Prefrontal Cortex Asymmetry for Memory Encoding of Words and Abstract Shapes

Previous work suggested a differential contribution of prefrontal cortex (PFC) to successful encoding depending on the stimulus material. Here, we tested the hypothesis that encoding of words preferentially involves the left PFC, while encoding of nonverbal items (abstract shapes) relies on the right PFC. We used an experimental design that evaluated encoding of both words and abstract shapes in the same healthy volunteers. A transient virtual lesion of the left or the right PFC was elicited with transcranial magnetic stimulation (TMS) while subjects memorized verbal and nonverbal items. We found that encoding of verbal material was disrupted by left PFC stimulation, whereas encoding of nonverbal material was disrupted by right PFC stimulation. These results demonstrate a functionally relevant lateralization of prefrontal contribution for verbal and nonverbal memory encoding.

Keywords: episodic memory, frontal cortex, nonverbal, transcranial magnetic stimulation, verbal

Introduction

Episodic memory (explicit memory for recently experienced events) depends upon a number of circumscribed, interconnected brain regions, including the medial temporal lobe and the prefrontal cortex (PFC) (Milner and Petrides, 1984; Cohen et al., 1985; Tulving et al., 1994; Wagner et al., 1999; Golby et al., 2001; Otten and Rugg, 2001; Rugg et al., 2002; Johnson et al., 2003). Previous lesion studies proposed a link between material-specific lateralization and encoding for both medial temporal lobe and PFC (Riege et al., 1980; Whitehouse, 1981; Milner and Petrides, 1984; Cohen et al., 1985; Squire, 1992; Cohen, 1993; Schacter and Tulving, 1994). However, while medial temporal lesions critically impair memory formation (Squire, 1992; Cohen, 1993; Schacter and Tulving, 1994), the impact of prefrontal lesions is less clear (for a review see Buckner et al., 1999). Additionally, lesion studies could not distinguish between brain regions that play a role in encoding as opposed to retrieval of memories (Otten and Rugg, 2001; Johnson et al., 2003).

Functional imaging studies consistently demonstrated prefrontal activation during memory encoding, but yielded heterogeneous results on the issue of lateralization and intrahemispheric location. Prefrontal lateralization during encoding may depend on the material presented (Brewer et al., 1998; Wagner et al., 1998, 1999; Kirchhoff et al., 2000) as well as on the stage of memory processing studied (encoding versus retrieval; Tulving et al., 1994; Smith and Jonides, 1999; Haxby et al., 2000). Within the left PFC, an anterior–posterior gradient has been proposed for encoding of words that rely on semantic versus phonological processing (Fiez, 1997; Poldrack et al., 1999; Devlin et al., 2003). Imaging studies that directly compared encoding of verbal and nonverbal items raised the hypothesis that the ‘verbalizability’ of the item to remember determines the neural substrate underlying the encoding process (Kelley et al., 1998; Golby et al., 2001; Otten and Rugg, 2001; Johnson et al., 2003).

However, activation of a brain area in association with performance of a memory task does not prove a causal link (Wagner et al., 1999; Fletcher and Henson, 2001; Rugg et al., 2002). One way to evaluate the functional contribution of a particular brain region to a specific function is transcranial magnetic stimulation (TMS) (Hallett, 2000; Pascual-Leone et al., 2000). This technique allows probing encoding processes in intact humans while activity in specific brain regions is disrupted (‘virtual lesion’). TMS reports of memory encoding showed disparate results: right (Epstein et al., 2002) and left (Rossi et al., 2001) prefrontal involvement with presentation of pictorial items, and left (Kohler et al., 2004) and bilateral (Sandrini et al., 2003) prefrontal involvement with presentation of words. None of these studies directly compared verbal and nonverbal stimuli. Taken together, these reports indicate that the specific role of the PFC in encoding of information is still controversial.

Here, we studied the effects of a ‘virtual lesion’ of left and right PFC on encoding of both words and abstract shapes in the same group of healthy volunteers. In particular, if constructing a novel representation of a word or a nonverbal abstract stimulus differentially depends on the integrity of left or right PFC, disrupting these areas should negatively influence recognition performance.

