior occipital gyrus and bilateral angular gyri; areas that have previously been reported to process concrete nouns in the native language. An exploratory analysis revealed higher functional connectivity for concrete in contrast to abstract nouns between the left angular gyrus and the left lingual gyrus as well as between the left parahippocampal gyrus and the posterior cingulate cortex. The posterior cingulate cortex has been previously found to be involved in the processing of concrete nouns in the native language [e.g., Binder et al., 2005; Fliessbach et al., 2006; Harris et al., 2006; Roxbury et al., 2014; Sabsevitz et al., 2005; Wallentin et al., 2005; Wang et al., 2010]. Overall, the results revealed distinct representations for foreign abstract and concrete nouns even after a short learning phase. These representations were comparable to the representations found for the native language [Roxbury et al., 2014; Wang et al., 2010].

Similar representations of native and foreign language are not self-evident. Native and foreign languages are typically learned differently: whereas native language is acquired implicitly in childhood under real life conditions, foreign language is mostly learned in adolescence in a classroom setting. Whether native and foreign languages are represented in the same brain areas was previously studied using different approaches [see Halsband, 2006, for a review]. Studies in patients with brain lesions, for example, suggest differences in the cortical representation of native and foreign language. Such studies have shown that language abilities can differ between foreign and native language with respect to the extent of recovery after brain damage [Fabbro, 1999, 2001]. During tests on vocabulary proficiency on bilinguals with implanted cortical electrodes, Ojemann and Whitaker [1978] found that stimulation of different sites within the temporal cortex impaired either the production of the native, the foreign, or of both languages. Mueller et al. [2005] found that brain responses measured as event-related potentials to several types of grammatical violation differed between native speakers and high-proficiency bilinguals of Japanese. This finding suggests similarities but also differences in the representation of native and foreign language. Overall, there is evidence that cortical representations of foreign and native language converge when proficiency in the foreign language increases [see Abutalebi and Green, 2007]. Given this background, it is remarkable that we found similar word representations for the foreign language in comparison to previous findings for the native language [Halsband et al., 2002; Roxbury et al., 2014; Wang et al., 2010] even after a learning phase that took one week only and participants did not use the foreign language vocabulary in everyday life and had no access to learning materials. Altogether, our results show that even very little experience with the foreign nouns can lead to representations similar to the native language.

Representation of Foreign Abstract Nouns in the Brain

In the comparison between native and foreign noun types, the translation of foreign abstract nouns elicited a left-lateralized fronto-temporal network. This is consistent with the findings of the meta-study by Wang et al. [2010]. Previous research on native language put forward different interpretations for the functional role of the inferior frontal gyrus and the middle temporal gyrus in the representation of abstract nouns. Wang et al. [2010] concluded that the inferior frontal and the middle temporal gyrus are part of a network that enables verbal processing. Fiebach and Friederici [2004], Friederici et al. [2000], Hayashi et al. [2014], and Wang et al. [2010] interpreted the involvement of the inferior frontal gyrus as critical for retrieval of semantic knowledge. Alternatively, the inferior frontal gyrus responses on semantic tasks may originate from differences in task difficulty [Binder et al., 2009]. Thus, the network responses found in our study may reflect greater effort to retrieve semantic meaning for abstract nouns than for concrete nouns. We cannot fully rule out differences in task difficulty: they could have affected the results found for abstract nouns. In fact, participants were significantly less accurate when translating abstract nouns in comparison to concrete nouns [Binder et al., 2005; Jessen et al., 2000]. However, the pattern of brain areas did not change in our study when we controlled for differences in behavioral performance. We, therefore, assume that the responses in the inferior frontal gyrus are—at least partly—due to specific linguistic processes concerning abstract nouns [Fiebach and Friederici, 2004; Friederici et al., 2000; Hayashi et al., 2014; Wang et al., 2010]. The other part of the network involved in processing foreign abstract nouns was a cluster in the left middle temporal gyrus. The posterior portion of the middle temporal gyrus is an area involved in the general processing of semantics in the native language [see Vigneau et al., 2006, for a meta-analysis]. Damage to the left posterior middle temporal gyrus can result in severe deficits in word comprehension [Dronkers et al., 2004]. Binder et al. [2005] found larger responses in the middle temporal gyrus when participants processed both abstract and concrete nouns of the first language in comparison to non-words consisting of letter strings that matched real words with respect to orthography and phonology. Our study revealed that the middle temporal gyrus plays an even greater role for translating abstract nouns in a foreign language than for translating concrete nouns. On our whole-brain analysis, for both the inferior frontal and the middle temporal cluster, the exact location corresponded with two clusters reported by Wang et al. [2010] (peak coordinates were located less then 5 mm away from each other, Fig. 3A). This indicates that the same areas are involved in processing abstract nouns in the native and the foreign language. For general semantic processing, the middle temporal gyrus has recently been identified as a crucial area for semantic control; a cognitive process monitoring semantic associations between concepts (e.g., car and road) and matching concepts according to relevant dimensions [e.g., matching the color red to a stop sign and to a red blossom, as described in Davey et al., 2016]. For our results, the involvement of the middle temporal gyrus may indicate that a higher level of semantic control for the translation of foreign abstract nouns is required than for the translation of foreign concrete nouns.

