MIND, BRAIN, AND EDUCATION

Neural Correlates of High Performance in Foreign Language Vocabulary Learning

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ABSTRACT—Learning vocabulary in a foreign language is a laborious task which people perform with varying levels of success. Here, we investigated the neural underpinning of high performance on this task. In a within-subjects paradigm, participants learned 92 vocabulary items under two multimodal conditions: one condition paired novel words with iconic gestures and the other with meaningless gestures. Memory performance was assessed through single-word translation tests. High performers consistently learned more items than low performers, regardless of the training condition, the time, and the difficulty of the task. Brain activity measured upon word recognition using functional magnetic resonance imaging was parametrically related to the behavioral data. High performance correlated with activity in the left angular gyrus (BA 39) and in the right extrastriate cortex (BA 19). These cortical areas mediate integration of information across different modalities as well as memory processes. Thus, high performance in vocabulary learning seems to depend on individual capacities to integrate and associate a word's semantics with sensorial stimuli. This may have important implications for education.

Ensuring that vocabulary items are not forgotten over time has always been a challenge in language learning and teaching. Multiple factors contribute to the memorization of new words. Some of them are endogenous and encompass individual capacities that have been described as phonological memory (Baddeley, 1998), the interplay between phonological and long-term memory (Gathercole, 2006), or more recently as phonological sensitivity (Morra & Camba, 2009). Furthermore, learning new words is related to the capacity to associate them with preexisting semantic representations (Dobel et al., 2009).

Other factors like input structure and training are exogenous. The way words are shaped, that is, their phonotactics, often determines their learnability. Some words are easier to acquire because of their peculiarity and associability (Dunabeitia, Carreiras, & Perea, 2008).

Educators can substantially influence two factors in language learning; these encompass the way learners are trained and their motivation. With regard to training, new strategies have been introduced in formal instruction. Whereas in the past learners were mainly exposed to listening and reading materials, nowadays multimodal teaching is quite widespread. Pictures, videos, and music accompany text and enrich new vocabulary in the foreign language. Also, cospeech gestures, although not as widespread, have proved to have an impact on vocabulary acquisition (Kelly, McDevitt, & Esch, 2009; Macedonia, 2003). Multimodal strategies confer a multisensory connotation to novel lexical material and encode it deeply, thereby improving its learnability and longevity (Shams & Seitz, 2008). However, it can be observed that, independent of the training learners undergo, memory performance can vary considerably within homogeneous populations like students in language classes in high schools and universities.

Among educationalists, motivation is also considered a key factor in learning foreign languages. Gardner introduced the distinction between integrative and instrumental motivation (Gardner & Lambert, 1959). Integrative motivation "involves an interest in learning the language because of a sincere and personal interest in the people and culture represented by the other language group." Instrumental motivation is the "combination of effort and desire to achieve the goal of learning the language." Although over the years the concept of motivation has been controversial and described differently in numerous theories, recent research on motivation still emphasizes the importance of the goal (Pintrich, Meece, & Schunk, 2008). Learners' goals provide impetus in order to produce cognitive and overt actions leading to learning. Hence,

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educators can instill and sustain motivation as a process geared to attaining the learners' goal(s) (Alderman, 2007). However, although there is a great deal of emphasis placed on the need for classroom practitioners to motivate learners (Brophy, 2010), motivation does not seem to reliably correlate with learning performance. Moreover, motivation is hard to control in experimental settings (Keller, 2009).

Learning performance is a rather complex phenomenon encompassing many factors including those of brain functions that might differ from subject to subject. In neuroscience, little is known about the brain functions determining superior learning performance—in our specific case, vocabulary learning. Therefore, the aim of the present study was to investigate neural processes determining this skill and to target the brain areas that mediate it.

In a within-subjects experiment, participants learned novel words by pairing them with both iconic and meaningless gestures. Iconic cospeech gestures have proved to have an impact on verbal memory (Zimmer & Engelkamp, 2003) compared with pure verbal encoding. Therefore, iconic gestures are considered to be facilitating in our experimental paradigm. We expect subjects to perform better when using them during word encoding. Meaningless gestures, on the other hand, interfere with the semantics of the words they accompany (Kelly, Creigh, & Bartolotti, 2010; Macedonia, Müller, & Friederici, in press). This learning condition can be considered as impeding. We expect subjects to perform poorly when using meaningless gestures, with high performers overcoming difficulties better. We hypothesize that altogether high performers will learn more vocabulary items compared with low performers. Further, we hypothesize that high performers will also use the facilitating condition to their advantage but that they might not show significant differences in performance in their learning behavior between both the facilitating and the impeding training.