Materials and Methods

Participants

Fifteen neurologically intact native speakers of English (nine female), 22–35 years old (average 28), naive to the experimental hypotheses, gave their written informed consent for the study. The protocol was approved by the National Institute of Neurological Disorders and Stroke Institutional Review Board and by the Food and Drug Administration. All subjects were right-handed (mean handedness score (Oldfield, 1971) ± SD: 95% ± 8.5).
Overall Study Design
Each subject participated in two separate sessions: one for word encoding and recognition and one for picture encoding and recognition. Words were balanced for length, familiarity, and concreteness ratings (Kucera and Francis, 1967) (Fig. 1a). Picture stimuli were generated by the same fractal algorithm as trial-unique probes to restrict verbal identifications and to encourage encoding on the basis of internal spatial organization of the items (Miyashita, 1988; Miyashita et al., 1991) (Fig. 1b). In each block, subjects were instructed to memorize words or pictures carefully for a subsequent memory recognition test. In each of the sessions, encoding was followed by a recognition test in which subjects were instructed to press one of three buttons as quickly and accurately as possible to characterize the presented items as: ‘well-remembered’ (high-confidence studied), ‘familiar’ (low-confidence studied), or new (Wagner et al., 1998). Repetitive transcranial magnetic stimulation (rTMS) trains were applied only during the encoding process (Fig. 2a,b).

Experimental Set-up
Each session (words or pictures) comprised two parts: encoding and recognition. During encoding, words or pictures were presented for 1500 ms each, with inter-item presentation intervals of 1500 ms (Fig. 2a,b). In the encoding period (presentation of 108 words or pictures), the TMS coil was tangentially positioned over left PFC, right PFC, or perpendicularly to the scalp surface, with one of the wings touching the scalp over Fz (international 10–20 EEG system) in a sham condition (Lisanby et al., 2001) (36 trials for each coil position). For Sham, the scalp contact and discharging noise were similar to active stimulation, but the induced magnetic field did not activate cortical neurons. In 27 of the 36 trials for each position, an rTMS train of 500 ms, starting at the onset of viewing of the word or picture, was delivered. In nine of the 36 trials, no rTMS was delivered as an additional control. Stimulated and not-stimulated trials were randomly intermixed. Trials without rTMS were later averaged across coil positions. For each scalp position, items were presented in one block for words and in six blocks for pictures. A short break (15 min for word session and 1 min for picture session) separated encoding from recognition. During recognition, words or pictures were presented for 2000 ms, with inter-item presentation intervals of 1000 ms.

Stimulus Material
The number of blocks per stimulus type (see above) was designed to render comparable recognition rates in a preliminary study (corrected recognition rate, mean ± SE: 63 ± 4.2% for words and 61 ± 3.8% for pictures; hit rate, mean ± SE: 74 ± 4.1% for words and 76 ± 3.9%). Order
of word and picture tasks and order of stimulation sites were random-ized across subjects.

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Transcranial Magnetic Stimulation

We determined stimulation positions using a frameless, MRI-guided, stereotactic system for coil positioning. Initially, T1-weighted MRI in each subject was obtained using a 1.5 T scanner and a standard head-coil, fast spoiled gradient-echo at steady-state images, repetition time = 11.2 ms, echo time = 2.1 ms, inversion time = 300 ms, flip angle = 30°, field of view = 24 cm, 256 × 256 matrix, 124 slices, voxel size = 0.94 × 0.94 × 1.5 mm, GE, Milwaukee, WI, USA. Subjects lay supine on a scanner bed. Foam cushions and elastic tape were used to minimize head motion. The MRI data were later fed to a Macintosh computer.

Preceding stimulation, left and right prefrontal targets (BA 45/47, overlying the left anterior and ventral extent of the inferior frontal gyrus) were identified in axial, sagittal, and 3-D views of each individual MRI. The target site for stimulation was the boundary between the pars triangularis and pars opercularis of the left inferior PFC (Devlin et al., 2005). They were then projected over each subject’s scalp surface, and frameless stereotaxy (Brainsight, Rogue Research, Inc., Montreal, Canada, http://www.rogue-research.com) was used to position the center of the coil (junction of the wings) over this site in each individual with the handle parallel to the mid-sagittal line and pointing backwards.