The ROI analysis revealed a cluster in the anterior superior temporal gyrus (STG1 in Fig. 1) involved in translation of abstract nouns in the foreign language. This finding is consistent with a TMS study in the native language [Papagno et al., 2009]. Papagno et al. [2009] showed that the accuracy in discriminating between abstract nouns and non-words decreased when TMS was administered to the left superior temporal gyrus (BA22). In contrast to Wang et al. [2010], we did not find significant responses in the more posterior superior temporal area (STG2 in Fig. 1A) and the more anterior middle temporal areas (MTG1, MTG2 in Fig. 1A). This might indicate that these areas are not involved in translating foreign abstract nouns because accuracy was high on our task.

In summary, our results revealed that foreign abstract nouns were represented in a network previously found to be involved in processing linguistic aspects of abstract nouns in the native language (inferior frontal gyrus, posterior middle temporal gyrus) [Fiebach and Friederici, 2004] as well as in the superior temporal gyrus but not in the anterior middle temporal gyrus as reported for the native language [e.g., Noppeney and Price, 2004].

Representation of Foreign Concrete Nouns in the Brain

We found that the angular gyri in both hemispheres, a cluster in the left superior occipital gyrus as well as two clusters within the left parahippocampal gyrus elicited larger responses when translating concrete nouns in comparison to translating abstract nouns. Although parietal areas were only reported as a trend in Wang et al.'s [2010] meta-study, a recent study [Roxbury et al., 2014] confirmed that the angular gyri are involved in processing concrete nouns in the native language. For foreign concrete nouns, Halsband et al. [2002] found larger responses in the angular gyri with respect to a pseudoword reading task. Furthermore, Reiterer et al. [2011] showed that the gray matter density of the inferior parietal lobe (which the angular gyrus is a part of) correlated with performance in foreign language sound imitation. The angular gyrus is an area involved in association of heteromodal information of semantic concepts [see Binder et al., 2009; Bonner et al., 2013; Geschwind, 2010; Seghier, 2013; Vigneau et al., 2006]. In other words, the angular gyrus is a critical area for combining semantic (e.g., the written word "apple") and sensory (e.g., the shape of an apple) information. A recent transcranial direct current stimulation study showed that the left angular gyrus played a causal role in the process of combining adjectives and nouns to meaningful concepts [Price et al., 2016]. This study confirms the crucial role of the angular gyrus in semantic processing. Macedonia et al. [2010] found that the left angular gyrus is involved in processing of concrete nouns in a foreign language. In their study, the BOLD signal in the left angular gyrus correlated with high performance on an old-new word-recognition task.