METHOD

In experiment 1, a within-subjects learning experiment, we trained participants to learn new vocabulary items by means of cospeech gestures and we recorded the subjects' memory performance. In experiment 2, we first acquired brain data related to word recognition. Thereafter, we correlated the subjects' brain activity with their behavioral performance in order to detect areas that are involved in successful vocabulary learning and investigate the functions related to it.

Experiment 1

Participants

Thirty-three native German-speaking participants (mean age 23.17, $M = 25$, $SD = 1.61$; 17 females, 16 males) were trained in two groups to counterbalance training conditions. All participants were recruited from the institute's database. They were right handed, with no reported history of neurological or language disorders.

Pretesting

Prior to the experiments, we tested participants in a German nonword repetition task in order to evaluate phonogical short-term memory and the capacity to learn novel words (Gathercole, 2006). Further, we administrated a verbal intelligence test in the participants' mother tongue, German (Hamburg-Wechsler-Intelligenztest für Erwachsene; Tewes, 1998). Then we interviewed participants on previous experience with foreign language learning, music, and sports. We asked participants about the number of languages they had learned, their level of proficiency, their learning habits, and their opinion on the efficiency of the language lessons during school time. Further, we asked whether participants had learned to play an instrument and, if so, to what degree of expertise. We also wanted to know whether participants practice any sports. Our aim was to detect potential correlations between participants' previous experience with foreign language learning and their performance during the experiment and also possible connections between their ability to learn foreign languages, their musicality, and their attitudes toward sensorimotor learning.

Procedure

The training material comprised vocabulary items of an artificial corpus called Vimmi (Table 1). We opted for an artificial corpus in order to avoid similarities between languages known to the subjects and the target language, thereby hindering participants memorizing items by means of association. The 92 vocabulary items were automatically generated by a script in Perl, a general-purpose programming language for text manipulation (Hammond, 2003). They conformed with Italian phonotactic rules and were controlled for tautological occurrence of syllables, high frequency of particular consonants or vowels, appearance of strings sounding unusual to German-speaking subjects, associability with words from European languages previously learned by the subjects, and similarity to common proper nouns comprising names of products available on the German market. Considering phonotactics in Vimmi, semantics, and frequency of the words in German, the items were equally distributed across the two training conditions in a counterbalanced manner. For the scanning session, 23 items which were unknown to the participants were additionally created (Table 2).

During the training, participants were instructed to watch a video showing an actress performing a cospeech gesture (Figure 1). Synchronously, the word in Vimmi was played aloud and appeared under the video, first in Vimmi then followed by its translation into German (the participants' mother tongue). Thereafter, participants were instructed to

Table 1
Vimmi Corpus With Corresponding Translations Into German and English

Number	*Vimmi*	*German*	*English translation*
1	fo	Reißverschluss	Zip
2	dra	Ohrring	Earring
3	bae	Pfeffermühle	Pepper mill
4	lefu	Petersilie	Parsley
5	bati	Besen	Broom
6	zude	Becher	Mug
7	paltra	Treppe	Stair
8	pewo	Föhn	Hair-dryer
9	geloro	Gießkanne	Ewer
10	kabida	Taschentuch	Handkerchief
11	lamube	Seife	Soap
12	denule	Regal	Shelf
13	urabe	Geige	Violin
14	kiale	Stempel	Stamp
15	boreda	Faden	Thread
16	wobeki	Tempel	Temple
17	fesuti	Stuhl	Chair
18	pigemola	Kaffee	Coffee
19	ruzanego	Brücke	Bridge
20	saluzafo	Erde	Earth
21	loeke	Blume	Flower
22	keme	Shampoo	Shampoo
23	bikute	Pullover	Pullover
24	ri	Kirsche	Cherry
25	lun	Autowaschanlage	Car wash site
26	ean	Nagellack	Nail polish
27	tola	Baumstamm	(Tree) trunk
28	gosa	Spitzer	(Pencil) sharpener
29	kudi	Fächer	Fan
30	mogra	Sekt	(Sparkling) wine
31	wari	Streichholz	Match
32	dalefi	Zange	Pincer
33	furome	Handschuh	Hand glove
34	nobani	Gabel	Fork
35	pabezi	Kopfhörer	Headset
36	esepo	Würfel	Die
37	zuowe	Socken	Sock
38	lenope	Brille	Eyeglasses
39	deschoga	Hammer	Hammer
40	nokaschu	Koffer	Suitcase
41	dikemori	Flugzeug	Airplaine
42	lodefawi	Boot	Boat
43	beropuga	Fenster	Window
44	toari	Antenne	Antenna
45	tizo	Lippenstift	Lipstick
46	tofita	Bürgersteig	Sidewalk
47	wa	Serviette	Napkin
48	rel	Halskette	Necklace
49	iol	Wattestäbchen	Cotton bud
50	doba	Zahnpasta	Tooth paste
51	nado	Zweig	Twig
52	seza	Deckel	Lid
53	fapro	Butter	Butter
54	piba	Bohrmaschine	Drill
55	pukoni	Wasserhahn	Water tap
56	ratube	Klebeband	Tape
57	wepuda	Gebirge	Mountain
58	fukepa	Mütze	Bonnet
59	ilado	Schere	Scissors
60	foine	Schale	Bowl
61	zagido	Seil	Rope
62	zobako	Käse	Cheese
63	koneru	Schlüssel	Key
64	wubonige	Kreuz	Cross
65	mulogite	Regen	Rain
66	miresado	Dach	Roof
67	peabe	Käfig	Cage
68	detu	Birne	Pear
69	rowite	Wiege	Cradle
70	gu	Spülmittel	Dish liquid
71	nen	Kürbis	Pumpkin
72	gao	Radiergummi	Eraser
73	gitu	Briefmarke	(Postage) stamp
74	tedo	Flöte	Flute
75	lasi	Blech	Plate
76	brido	Handtuch	Towel
77	fola	Krücke	Crutch
78	renobe	Säge	Saw
79	mofire	Gebiss	Denture
80	koludi	Parfüm	Perfume
81	lofuse	Krawatte	Necktie
82	uteli	Knopf	Button
83	woade	Schwamm	Sponge
84	dirube	Zettel	Slip (of paper)
85	sabelo	Thermometer	Thermometer
86	ganuma	Messer	Knife
87	tanedila	Welle	Wave
88	mapusebo	Telefon	Telephone
89	kadonega	Spiegel	Mirror
90	raone	Fernbedienung	Remote control
91	kewo	Banane	Banana
92	nukile	Poster	Poster