Parameters of TMS and Recording Procedures

rTMS was applied using a Magstim Rapid stimulator (Magstim Co., Whitland, south west Wales, UK) with a focal figure-of-eight coil (dual 70 mm coil). Short 20 Hz rTMS trains at 90% motor-threshold (MT) intensity were delivered for 500 ms in synchrony with the onset of each word or picture during the encoding part of each session. For MT determination, electromyographic responses were recorded with surface electrodes positioned on the skin overlying the right and left first dorsal interosseous muscle (FDI). MT was defined as the minimal intensity of the stimulator output capable of evoking a motor-evoked potential greater than 50 μV with 50% probability (Rossini et al., 1994).

Motor thresholds were (mean ± SD) 54.9 ± 7.0% (range between 42% and 74% for the right hand) and 55.1 ± 7.4% (range between 42% and 74% for the left hand, NS). rTMS trains were applied at 90% of individual motor thresholds.

Sub-threshold rTMS did not lead to overt eye-blinking in any subject.

Data Analysis

Data on word and picture sessions were analyzed separately and expressed as mean ± SE. Probability of a hit (Phit, well-remembered), (Phit, well-remembered + familiar), and probability of a false alarm (Pfalse alarms, well-remembered), (Pfalse alarms, well-remembered + familiar) were calculated for L-TMS, R-TMS, and Sham. From these data, hit rate (Phit, well-remembered), corrected recognition rate (Phit, well-remembered − Pfalse alarms, well-remembered), discrimination measure d′, and reaction time (reaction time of well-remembered hits) were calculated. Discrimination measure d′ is derived from signal detection theory, which reflects the subject’s ability to distinguish between test and distractor items: d′ = Φ−1(Phit) − Φ−1(Pfalse alarms) = Φ−1 a false alarm rate (Pfalse alarms, well-remembered) and Φ−1 a inverse cumulative distribution function for the standard normal distribution (Snodgrass and Corwin, 1988).

Repeated-measure ANOVAs (ANOVA(d)) with repeated measures STIMULATION SITE (L-TMS, R-TMS and Sham) and the factor STIMULUS TYPE (words/abstract shapes) were used to analyze hit rate and corrected recognition rate. Hit rate during unstimulated trials was 73.6 ± 16.2% for words and 76.1 ± 15.6% for pictures, similar to levels during Sham stimulation, and was not included in the ANOVA. Paired t-tests, corrected for multiple comparisons of dependent observations (Bonferroni) were used for post hoc comparisons.

Results

Outcome measures were hit rate, corrected recognition rate, discrimination measure d′, and reaction time, including ‘well-remembered’ items only, and calculated separately for words and pictures as a function of stimulation site.

Hit Rate (HR), Corrected Recognition Rate (CRR), Discrimination Measure d′

ANOVA revealed a significant interaction of STIMULATION SITE by STIMULUS TYPE [for CRR: F(2,56) = 18.3, P < 0.0001; for HR: F(2,56) = 14.9, P < 0.0001; for d′: F(2,56) = 17.7, P < 0.0001].

Post hoc testing revealed that recognition performance for words was significantly affected by stimulation site: corrected recognition rate (Fig. 3a), hit rate (Fig. 3b), and d′ for words after L-TMS were worse than after R-TMS or Sham (CRR: L-TMS versus R-TMS, P < 0.001, L-TMS versus Sham, P < 0.01; HR: L-TMS versus R-TMS, P < 0.01; L-TMS versus Sham, P < 0.001; d′: L-TMS versus R-TMS, P < 0.001; L-TMS versus Sham, P < 0.001). These results point to a left lateralization effect of encoding processing for words.

For abstract shapes (Fig. 5c,d), post hoc testing revealed that corrected recognition rate (Fig. 5c), hit rate (Fig. 3d), and d′ after R-TMS were worse than after L-TMS and Sham (for CRR: R-TMS versus L-TMS, P < 0.02, R-TMS versus Sham, P < 0.01; for HR: R-TMS versus L-TMS, P < 0.05, R-TMS versus Sham, P < 0.01, for d′: R-TMS versus L-TMS, P < 0.03; R-TMS versus Sham, P < 0.001), indicating a robust right lateralization effect of encoding abstract pictures that could not be easily verbalized.

Table 1 provides the complete list of hit rates and false alarm rates for words and pictures, separately for ‘well-remembered’ items and ‘well-remembered + familiar’ items.

Reaction Time

For reaction times, there was no significant interaction of STIMULATION SITE with STIMULUS TYPE: F(2,56) = 32.5, P = 0.09, and no significant main effect of STIMULATION SITE or STIMULUS TYPE, suggesting that the results on corrected recognition rate, hit rate, and d′ cannot be explained by a speed-accuracy trade-off.