At the anatomical level, Lopez-Barroso et al. [2013] showed that the ability to acquire new words depends on microstructural properties of the arcuate fasciculus; a fiber bundle connecting temporal, parietal and frontal areas. Following a similar route, Rodriguez-Fornells et al. [2009] included the dorsal route in their neurophysiological model of foreign language learning. In our study, the larger responses elicited in the inferior parietal cortex (i.e., the angular gyrus) for concrete nouns in comparison to abstract nouns may reflect a more critical role of the dorsal route for processing concrete nouns.

The concrete nouns selected for our study referred to objects that can be perceived visually. Therefore, it was likely that visual areas are involved in the translation of concrete nouns in the foreign language [Mellet et al., 1998]. First, we found that the areas within the parahippocampal gyrus and the superior occipital gyrus reported by Wang et al. [2010] served in processing concrete foreign words. Areas within the parahippocampal gyrus have previously been found to be critical for processing visual input about natural environments [Epstein and Kanwisher, 1998]. Resent research [Jouen et al., 2015] revealed that the parahippocampal gyrus is part of a network involved in processing both sentences describing scenes and pictures displaying scenes. Altogether, these findings indicate that the parahippocampal gyrus is related to both semantic and visual processing.

Second, the functional connectivity of the left angular gyrus with the left lingual gyrus supports the hypothesis that visual areas are involved in the translation of concrete nouns referring to visual objects. The lingual gyrus is an area associated with visual encoding [Machielsen et al., 2000] and learning of visual patterns [Roland and Gulyas, 1995]. Lesions to the lingual gyri can cause severe visual impairments [Bogousslavsky et al., 1987]. In our study, the functional connectivity of the left angular gyrus with the left lingual gyrus may reflect a process in which the visual representation of the object the word referred to was activated and potentially used to support the translation process [Mayer et al., 2015]. The functional connectivity between the parahippocampal gyrus and the posterior cingulate cortex could be linked to memory processes and mental imagery. It was found that damage to connections between the parahippocampal formation and the posterior cingulate cortex can result in memory deficits [see Vogt et al., 1992, for a review]. For concrete nouns in the native language, Wang et al. [2010] proposed that the posterior cingulate cortex is involved in mental imagery of words. In the present study, the functional connectivity found may have implications at a conceptual level of understanding the representation of recently learned foreign words. In line with the predictions for processing abstract and concrete nouns of the dual coding theory [see Clark and Paivio, 1991, for a review] our functional connectivity analyses may demonstrate that visual areas and areas known to be involved in mental imagery supported the translation of concrete words.

In summary, our results for foreign concrete nouns revealed that consistent with the native language concrete foreign nouns were represented in areas involved in visual processing (parahippocampal gyrus, lingual gyrus), areas associating semantic and sensory information (angular gyri), and areas specialized in mental imagery (posterior cingulate cortex) but not in the precuneus, the culmen, and the fusiform gyrus as reported for the native language [Wang et al., 2010].

Differences between the Representations of Native and Foreign Language in the Brain

Although the brain areas identified for translating foreign nouns correspond with previous findings in the native language, we also found differences. Translating concrete nouns did not involve the precuneus, the fusiform gyrus, and the culmen. Similarly, translating abstract nouns did not involve anterior temporal areas and posterior superior temporal gyrus as reported by Wang et al. [2010]. In our study, this may reflect differences with respect to long-term memory representations of words. Due to the particular paradigm that we used, we investigated representations of nouns that were learned and recalled within a short period of time (8 days after learning started). Previous work indicated that conditions like age of acquisition [e.g., Wattendorf and Festman, 2008] and proficiency [e.g., Moreno and Kutas, 2005] affect the representation of words in the brain [see also Abutalebi and Green, 2007]. Our participants reached high levels of accuracy within the learning phase. Thus, for the representation of foreign nouns, our results might indicate that the precuneus, the fusiform gyrus, the culmen, anterior temporal areas, and the posterior superior temporal gyrus may not be crucial components of vocabulary storage. Instead, these areas might rather represent the rich associations that have been learned for longer and potentially also in real life settings. Differences between the representations of foreign and native words might have also resulted from our region-of-interest approach. We did not measure brain responses when participants processed the German abstract and concrete nouns assigned to the Vimmi words. Individual differences between our participants and the averaged results of the meta-study [Wang et al., 2010] may partially account for our findings.