repeat the novel word aloud and to imitate the gesture. Participants were trained for 4 days, consisting of four sessions each. Every session lasted 29 min and contained 23 items, randomly subdivided into four smaller blocks. Each block was played six times, with the words randomized within each block. Altogether, every vocabulary item was presented 13 times daily. Training sessions changed in their order daily, alternating and counterbalancing iconic gestures and meaningless gestures. Memory performance was assessed previous to training starting from the second day. Participants translated randomized lists of the 92 items practiced from Vimmi into German and vice versa (duration 7.5 min each).

RESULTS AND DISCUSSION

Experiment 1

The average retrieval performance for the 33 participants over the four time points was a mean value of 55.66% ($SD = 15.66$)

Table 2
Unfamiliar Words in Vimmi Used for the Scanning Procedure

Number	*Unknown Words*	*German*	*English translation*
93	pe	—	—
94	tro	—	—
95	oem	—	—
96	fale	—	—
97	sago	—	—
98	fenu	—	—
99	grema	—	—
100	loni	—	—
101	dakalo	—	—
102	turone	—	—
103	neludo	—	—
104	zefako	—	—
105	ameda	—	—
106	doiku	—	—
107	menako	—	—
108	schaboki	—	—
109	paramo	—	—
110	madimoke	—	—
111	wozalefu	—	—
112	rifupoge	—	—
113	laimo	—	—
114	luto	—	—
115	kelasi	—	—