The results on hit rate, corrected recognition rate, and d′ cannot be attributed to a prior performance gradient between the words and pictures, since there was no difference between them in baseline performance: hit rate and reaction times did not differ significantly between words and shapes when
Table 1

<table>
<thead>
<tr>
<th>Stimulus site</th>
<th>Left PFC</th>
<th>Right PFC</th>
<th>Sham</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Words, hit rate</strong></td>
<td><strong>59.7 ± 3.5</strong></td>
<td><strong>74.5 ± 3.1</strong></td>
<td><strong>78.3 ± 3.5</strong></td>
</tr>
<tr>
<td><strong>Words, false alarm rate</strong></td>
<td><strong>26.0 ± 2.1</strong></td>
<td><strong>20.1 ± 2.6</strong></td>
<td><strong>22.2 ± 2.3</strong></td>
</tr>
<tr>
<td><strong>Pictures, hit rate</strong></td>
<td><strong>75.5 ± 3.7</strong></td>
<td><strong>65.3 ± 4.3</strong></td>
<td><strong>76.2 ± 3.1</strong></td>
</tr>
<tr>
<td><strong>Pictures, false alarm rate</strong></td>
<td><strong>18.7 ± 2.0</strong></td>
<td><strong>20.0 ± 2.1</strong></td>
<td><strong>15.5 ± 1.9</strong></td>
</tr>
</tbody>
</table>

Hit rates (P<0.05) and false alarm rates (P<0.05 for 'well remembered' (high confidence studied items), and 'well-remembered + familiar' (high confidence studied plus low confidence studied) items). Left PFC: stimulation over left PFC; right PFC: stimulation over right PFC; sham: sham stimulation.

Comparing the No-TMS or Sham conditions, indicating comparable difficulty for both tasks (t-test words versus pictures for No TMS, hit rate: P = 0.77, reaction times: P = 0.30; t-test words versus pictures for Sham, hit rate: P = 0.64, reaction times: P = 0.76).

Furthermore, TMS effects did not differ significantly between abstract and concrete words (ANOVA RRM for words only, with WORD CLASS (abstract, concrete) as within-subject factor, showed no significant effect of WORD CLASS (P = 0.64 for hit rate, P = 0.79 for corrected recognition rate). Therefore, data were pooled over abstract and concrete words.

**Discussion**

Verbal and nonverbal processes participate in encoding of episodic memory (Kelley et al., 1998; Golby et al., 2001). Encoding of pictures, for example, may be implemented through nonverbal and through verbal strategies (Kelley et al., 1998; Golby et al., 2001; Otten and Rugg, 2001; Johnson et al., 2005). In this way, a subject presented with the picture of a tree to memorize could later recall the item by its physical features or by recollection of the word 'tree'. Therefore, even when the task is to memorize the picture of a tree, its high ‘verbalizability’ could make the encoding process rely predominantly on verbal processing (Kelley et al., 1998).

The PFC is consistently activated in functional imaging studies in association with performance of memory tasks (see reviews by Buckner et al., 1999; Wagner et al., 1999; Fletcher and Henson, 2001; Rugg et al., 2002). Neuroimaging and lesion studies proposed that the PFC contribution to memory encoding differs depending on the ‘verbalizability’ of the stimulus material (Kelley et al., 1998; Golby et al., 2001; Otten and Rugg, 2001; Johnson et al., 2003). However, a cause–effect link between PFC activation and encoding has not been demonstrated (Wagner et al., 1999; Fletcher and Henson, 2001; Rugg et al., 2002). We evaluated the consequences of transient disruption of activity of PFC on encoding of both verbal and nonverbal items in a balanced experimental design using TMS. Both stimulus types were structured to differ maximally in ‘verbalizability,’ and examined encoding of both stimulus types in the same subjects. Abstract shapes were selected to minimize natural verbal labels or associations and to encourage encoding on the basis of internal spatial features of the items (Miyashita, 1988; Miyashita et al., 1991). They were all generated by the same fractal algorithm and exhibited similar pattern complexity (Miyashita et al., 1991). On the other hand, in the word encoding task, subjects were encouraged to find semantic associations during encoding, and to avoid using imagery strategies. A prestudy was conducted to identify groups of items that rendered similar recognition rates for both stimulus types. As a consequence, only items that were recognized with high confidence (well-remembered and not just familiar) were included in the analysis (Brewer et al., 1998; Wagner et al., 1998; Dobbins et al., 2005). The similar success rates documented in our study for encoding of abstract and concrete words is consistent with the view that subjects utilized predominantly semantic encoding strategies and did...
not rely on imagery of objects represented by the words (Schwanefluel et al., 1992).