The translation task used in our paradigm allowed us to only include trials in the analysis in which participants knew the correct meaning of the Vimmi word. We can therefore not rule out that as soon as participants heard the Vimmi word the representation of the German translation got activated. This alternative explanation is generally difficult to rule out with neuroimaging methods in studying representations of foreign languages. In experimental designs in which participants infer meaning from context [e.g., Mestres-Misse et al., 2009], they may complete the part of the sentence containing the novel word with the native language word best fitting the context. Similarly, on old-new recognition tasks [e.g., Kronke et al., 2013; Macedonia et al., 2010] the representation of the native language word corresponding to an old word might directly be activated. Additionally, with old-new recognition tasks it is hard to measure whether participants know the meaning of the foreign word or whether they are only familiar with it. It is, therefore, important to study foreign language representation with different experimental designs and different methods such as invasive [e.g., Ojemann & Whitaker, 1978] and non-invasive brain stimulation [e.g., Papagno et al., 2009] and neuroimaging methods with high temporal resolution [e.g., Kelly et al., 2009] to dissociate response patterns to native and foreign language.

Implications for Models of Vocabulary Acquisition

Rodriguez-Fornells et al. [2009] developed a neurophysiological model that consisted of a network of brain areas involved in inferring word meaning from the context. Participants in our study did not perform this task. They learned the meaning in a designated learning phase. Nevertheless, translating abstract nouns elicited strong responses in areas that are critical parts of the neurophysiological model. The middle temporal gyrus and the inferior frontal gyrus are both part of the sub-network considered the "ventral meaning inference interface" which is one out of three parallel pathways involved in learning the meaning of a novel word. This part of the network stores and retrieves contextual information about novel words. For learning concrete nouns, our results suggest a more critical role of the "dorsal route" within the model. This route connects temporal and inferior parietal areas and is involved in phonological storage and rehearsal of new words [Rodriguez-Fornells et al., 2009]. Our results indicate that there may be differences with respect to the involvement of sub-networks of the model depending on different word types.

Previous studies identified medial temporal areas such as the hippocampus as crucial for learning new vocabulary [Kronke et al., 2013; Ripolles et al., 2016; see Gaskell and Ellis, 2009, for a review]. Kronke et al. [2013] used a similar learning paradigm for novel words as the present study and investigated the representations of these words after learning during an fMRI session. They contrasted BOLD responses to the vocabulary acquired during their learning session with responses to pseudowords and found responses in the left hippocampus. In our whole-brain analyses, we did not find significant clusters in these areas which responded differently depending on whether an abstract or a concrete noun was translated. Given the findings of the previous studies, our results indicate that there are no differences between abstract and concrete foreign nouns that were recently acquired with respect to role of medial temporal areas such as the hippocampus.