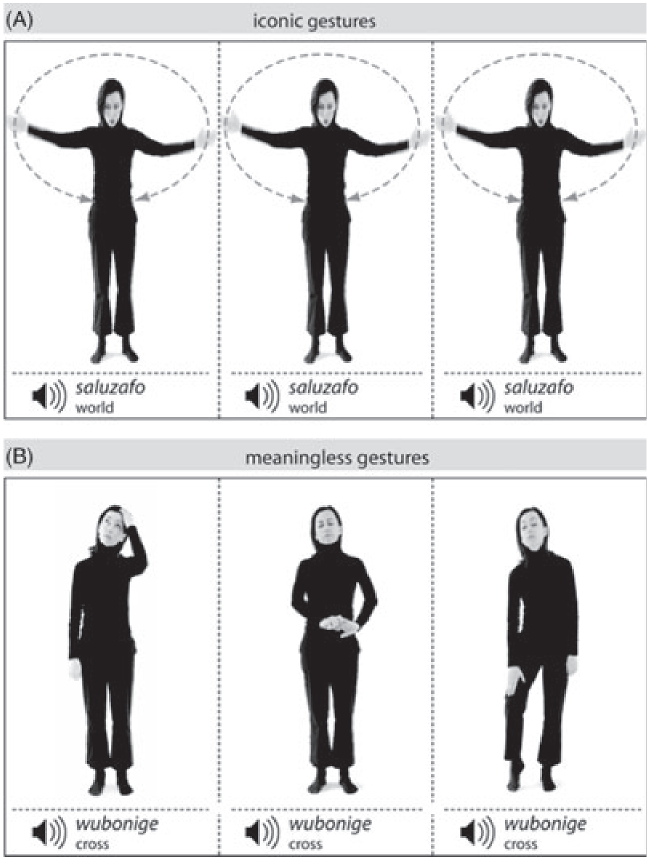

Fig. 1. Training material. Images from the videos used for the two training conditions. (A) Iconic and (B) meaningless gestures. The videos showed an actress performing the gestures to be imitated. The word was played aloud and appeared at the bottom of the screen in Vimmi, the artificial language. The translation into German followed after 3.5 ms. Participants were instructed to perform the gesture while saying the word aloud.

(training conditions and translation direction aggregated). The median value of 56.38% split the group into two subgroups: 17 high performers (12 females and 5 males) and 16 low performers (6 females and 10 males), with a mean performance of 68.71% ($SD = 6.09$) against a mean performance of 41.79% ($SD = 9.24$), respectively. Table 3 illustrates the overall performance for both subgroups at four time points. When considering the dependent variable's overall performance (i.e., mean retrieval aggregated for training and translation direction) in the repeated measures analysis of variance (ANOVA) with the within-subjects factor "time" and the between-subjects factor "group," the main effect "time" is significant, $F(1,31) = 883.21$, $p < .001$, and there is also a significant interaction between "time and group," $F(3,93) = 10.45$, $p < .001$.

In order to assess the influence of training and task difficulty on performance, we computed a repeated-measures ANOVA with the within-subjects factors "training" (iconic gestures and meaningless gestures), "time" (day 01 to day 04), "task difficulty" (translation from Vimmi into German, the easier task, and from German into Vimmi, the more difficult task), and the factor "group" (high and low performers) as a between-subjects factor.

The main effects of "training," "time," and "task difficulty" were significant, $F(1,31) = 22.47$, $p < .001$; $F(3,93) = 681.61$, $p < .001$; and $F(1,31) = 117.36$, $p < .001$, respectively. All participants benefited from using iconic gestures, progressed with time and they were better at translating from the foreign language into their mother tongue. The kind of training definitely had an impact on performance which was consistent over time, as indicated by the significant interaction between "time" and "training," $F(3,93) = 6.46$, $p < .01$. There was also a significant interaction between "time" and "group," $F(3,93) = 3.71$, $p < .10$. In fact, as the graphs in Figures 2 and 3 show, compared with low performers, high performers learned faster, starting with a steep increase on day 1 and reaching a ceiling toward the end of the training. Also, a significant interaction between "time," "group," and "task difficulty," $F(3,93) = 9.58$, $p < .001$, confirms that high performers learned faster in both language directions.

In sum, high performers learned more and faster, which provides evidence in support of our first hypothesis. Contradictory to our second hypothesis, both subpopulations showed similar learning behavior: retrieval performance was affected by all three factors, that is, training, time, and task difficulty. This result suggests that performance in vocabulary learning is only partially driven by the strategy of encoding and

Table 3
Differences in Performance in Vocabulary Learning Between High and Low Performers During the Training (Days 01–04)

	Total Performance % Items	*SD %*	*High Performers % Items*	*SD %*	*Low Performers % Items*	*SD %*
Day 01	19.28	10.52	27.39	8.18	10.66	3.33
Day 02	52.43	18.11	67.29	9.3	36.65	9.5
Day 03	71.45	19.41	86.76	7.43	55.19	14.06
Day 04	79.47	17.58	93.41	5.28	64.67	13.27

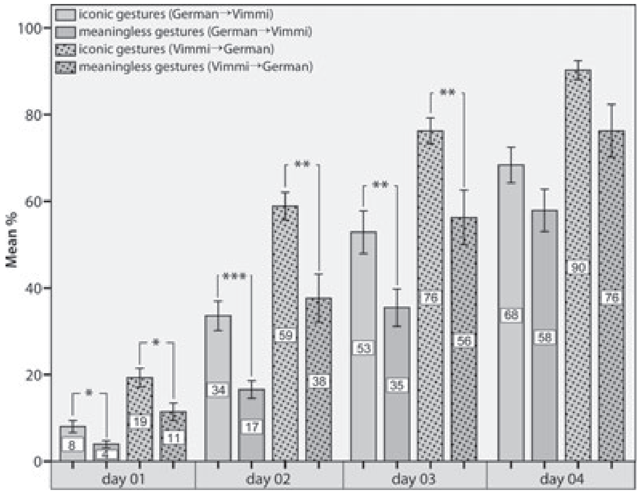

Fig. 2. Low performers' daily retrieval scores in the written translation from German into Vimmi and vice versa. Iconic gestures significantly helped to retrieve vocabulary compared with meaningless gestures at three time points and in both translation directions. In this and subsequent figures, error bars represent ±1 *SE*. $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