The main finding of the present study was that right PFC stimulation disrupted encoding of abstract shapes while left PFC stimulation disrupted encoding of words.

These results are consistent with a recent TMS study that found the left inferior PFC to be involved in encoding of words (albeit with a facilitating effect, most likely due to differences in stimulation parameters and coil type) (Kohler et al., 2004) and with the report of left-lateralization for semantic processing in the left inferior PFC (Devlin et al., 2003). In addition to semantic processing, it is likely that words were processed along a phonological dimension (Van Orden et al., 1988; Price et al., 1996), both strategies contributing to encoding success in the left inferior PFC, in spatially overlapping regions (Devlin et al., 2003). Therefore, we present experimental evidence for the proposal that activity in left PFC is crucial to encoding of verbal items. Our results also shed light on two contradictory reports regarding the encoding lateralization of pictorial items. In one, picture encoding was disrupted by left PFC stimulation (Rossi et al., 2001) and in the other by right PFC stimulation (Epstein et al., 2002). However, the pictures presented by Rossi et al. (Rossi et al., 2001) were highly verbalizable landscapes that could easily be remembered using verbal strategies, while activity in right PFC has a role in encoding of non-verbalizable items (abstract shapes in our study and unfamiliar abstract substrates within the PFC depending on stimulus features (Goldman-Rakic, 1995).

TMS was applied to the antero-ventral inferior prefrontal gyrus (BA 45/47), using a frameless stereotactic technique and the individual subjects’ MRI (Paus, 1999). Stereotactically guided focal coil placement here allowed a more accurate placement in relation to previous TMS studies (Rossi et al., 2001; Epstein et al., 2002; Sandrini et al., 2003), and evaluation of the effects of focal reversible inactivation of BA 45/47 on memory encoding in relation to lesion studies and to reports of intracarotid anesthesia of a complete hemisphere (Kelley et al., 2002).

While stimulation was focal and of relatively low intensity, it is conceivable that direct disruption of activity in area BA 45/47 trans-synaptically influenced other components of the network (Paus, 1999; Chouinard et al., 2003) involved in memory encoding such as ipsilateral frontal (Goldman-Rakic, 1995; Smith and Jonides, 1999; Baddeley, 2001) [e.g. affecting working memory processes (see Baddeley, 1986)], and medial temporal structures (Squire and Zola-Morgan, 1991). Neural substrates connecting these regions exist, and the medial temporal lobe may bind together the outcomes of information processed in frontal cortical regions to form lasting memory traces (Cohen et al., 1985; Squire and Zola-Morgan, 1991; Wagner et al., 1999; Rugg et al., 2002). Prefrontal TMS may disrupt the crucial input from frontal regions into medial temporal lobe structures (Buckner et al., 1999) in the healthy brain, thereby deteriorating encoding success. The finding that patients with chronic frontal lobe lesions often perform well on simple recognition memory tasks (Milner et al., 1985; Schacter and Tulving, 1994) indicates that other brain areas may be capable of taking over the function of PFC in the injured brain (Buckner et al., 1999; Kelley et al., 2002). An interesting question for future investigation will be to determine which brain regions underlie successful memory formation after lesions of the PFC.

Supplementary Material

Supplementary material can be found at: http://www.cercor.oupjournals.org/

Notes

The authors thank Nguyet Dang for providing technical help. A.F. was supported by a grant from the Deutsche Forschungsgemeinschaft, Bonn (FL 379/1-1).

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Cerebral Cortex V 14 N 4 © Oxford University Press 2004; all rights reserved Cerebral Cortex April 2004:14:404–409; DOI: 10.1093/cercor/bhh002
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Transcranial Magnetic Stimulation

We determined stimulation positions using a frameless, MRI-guided, stereotactic system for coil positioning. Initially, T1-weighted MRI in each subject was obtained using a 1.5 T scanner and a standard head coil, fast spoiled gradient-recalled at steady-state images, repetition time = 11.2 ms, echo time = 2.1 ms, inversion time = 300 ms, field of view = 24 cm, 256 × 256 matrix, 124 slices, voxel size = 0.94 × 0.94 × 1.5 mm, GE, Milwaukee, WI, USA. Subjects lay supine on a scanner bed. Foam cushions and elastic tape were used to minimize head motion. The MRI data were later fed to a Macintosh computer.