The Role of Different Learning Conditions for the Representation of Foreign Abstract and Concrete Nouns

In the present study, foreign nouns were taught using different learning conditions. Previous work suggested that visual occipito-temporal areas play an important role in processing concrete nouns that are high in imagery [e.g., Mellet et al., 1998]. This suggests that visual areas respond to concrete nouns learned with enrichment (i.e., gestures or pictures). We, however, did not find evidence that any brain regions differentially responded to the abstract and concrete nouns depending on the learning condition. In line with this finding, differences in behavioral accuracy were consistent across the two word types (concrete nouns, abstract nouns) with respect to the three learning conditions (no enrichment, picture enrichment, gesture enrichment). The finding is also relevant for the evaluation of the pictures and gestures used to enrich our learning materials [Mestres-Misse et al., 2014; Wiemer-Hastings and Xu, 2005]. The lack of interactions indicated that potential differences in the stimuli (e.g., abstract nouns were displayed as scenes whereas concrete nouns were displayed as single objects or objects embedded in scenes in our picture enrichment condition) did not affect the overall pattern of the BOLD responses elicited by the Vimmi words. Our results imply that the different learning methods for foreign vocabulary used in the present study are equally suited for abstract and concrete nouns [see also Mayer et al., 2015].

CONCLUSION

The results of the present study revealed remarkable similarities between the representations of recently learned abstract and concrete nouns and the representations previously found for native language nouns. There were, however, also some differences as not all regions found previously for native abstract and concrete nouns were also responsive for the recently learned foreign language words used in the present study. With respect to different learning methods, our study indicates that the learning methods used were equally suited for both noun types.

ACKNOWLEDGMENTS

This project was supported by a grant from the Deutsche Forschungsgemeinschaft (grant number KR 3735/3-1) and a Max Planck Research Group Grant to K.v.K.

REFERENCES

Abutalebi J (2008): Neural aspects of second language representation and language control. Acta Psychologica 128:466–478.

Abutalebi J, Green D (2007): Bilingual language production: The neurocognition of language representation and control. J Neurolinguistics 20:242–275.

Barros-Loscertales A, Gonzalez J, Pulvermuller F, Ventura-Campos N, Bustamante JC, Costumero V, Parcet MA, Avila C (2012): Reading salt activates gustatory brain regions: fMRI evidence for semantic grounding in a novel sensory modality. Cereb Cortex 22:2554–2563.

Binder JR, Desai RH, Graves WW, Conant LL (2009): Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. Cereb Cortex 19:2767–2796.

Binder JR, Westbury CF, McKiernan KA, Possing ET, Medler DA (2005): Distinct brain systems for processing concrete and abstract concepts. J Cogn Neurosci 17:905–917.

Bogousslavsky J, Miklossy J, Deruaz JP, Assal G, Regli F (1987): Lingual and fusiform gyri in visual processing - a clinicopathological