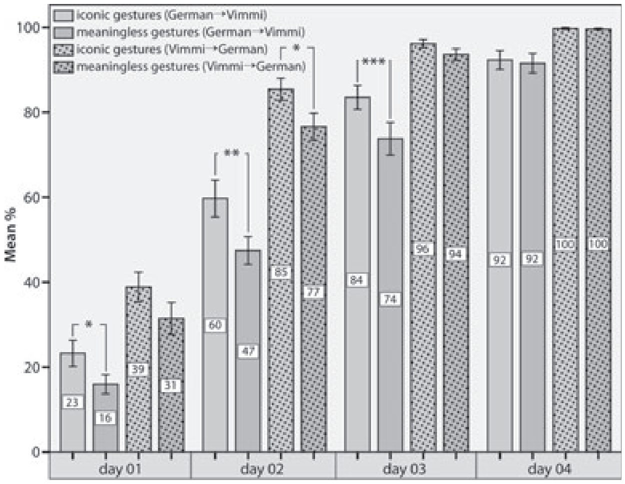

Fig. 3. High performers' daily retrieval scores in the written translation from German into Vimmi and vice versa. Besides day 2, iconic gestures induced significantly better vocabulary retrieval only in the more difficult translation direction, that is, from German into Vimmi.

the difficulty of the task. High performance, here the skill to acquire more vocabulary items independent of manipulations, must reside in individual capacities.

Interestingly, we found no correlations between the participants' behavioral performance assessed during the experiment, the pretesting scores from the nonword repetition task, and the verbal intelligence test. Also, there were no dependencies between the behavioral performance and previous experiences with foreign languages, music, and sport practice. Hence, we could not detect any potential predictors for superior performance in vocabulary learning through gestures from previously acquired capacities and skills.

As far as we could observe, motivation did not play a role in our experiment. Besides the payment (a plausible goal also mentioned by the participants), subjects had no other sources of motivation known to the experimenters. In fact, participants were not told to which language the words they were learning belong. Participants could not make any active use of the vocabulary items, completed anonymous forms during testing, and were not personally rewarded. Thus, although we did not actively control for motivation, we are convinced that no integrative or instrumental motivation could influence the experiment's results.

Taking the above considerations into account, in order to elucidate differences between high and low performers in brain functions determining these capacities, we recorded functional magnetic resonance imaging (fMRI) data relative to novel word acquisition, as described in experiment 2.

Experiment 2

Participants

Eighteen randomly selected subjects (mean age 23.44, median = 25, *SD* = 1.38, 10 females, 8 males) from the 33 subjects who participated in experiment 1 took part in the fMRI experiment.

Procedure

Before entering the fMRI scanner, participants were instructed that they would be aurally and visually presented with trained and unknown words. Their task would be to target unknown words and press a button with their left hand if they detected any. In the fMRI scanner, participants were randomly presented with the 92 words they had previously learned (Table 1) intermixed with 23 unknown items (Table 2). The stimulus was introduced with a fixation cross for 300 ms. The Vimmi word followed and remained on the screen for 1,000 ms. The interstimulus interval lasted 8,000 ms. All training conditions were balanced across the presentation blocks. The entire scanning session comprised 138 trials. It included 92 trained items, 23 fillers, and 23 null events (low-level baseline). During the null event trials, participants saw a black screen for 10 s. All items were presented in pseudo-randomized order in a single block lasting 23 min. An event-related paradigm was used with 10 s epochs to measure the blood-oxygen-level dependence (BOLD) response.

Neuroimaging Parameters

A 3-T Bruker (Ettlingen, Germany) Medspec 30/100 system acquired 20 axial slices (4 mm thick, 1-mm interslice distance, FOV 19.2 cm, data matrix of 64 × 64 voxels, inplane resolution of 3 × 3 mm) every 2 s during functional measurements (BOLD sensitive gradient EPI sequence, TR = 2 s, TE = 30 ms, flip angle = 90°, acquisition bandwidth = 100 Hz). Prior to functional imaging, T1-weighted modified driven equilibrium Fourier transform (MDEFT) images (data matrix 256 × 256, TR = 1.3 s, TE = 10 ms) were obtained with a nonslice-selective inversion pulse followed by a single excitation of each slice (Norris, 2000). These images were used to coregister functional scans with previously obtained high-resolution whole-head three-dimensional (3D) brain scans: 128 sagittal slices, 1.5-mm thickness, FOV 25.0 × 25.0 × 19.2 cm, data matrix of 256 × 156 voxels.