Preceding stimulation, left and right prefrontal targets (BA 45/47, overlying the left anterior and ventral extent of the inferior frontal gyrus) were identified in axial, sagittal, and 3-D views of each individual MRI. The target site for stimulation was the boundary between the pars triangularis and pars opercularis of the left inferior PFC (Devlin et al., 2005). They were then projected over each subject’s scalp surface, and frameless stereotaxy (Brainsight, Rogue Research, Inc., Montreal, Canada, http://www.rogue-research.com) was used to position the center of the coil (junction of the wings) over this site in each individual with the handle parallel to the mid-sagittal line and pointing backwards.

Parameters of TMS and Recording Procedures

rTMS was applied using a Magstim Rapid stimulator (Magstim Co., Whitland, south west Wales, UK) with a focal figure-of-eight coil (dual 70 mm coil). Short 20 Hz rTMS trains at 90% motor-threshold (MT) intensity were delivered for 500 ms in synchrony with the onset of each word or picture during the encoding part of each session. For MT determination, electromyographic responses were recorded with surface electrodes positioned on the skin overlying the right and left first dorsal interosseous muscle (FDI). MT was defined as the minimal intensity of the stimulator output capable of evoking a motor-evoked potential greater than 50 µV with 50% probability (Rossini et al., 1994).

Motor thresholds were calculated for L-TMS, R-TMS, and Sham. From these data, hit rate (hit), corrected recognition rate (hit, well remembered), discrimination measure d’, and reaction time (reaction time of well-remembered hits) were calculated. Discrimination measure d’ is derived from signal detection theory, which reflects the subject’s ability to distinguish between test and distractor items: d’ = Φ–1(hit) – Φ–1(fail), with Φ(hit) = hit rate (well remembered), Φ(fail) = false alarm rate (false alarms, well remembered) and Φ–1 a inverse cumulative distribution function for the standard normal distribution (Snodgrass and Corwin, 1988).

Repeated-measure ANOVAs with repeated measures STIMULATION SITE (L-TMS, R-TMS and Sham) and the factor STIMULUS TYPE (words/abstract shapes) were used to analyze hit rate and corrected recognition rate. Hit rate during unstimulated trials was 73.6 ± 16.2% for words and 76.1 ± 15.6% for pictures, similar to levels during Sham stimulation, and was not included in the ANOVA. Paired t-tests, corrected for multiple comparisons of dependent observations (Bonferroni) were used for post hoc comparisons.

Results

Outcome measures were hit rate, corrected recognition rate, discrimination measure d’, and reaction time, including ‘well-remembered’ items only, and calculated separately for words and pictures as a function of stimulation site.

Hit Rate (HR), Corrected Recognition Rate (CRR), Discrimination Measure d’

ANOVA revealed a significant interaction of STIMULATION SITE by STIMULUS TYPE [for CRR: F(2,56) = 18.3, P < 0.0001; for HR: F(2,56) = 14.9, P < 0.0001; for d’: F(2,56) = 17.7, P < 0.001].

Post hoc testing revealed that recognition performance for words was significantly affected by stimulation site: corrected recognition rate (Fig. 3a), hit rate (Fig. 3b), and d’ for words after L-TMS were worse than after R-TMS or Sham (CRR: L-TMS versus R-TMS, P < 0.001, L-TMS versus Sham, P < 0.01; HR: L-TMS versus R-TMS, P < 0.01; L-TMS versus Sham, P < 0.001; d’: L-TMS versus R-TMS, P < 0.001; L-TMS versus Sham, P < 0.001).

These results point to a left lateralization effect of encoding processing for words.

For abstract shapes (Fig. 3c,d), post hoc testing revealed that corrected recognition rate (Fig. 3c), hit rate (Fig. 3d), and d’ after R-TMS were worse than after L-TMS and Sham (for CRR: R-TMS versus L-TMS, P < 0.02, R-TMS versus Sham, P < 0.01; for HR: R-TMS versus L-TMS, P < 0.05, R-TMS versus Sham, P < 0.01, for d’: R-TMS versus L-TMS, P < 0.03; R-TMS versus Sham, P < 0.001), indicating a robust right lateralization effect of encoding abstract pictures that could not be easily verbalized.