study of superior altitudinal hemianopia. J Neurol Neurosurg Psychiatry 50:607–614.
Bonner MF, Peelle JE, Cook PA, Grossman M (2013): Heteromodal conceptual processing in the angular gyrus. Neuroimage 71: 175–186.
Clark JM, Paivio A (1991): Dual coding theory and education. Educ Psychol Rev 3:149–210.
Cousins KAQ, York C, Bauer L, Grossman M (2016): Cognitive and anatomic double dissociation in the representation of concrete and abstract words in semantic variant and behavioral variant frontotemporal degeneration. Neuropsychologia 84:244–251.
Davey J, Thompson HE, Hallam G, Karapanagiotidis T, Murphy C, De Caso I, Krieger-Redwood K, Bernhardt BC, Smallwood J, Jefferies E (2016): Exploring the role of the posterior middle temporal gyrus in semantic cognition: Integration of anterior temporal lobe with executive processes. Neuroimage 137:165–177.
Dronkers NF, Wilkins DP, Van Valin RD, Redfern BB, Jaeger JJ (2004): Lesion analysis of the brain areas involved in language comprehension. Cognition 92:145–177.
Epstein R, Kanwisher N (1998): A cortical representation of the local visual environment. Nature 392:598–601.
Fabbro F (1999): The Neurolinguistics of Bilingualism: An Introduction. New York: Psychology Press.
Fabbro F (2001): The bilingual brain: Cerebral representation of languages. Brain Lang 79:211–222.
Fernandino L, Humphries CJ, Conant LL, Seidenberg MS, Binder JR (2016): Heteromodal cortical areas encode sensory-motor features of word meaning. J Neurosci 36:9763–9769.
Fiebach CJ, Friederici AD (2004): Processing concrete words: fMRI evidence against a specific right-hemisphere involvement. Neuropsychologia 42:62–70.
Fliessbach K, Weis S, Klaver P, Elger CE, Weber B (2006): The effect of word concreteness on recognition memory. Neuroimage 32:1413–1421.
Francis WS, Goldmann LL (2011): Repetition priming within and between languages in semantic classification of concrete and abstract words. Memory 19:653–663.
Friederici AD, Opitz B, von Cramon DY (2000): Segregating semantic and syntactic aspects of processing in the human brain: An fMRI investigation of different word types. Cereb Cortex 10:698–705.
Friston KJ, Zarahn E, Josephs O, Henson RNA, Dale AM (1999): Stochastic designs in event-related fMRI. Neuroimage 10:607–619.
Gaskell MG, Ellis AW (2009): Word learning and lexical development across the lifespan. Philos Trans R Soc B Biol Sci 364: 3607–3615.
Geschwind N (2010): Disconnexion syndromes in animals and man: Part I. Neuropsychol Rev 20:128–157.
Gonzalez J, Barros-Loscertales A, Pulvermuller F, Meseguer V, Sanjuan A, Belloch V, Avila C (2006): Reading cinnamon activates olfactory brain regions. Neuroimage 32:906–912.
Halsband U (2006): Bilingual and multilingual language processing. J Physiol Paris 99:355–369.
Halsband U, Krause BJ, Sipila H, Teras M, Laihinen A (2002): PET studies on the memory processing of word pairs in bilingual Finnish-English subjects. Behav Brain Res 132:47–57.
Harris GJ, Chabris CF, Clark J, Urban T, Aharon I, Steele S, McGrath L, Condouris K, Tager-Flusberg H (2006): Brain activation during semantic processing in autism spectrum disorders via functional magnetic resonance imaging. Brain Cogn 61:54–68.
Hayashi A, Okamoto Y, Yoshimura S, Yoshino A, Toki S, Yamashita H, Matsuda F, Yamawaki S (2014): Visual imagery while reading concrete and abstract Japanese kanji words: An fMRI study. Neuroscience Research 79:61–66.
Hoffman P, Binney RJ, Ralph MAL (2015): Differing contributions of inferior prefrontal and anterior temporal cortex to concrete and abstract conceptual knowledge. Cortex 63:250–266.
Huang HW, Lee CL, Federmeier KD (2010): Imagine that! ERPs provide evidence for distinct hemispheric contributions to the processing of concrete and abstract concepts. Neuroimage 49: 1116–1123.
Jessen F, Heun R, Erb M, Granath DO, Klose U, Papassotiropoulos A, Grodd W (2000): The concreteness effect: Evidence for dual coding and context availability. Brain Lang 74:103–112.
Jouen AL, Ellmore TM, Madden CJ, Pallier C, Dominey PF, Ventre-Dominey J (2015): Beyond the word and image: Characteristics of a common meaning system for language and vision revealed by functional and structural imaging. Neuroimage 106:72–85.
Kelly SD, McDevitt T, Esch M (2009): Brief training with co-speech gesture lends a hand to word learning in a foreign language. Lang Cogn Process 24:313–334.
Kemmerer D (2014): Word classes in the brain: Implications of linguistic typology for cognitive neuroscience. Cortex 58:27–51.
Khader PH, Jost K, Mertens M, Bien S, Rosler F (2010): Neural correlates of generating visual nouns and motor verbs in a minimal phrase context. Brain Res 1318:122–132.
Klostermann EC, Kane AJM, Shimamura AP (2008): Parietal activation during retrieval of abstract and concrete auditory information. Neuroimage 40:896–901.
Kronke KM, Mueller K, Friederici AD, Obrig H (2013): Learning by doing? The effect of gestures on implicit retrieval of newly acquired words. Cortex 49:2553–2568.
Lehmann D, Pascual-Marqui RD, Strik WK, Koenig T (2010): Core networks for visual-concrete and abstract thought content: A brain electric microstate analysis. Neuroimage 49:1073–1079.
Liljestrom M, Tarkiainen A, Parviainen T, Kujala J, Numminen J, Hiltunen J, Laine M, Salmelin R (2008): Perceiving and naming actions and objects. Neuroimage 41:1132–1141.
Lopez-Barroso D, Catani M, Ripolles P, Dell'Acqua F, Rodriguez-Fornells A, de Diego-Balaguer R (2013): Word learning is mediated by the left arcuate fasciculus. Proc Natl Acad Sci USA 110:13168–13173.
Macedonia M, Knosche TR (2011): Body in mind: How gestures empower foreign language learning. Mind Brain Educ 5:196–211.
Macedonia M, Muller K, Friederici AD (2010): Neural correlates of high performance in foreign language vocabulary Learning. Mind Brain Educ 4:125–134.
Macedonia M, Muller K, Friederici AD (2011): The impact of iconic gestures on foreign language word learning and its neural substrate. Hum Brain Mapp 32:982–998.
Machielsen WCM, Rombouts S, Barkhof F, Scheltens P, Witter MP (2000): fMRI of visual encoding: Reproducibility of activation. Hum Brain Mapp 9:156–164.
Maldjian JA, Laurienti PJ, Kraft RA, Burdette JH (2003): An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. Neuroimage 19:1233–1239.
Martensson F, Roll M, Apt P, Horne M (2011): Modeling the meaning of words: Neural correlates of abstract and concrete noun processing. Acta Neurobiol Exp 71:455–478.
Mayer KM, Yildiz IB, Macedonia M, von Kriegstein K (2015): Visual and motor cortices differentially support the translation of foreign language words. Curr Biol 25:530–535.