Analysis

The fMRI data were analyzed using the Lipsia software package (Lohmann et al., 2001). Functional data were corrected for motion and the temporal offset between the slices. Thereafter, functional slices were aligned with a 3D stereotactic coordinate reference system. The registration parameters were acquired on the basis of the MDEFT slices to achieve an optimal match between these slices and the individual 3D reference data set which was standardized to the Talairach stereotactic space (Talairach & Tournoux, 1988).

The registration parameters were further used to transform the functional slices using trilinear interpolation, so that the resulting functional slices were aligned with the stereotactic coordinate system. In the last step of preprocessing, the data were smoothed with a Gaussian filter of 10 mm FWHM and a temporal high-pass filter with a cutoff frequency of 1/100 Hz was applied. Statistically, we used a parametric analysis to investigate those areas whose activity showed a positive relation between regional brain activity with increasing levels of memory performance. The statistical evaluation was based on a general linear regression (Neumann & Lohmann, 2003). As a regressor, we used the behavioral performance of the subjects. Prewhitening was applied to the data (Worsley et al., 2002). Statistical inference often assumes independent and identically distributed random variables. However, in practical applications this assumption may be violated. Whitening is a decorrelation method that creates new random variables which are uncorrelated and have the same variances as the original random variables. Finally, the linear model was reestimated using least squares on the whitened data to produce estimates of effects and their standard errors. The design matrix was generated using the canonical hemodynamic response function (Friston et al., 1998). Subsequently, contrast images were generated by computing the difference between the parameter estimates of the iconic and meaningless condition. All contrast images were entered into a second-level random effects analysis. A one-sample t test was performed to evaluate whether observed iconic–meaningless differences were significantly different from zero (t values were transformed into z values). The results were corrected for multiple comparisons using cluster-size and cluster-value thresholds obtained by Monte Carlo simulations using a significance level of $p < .05$ (clusters in the resulting maps hemispheric symmetry was also taken into account (Lohmann, Neumann, Müller, Lepsien, & Turner, 2008). In addition to the one-sample t test, a regression analysis was performed using a behaviorally obtained parameter of the average memory performance over four learning days. Thus, the second-level design matrix (consisting of a single column filled with ones in case of a one-sample t test) was extended by a further column with the parameter value for each participant (Table 4).

Table 4
Mean Memory Performance of the Subjects who Participated in the fMRI Experiment

Subject Number	*Performance %*
01	61.41
02	77.72
04	72.04
05	65.76
06	76.77
07	40.83
09	46.60
10	49.93
13	40.66
15	74.59
19	67.83
20	74.52
24	33.08
26	74.73
29	46.26
31	58.93
34	61.41
36	72.49

Note: Data are aggregated for time (days 01–04), training (iconic vs. meaningless gestures), and task difficulty (translation from German into Vimmi and vice versa). The average performance scores were entered as a regressor in the parametric analysis correlating behavioral with brain data.

RESULTS AND DISCUSSION

Our parametric analysis is based on the main contrast analysis which we describe in a recent article (Macedonia et al., in press). In that article, our aim was to investigate the brain response on the two vocabulary training modalities in order to understand their influence on learning. In short, we found that words learned with iconic gestures elicited greater signal intensity in the dorsal medial premotor cortex bilaterally during recognition/retrieval. These activations in the premotor cortices suggest motor simulation processes occurring upon word presentation. Words encoded through meaningless gestures elicited a network for cognitive control indicating incongruence detection, integration effort, and information suppression between the word's semantics and the meaningless gestures (Figure 4). These brain patterns confirmed that iconic gestures leave a motor trace in the word representation and can be considered as facilitating. Meaningless gestures accompanying words, on the other hand, seem to disturb the encoding process and can be considered as hindering for this task.

In the present study, the parametric analysis relating the main contrast with the mean performance of each single subject was performed to uncover the neural basis of high performance. We expected the results to parametrically mirror the brain patterns present in the main contrast. First, because all words were encoded through motor activity, it would not have been surprising if the increase in subjects' performance correlated with an increase in activity in the premotor cortex. However, this was not the case. Second, the main contrast had also shown that cognitive control was the mechanism engaged in learning by inhibiting the meaningless gestures. Thus, superior performance could have correlated with this capacity: A high performer was more capable of minimizing the influence of the meaningless gestures. In fact, recent neuroscientific research has proposed that cognitive control is engaged in selection-suppression processes during language switching in bilinguals (Rodriguez-Fornells, Balaguer, & Münte, 2006). Other studies have confirmed enhanced cognitive control for high proficiency at language use (Costa, Hernández, & Sebastián-Gallés, 2008; Emmorey, Luk, Pyers, & Bialystok, 2008). Hence, in our experiment high performance could potentially have correlated with activity in brain regions engaged in cognitive control. This, however, was not found. Rather, the parametric analysis revealed a positive correlation between performance and significant brain activity in the left angular gyrus (BA 39) and in the right extrastriate cortex (BA 19) (Figure 5), two areas comprised in the larger language network. In other words, the better participants performed, the more the brain was active in the areas mentioned above.