Table 1 provides the complete list of hit rates and false alarm rates for words and pictures, separately for ‘well-remembered’ items and ‘well-remembered + familiar’ items.

Reaction Time

For reaction times, there was no significant interaction of STIMULATION SITE with STIMULUS TYPE: F(2,56) = 32.5, P = 0.09, and no significant main effect of STIMULATION SITE or STIMULUS TYPE, suggesting that the results on corrected recognition rate, hit rate, and d’ cannot be explained by a speed-accuracy trade-off.

The results on hit rate, corrected recognition rate, and d’ cannot be attributed to a prior performance gradient between the words and pictures, since there was no difference between them in baseline performance: hit rate and reaction times did not differ significantly between words and shapes when
Comparing the No-TMS or Sham conditions, indicating comparable difficulty for both tasks (t-test words versus pictures for No TMS, hit rate: $P = 0.77$, reaction times: $P = 0.30$; t-test words versus pictures for Sham, hit rate: $P = 0.64$, reaction times: $P = 0.76$).

Furthermore, TMS effects did not differ significantly between abstract and concrete words [ANOVA for words only, with WORD CLASS (abstract, concrete) as within-subject factor, showed no significant effect of WORD CLASS ($P = 0.64$ for hit rate, $P = 0.79$ for corrected recognition rate]. Therefore, data were pooled over abstract and concrete words.

**Discussion**

Verbal and nonverbal processes participate in encoding of episodic memory (Kelley et al., 1998; Golby et al., 2001). Encoding of pictures, for example, may be implemented through nonverbal and through verbal strategies (Kelley et al., 1998; Golby et al., 2001; Otten and Rugg, 2001; Johnson et al., 2005). In this way, a subject presented with the picture of a tree to memorize could later recall the item by its physical features or by recollection of the word ‘tree’. Therefore, even when the task is to memorize the picture of a tree, its high ‘verbalizability’ could make the encoding process rely predominantly on verbal processing (Kelley et al., 1998).

The PFC is consistently activated in functional imaging studies in association with performance of memory tasks (see reviews by Buckner et al., 1999; Wagner et al., 1999; Fletcher and Henson, 2001; Rugg et al., 2002). Neuroimaging and lesion studies proposed that the PFC contribution to memory encoding differs depending on the ‘verbalizability’ of the stimulus material (Kelley et al., 1998; Golby et al., 2001; Otten and Rugg, 2001; Johnson et al., 2003). However, a cause–effect link between PFC activation and encoding has not been demonstrated (Wagner et al., 1999; Fletcher and Henson, 2001; Rugg et al., 2002). We evaluated the consequences of transient disruption of activity of PFC on encoding of both verbal and nonverbal items in a balanced experimental design using TMS. Both stimulus types were structured to differ maximally in ‘verbalizability’, and examined encoding of both stimulus types in the same subjects. Abstract shapes were selected to minimize natural verbal labels or associations and to encourage encoding on the basis of internal spatial features of the items (Miyashita, 1988; Miyashita et al., 1991). They were all generated by the same fractal algorithm and exhibited similar pattern complexity (Miyashita et al., 1991). On the other hand, in the word encoding task, subjects were encouraged to find semantic associations during encoding, and to avoid using imagery strategies. A prestudy was conducted to identify groups of items that rendered similar recognition rates for both stimulus types. As a consequence, only items that were recognized with high confidence (well-remembered and not just familiar) were included in the analysis (Brewer et al., 1998; Wagner et al., 1998; Dobbins et al., 2003). The similar success rates documented in our study for encoding of abstract and concrete words is consistent with the view that subjects utilized predominantly semantic encoding strategies and did not adopt imagery strategies.
interested question for future investigation will be to determine which brain regions underlie successful memory formation after lesions of the PFC.

**Supplementary Material**

Supplementary material can be found at: http://www.cercor.oupjournals.org/

**Notes**

The authors thank Nguyet Dang for providing technical help. A.F. was supported by a grant from the Deutsche Forschungsgemeinschaft, Bonn (FL379/1-1).

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**References**