Mellet E, Tzourio N, Denis M, Mazoyer B (1998): Cortical anatomy of mental imagery of concrete nouns based on their dictionary definition. Neuroreport 9:803–808.

Mestres-Misse A, Munte TF, Rodriguez-Fornells A (2009): Functional neuroanatomy of contextual acquisition of concrete and abstract words. J Cogn Neurosci 21:2154–2171.

Mestres-Misse A, Munte TF, Rodriguez-Fornells A (2014): Mapping concrete and abstract meanings to new words using verbal contexts. Second Lang Res 30:191–223.

Moreno EM, Kutas M (2005): Processing semantic anomalies in two languages: An electrophysiological exploration in both languages of Spanish-English bilinguals. Cogn Brain Res 22: 205–220.

Mueller JL, Hahne A, Fujjj Y, Friederici AD (2005): Native and nonnative speakers' processing of a miniature version of Japanese as revealed by ERPs. J Cogn Neurosci 17:1229–1244.

Mugler JP, Brookeman JR (1990): Three-dimensional magnetization-prepared rapid gradient-echo imaging (3D MP RAGE). Magn Reson Med 15:152–157.

Noppeney U, Price CJ (2004): Retrieval of abstract semantics. Neuroimage 22:164–170.

Ojemann GA, Whitaker HA (1978): Language localization and variability. Brain Lang 6:239–260.

Paivio A, Yuille JC, Madigan SA (1968): Concreteness imagery and meaningfulness values for 925 nouns. J Exp Psychol 76:1–25.

Papagno C, Fogliata A, Catricala E, Miniussi C (2009): The lexical processing of abstract and concrete nouns. Brain Res 1263: 78–86.

Price AR, Peelle JE, Bonner MF, Grossman M, Hamilton RH (2016): Causal evidence for a mechanism of semantic integration in the angular gyrus as revealed by high-definition transcranial direct current stimulation. J Neurosci 36:3829–3838.