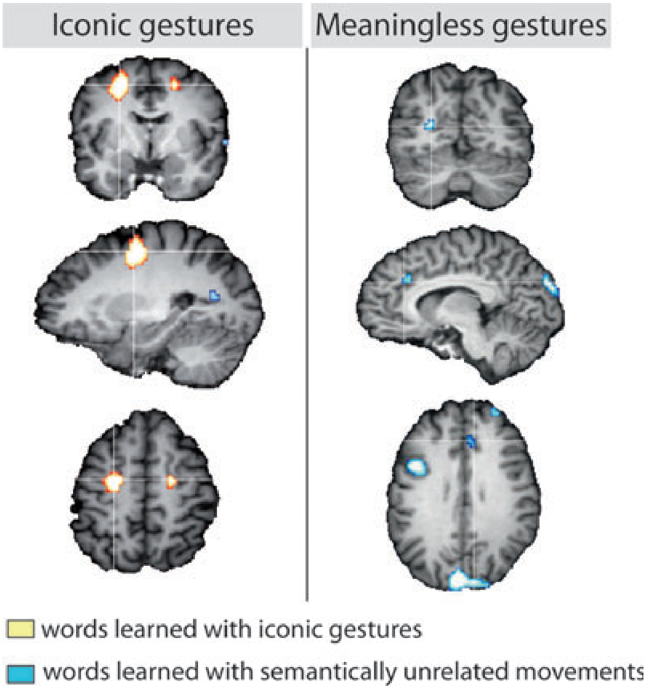

Fig. 4. Functional magnetic resonance imaging results. Main contrast for iconic gestures versus meaningless gestures. Areas of signal intensity change relative to words encoded according to the training conditions (i.e., iconic gestures vs. meaningless gestures). (A) Iconic gestures elicited activity in the dorsal right and in the left premotor cortices (BA6). (B) Meaningless gestures activated a bilateral large-scale network of cognitive control. The color-coded regions in both figures show clusters of activity computed according to Bayesian statistics (high Bayesian posterior probability of condition).

The angular gyrus has been described throughout the literature as a brain region engaged in numerous integrative functions and at different levels in the processing of words. These processes go from the conversion of orthography into phonology during reading (Callan, Callan, & Masaki, 2005; Joubert et al., 2004; Lee et al., 2003) to the processing of word semantics (Sharp et al., 2009) and in writing (Brownsett & Wise, 2009). Patient studies describe agraphia and alexia (Sakurai, Asami, & Mannen, 2009) as deficits caused by lesions of the angular gyrus confirming the function of this brain area in healthy subjects. Two meta-analyses of neuroimaging studies that consider the differences in experimental designs characterize the angular gyrus as a word area mediating word comprehension (Vigneau et al., 2006) and recently as a component of an extended heteromodal network engaged in semantics affecting language processing and retrieval (Binder, Desai, Graves, & Conant, 2009).

A recent study on word learning described the process of acquisition as the integration of the novel lexemes and existing semantic representations (Dobel et al., 2009). This study also demonstrated that, after learning, novel words show a largely reduced N400, a semantic component. This provides evidence for the view that learning new words is a semantically

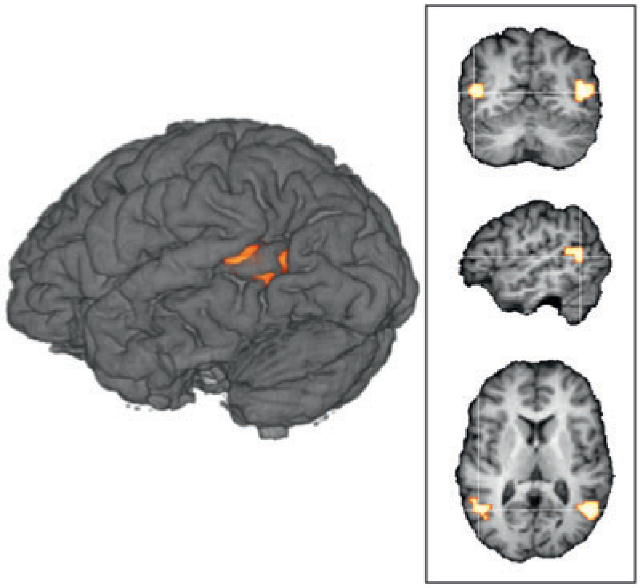

Fig. 5. Brain images show that high performance in vocabulary learning correlated with activity in the left angular gyrus (BA 39), Talairach coordinates −51, −60, 12, and in the right extrastriate cortex (BA 19), 45, −60, 12. Clusters (color-coded in red/yellow) were obtained using a voxel threshold of $p < 0.005$. Results are significant after correction for multiple comparisons ($p < 0.05$).