Reilly J, Kean J (2007): Formal distinctiveness of high- and low-imageability nouns: Analyses and theoretical implications. Cogn Sci 31:157–168.

Reiterer SM, Hu X, Erb M, Rota G, Nardo D, Grodd W, Winkler S, Ackermann H (2011): Individual differences in audio-vocal speech imitation aptitude in late bilinguals: Functional neuroimaging and brain morphology. Front Psychol 2:1–12.

Ripolles P, Marco-Pallares J, Alicart H, Tempelmann C, Rodriguez-Fornells A, Noesselt T (2016): Intrinsic monitoring of learning success facilitates memory encoding via the activation of the SN/VTA-Hippocampal loop. Elife 5:e17441.

Rodriguez-Fornells A, Cunillera T, Mestres-Misse A, de Diego-Balaguer R (2009): Neurophysiological mechanisms involved in language learning in adults. Philos Trans R Soc B Biol Sci 364:3711–3735.

Roland PE, Gulyas B (1995): Visual memory, visual-imagery, and visual recognition of large field patterns by the human brain - functional-anatomy by positron emission tomography. Cereb Cortex 5:79–93.

Roxbury T, McMahon K, Copland DA (2014): An fMRI study of concreteness effects in spoken word recognition. Behav Brain Funct 10:34.

Sabsevitz DS, Medler DA, Seidenberg M, Binder JR (2005): Modulation of the semantic system by word imageability. Neuroimage 27:188–200.

Seghier ML (2013): The angular gyrus: Multiple functions and multiple subdivisions. Neuroscientist 19:43–61.

Shallice T, Cooper RP (2013): Is there a semantic system for abstract words? Front Hum Neurosci 7:175.

Shibahara N, Wagoner BL (2002): Hemispheric asymmetry in accessing word meaning concrete and abstract nouns. Percept Mot Skills 94:1292–1300.

Soros P, Cornelissen K, Laine M, Salmelin R (2003): Naming actions and objects: Cortical dynamics in healthy adults and in an anomic patient with a dissociation in action/object naming. Neuroimage 19:1787–1801.

Vigliocco G, Kousta ST, Della Rosa PA, Vinson DP, Tettamanti M, Devlin JT, Cappa SF (2014): The neural representation of abstract words: The role of emotion. Cereb Cortex 24:1767–1777.

Vigneau M, Beaucousin V, Herve PY, Duffau H, Crivello F, Houde O, Mazoyer B, Tzourio-Mazoyer N (2006): Meta-analyzing left hemisphere language areas: Phonology, semantics, and sentence processing. Neuroimage 30:1414–1432.

Vogt BA, Finch DM, Olson CR (1992): Functional heterogeneity in cingulate cortex: The anterior executive and posterior evaluative regions. Cereb Cortex 2:435–443.

Wallentin M, Ostergaard S, Lund TE, Ostergaard L, Roepstorff A (2005): Concrete spatial language: See what I mean? Brain Lang 92:221–233.

Wang J, Conder JA, Blitzer DN, Shinkareva SV (2010): Neural representation of abstract and concrete concepts: A meta-analysis of neuroimaging studies. Hum Brain Mapp 31:1459–1468.

Wattendorf E, Festman J (2008): Images of the multilingual brain: The effect of age of second language acquisition. Annu Rev Appl Linguist 28:3–24.

Weiss S, Rappelsberger P (1996): EEG coherence within the 13–18 Hz band as a correlate of a distinct lexical organisation of concrete and abstract nouns in humans. Neurosci Lett 209:17–20.

Wiemer-Hastings K, Xu X (2005): Content differences for abstract and concrete concepts. Cogn Sci 29:719–736.

Zhang Q, Guo CY, Ding JH, Wang ZY (2006): Concreteness effects in the processing of Chinese words. Brain Lang 96:59–68.