driven process and that activity in the angular gyrus might reflect semantic processing. High performers might thus have a better capacity to integrate word semantics with newly acquired phoneme chains and gestures. An indicator for better semantic processing in high performers might be the steep increase in learning after the training on day 1 (Figures 2 and 3). We speculate that after 1 day, the behavioral results possibly reflect the capacity to better connect the different pieces of information rather than memory retrieval.

The second focus of activity was localized in the right extrastriate. Here, the involvement of this brain area might reflect higher visual association. Considering that, in both training conditions, participants were cued to watch videos with an actress performing the gestures, activity in the extrastriate cortex might be related to visual processing of the body (Aleong & Paus, 2009) and biological motion processes (Jastorff & Orban, 2009). Also, the extrastriate has been localized in word processing tasks for visually presented words in which subjects matched characters (Flowers et al., 2004) and related them to the word's semantics (Kuriki, Takeuchi, & Hirata, 1998). Considering that the stimuli were multimodal (i.e., the training comprised body images and written words), the role of the extrastriate here is not clear-cut. The same neural tissue might process visual information related to both the body and the written words. Interestingly, according to Binder's meta-analysis (Binder et al., 2009), the extrastriate at least partly accomplishes the functions of the angular gyrus as previously described in this article. Because BA 19 also "may serve a semantic rather than a modal visual associative function," BA 19 can be considered in its functionality as a posterior extension of BA 39. A closer look at our activation list (Table 5) reveals that the Talairach coordinates for the left angular gyrus and for the right extrastriate are very close to each other, respectively, −51, −60, 12 and 45, −60, 12. Therefore, according to Binder's proposal, the right extrastriate could be considered as the posterior portion of the angular gyrus and execute functions of semantic integration in the right hemisphere. It is conceivable that, because of anatomical variability among participants, in our participants' sample a slight shift is given in the topography of the right angular gyrus.

Besides reflecting enhanced processing of multimodal information, high performance in vocabulary learning might also be based on the capacity to store and to retrieve it better. Interestingly, activity in the angular gyrus has also been related to working memory processes that occur during verbal tasks (Binder, Medler, Desai, Conant, & Liebenthal, 2005; Buchweitz, Mason, Hasegawa, & Just, 2009; Collette et al., 2001). This would be in line with Baddeley's (Baddeley, 2003) and Gathercole's (Gathercole, 2006) view maintaining that foreign language learning capacity is based on working memory.

CONCLUSION

The present study has demonstrated that high performance in vocabulary learning mainly resides in the capacity to learn more vocabulary independent of training, time, and task difficulty. Activity in the parietal cortex, specifically in the left angular gyrus and in the right extrastriate, is the neural correlate of this skill. These brain areas mediate integration of multimodal information and memory processes. Because of

Table 5
Brain Regions Parametrically Modulated by Behavioral Performance

		BA			*Left Hemisphere*			*Right Hemisphere*			
	Brain Area	*x*	*y*	*z*	*Z*	*k* (*mm*^{3})	*x*	*y*	*z*	*Z*	*k* (*mm*^{3})
Angular gyrus	39	−51	−60	12	3.67	1998					
Extrastriate	19						45	−60	12	4.04	2565

our experimental design and the poor temporal resolution of fMRI, we could not unequivocally relate high performance to integration or to memory. In fact, they might be complementary in achieving superior performance, and their role should be disentangled with appropriate experimental designs. Based on our results, we draw the conclusion that high performers respond more efficiently to the stimuli provided during encoding because of their better capacities for integration of the multimodal information.

The present findings provide a new understanding of performance in foreign language word learning, with implications for educational practice. In fact, although it is tempting to attribute an important role to motivation in learning success, according to our data, low performance has to do with brain functionality. High performers, in contrast to low performers, are characterized by the ability to integrate multisensorial information, resulting in superior performance. A rethink is needed in order to provide all learners with appropriate learning activities. In the specific case of vocabulary learning, such activities should be training and enhancement of the low performers' capacities for multisensory information processing. More research in this field is necessary in order to establish a clear link between results from neuroscientific experiments and education.

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