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Brief article

Lateralization of object-shape information in semantic processing

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Abstract

An experiment was conducted to examine whether perceptual information, specifically the shape of objects, is activated during semantic processing. Subjects judged whether a target word was related to a prime word. Prime–target pairs that were not associated, but whose referents had similar shapes (e.g. LADDER-RAILROAD) yielded longer "no" responses than unassociated prime–target pairs, suggesting that shape information had been activated. A visual-field manipulation showed that, in right-handed subjects, this effect was localized in the left hemisphere. This finding is consistent with behavioral, brain imaging, and lesion data, which suggest that object shape at the category level is represented in the left hemisphere.

Keywords: Semantic priming; Perceptual information; Object shape; Lateralization; Sensorimotor representations; Perceptual symbols

Several theories have proposed that language activates sensorimotor representations related to the denoted concepts (Barsalou, 1999; Damasio, 1994; Zwaan, 2004). Consistent with this view, brain-imaging studies have shown that words denoting concrete entities activate cortical areas outside the classical language areas (Broca's and Wernicke's) that are associated with sensorimotor processes involving the entity denoted by the word. For example, tool words activate, among other areas, the premotor cortex and animal words activate the visual cortex (e.g. Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004; Martin, Wiggs, Ungerleider, & Haxby, 1996; Pulvermüller, Härle,

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& Hummel, 2001). In addition, brain-lesion studies reveal that damage to these sensorimotor areas compromises the ability to name objects from pictures (see Damasio et al., 2004 for a comprehensive analysis).

There has also been behavioral research on the role of sensorimotor representations in lexical processing. The typical paradigm uses prime–target pairs in which the words are not associated (e.g. targets are not spontaneously produced in response to a prime word), but whose referents have similar shapes (e.g. SPOKE-PIN). The idea is that if shape information is activated during lexical processing, it should influence priming. The evidence for this view has been mixed. Some experiments have shown priming effects for word pairs such as "button-coin" (Kellenbach, Wijers, & Mulder, 2000, ERP data; Moss, Ostrin, Tyler, & Marslen-Wilson, 1995; Pecher, Zeelenberg, & Raaijmakers, 1998, Experiments 4 and 6; Schreuder, Flores d'Arcais, & Glazenborg, 1984), but other experiments have not (e.g. Kellenbach et al., lexical-decision data; Pecher et al., Experiments 1–3, and 5). One reason why the evidence might be mixed is that the behavioral methods used are not sensitive to hemispheric differences with regard to representations of object shape and their connections to lexical representations.

Evidence from various sources suggests that the links between visual representations of (generic) object shape and lexical representations are lateralized to the left hemisphere (LH). For example, using a visual-field paradigm, Marsolek (1995, 1999) found support for the theory that the right hemisphere (RH) and LH are differentially involved in object recognition. The RH specializes in the recognition of different exemplars of a category, whereas the LH specializes in the recognition of more abstract visual categories. For example, whereas the RH distinguishes between different types of pianos (an upright piano vs. a grand piano), the LH does not. It is likely that object nouns will activate these more abstract visual representations, whereas more specific descriptors (e.g. "dad") will activate specific exemplars (e.g. a mental image of your father). As a result, one would expect the LH to be more sensitive to word-induced shape overlap than the RH. Simons et al. (2003) provided converging evidence for this view in an fMRI study, showing that the left fusiform cortex differentiated more between objects from novel categories than different exemplars from studied categories, whereas right fusiform cortex differentiated more between exemplars of categories. In addition, lexical-semantic manipulations of object priming created activation patterns in left fusiform cortex.

Results from a recent meta-analysis of lesion and positron-emission tomography (PET) further enhance our understanding of the links between lexical and visual representations in the LH (Damasio et al., 2004). Lesions primarily to the LH compromise naming concrete objects with category specific sites within the LH (e.g. tools versus animals) and left-hemispheric regions are activated during the naming of concrete items at the category level (e.g. "cup" rather than "my cup"). Damasio et al. assume that in this process the pattern of activation shifts from (1) (bilateral) primary and early visual cortices, via (2) parieto-occipital cortices (which hold dispositions for concept retrieval), via (3) concept-related areas in the inferior temporal left cortex, which result in a reconstruction of explicit sensorimotor patterns pertaining to the referent, to (4) classical language areas (Broca's and Wernicke's), required to produce a naming response. Relevant to the present study, they assume that the process runs in reverse when subjects are first presented with a word. In other words, the presentation of a word denoting a concrete object will first activate the classical language areas and will subsequently activate sensorimotor patterns in the inferior temporal left cortex, including representations of the object's shape.

1. The present study

We employed a semantic-relatedness judgment task (Zwaan & Yaxley, 2003a,b) to assess the activation of shape information during semantic processing. For example, when judging whether the words "RACKET" and "BANJO" are semantically related, subjects are supposed to respond "no". However, tennis rackets and banjos have roughly similar shapes. If the target word refers to an object that has a similar shape as the first-mentioned object, it will activate the same, or a similar, shape representation. This representation will send activation back to the word representation. Assuming that activation has to be below a certain threshold for a "no" response to occur, this heightened level of activation will produce either slow responses (it will take longer for the activation to get below the threshold), and/or incorrect responses (the activation is still above a "yes" threshold when the response is initiated). As a result, we would expect slower and/or less accurate responses to associatively unrelated prime–target pairs whose referents have similar shapes than to associatively unrelated control pairs whose referents have dissimilar shapes.

We used a visual-field manipulation in conjunction with our semantic-relatedness judgment task. The prime word was presented centrally and the target word was flashed either to the left or right visual field. Subjects decided whether the words were semantically related. Presentation of words referring to concrete objects at the category level should activate not only the language areas, but also sensorimotor representations in the LH. These should include visual representations of the object's shape. As a result, compared to the RH, the LH should show more sensitivity to shape overlap between prime and target, resulting in slower and/or less accurate "no" responses compared to control items.

In summary, our main hypotheses are as follows. First, if shape information is activated during semantic processing, then "NO" responses should be slower to shape-related target words than to shape-unrelated target words. Second, if the lexical object-shape links are primarily left lateralized, this effect should be stronger in the LH than in the RH. Combined, these hypotheses predict an interaction between object shape (match vs. mismatch) and hemisphere.

2. Method

2.1. Subjects

Fifty-six Florida State University undergraduates from general psychology classes participated for course credit. All were native English speakers with a 75% (range 50–100%) score for right-handedness on Oldfield (1971) handedness inventory.

2.2. Materials

The experimental materials consisted of 72 word pairs, adapted from the materials of Kellenbach et al. (2000). Due to cultural and linguistic differences between Dutch and (American) English, some of their stimulus items could not be used. For example, every Dutch child knows what a "dropsleutel" ("licorice key") is, but this candy is unfamiliar to the typical American subject.

All words were concrete nouns ranging from 1 to 3 syllables long. Twenty-four of these items were experimental word pairs consisting of the names of associatively unrelated objects that have the same shape (e.g. PIE and CLOCK). To create shape-unrelated versions of each shape-related item pair, we replaced target words in each of the experimental word pairs. All replacement words matched the original target words with respect to number of letters and syllables. Additionally, where possible, replacement items were matched according to their ordinal classification of Kučera and Francis (1967) written frequency norms as obtained from the MRC psycholinguistic database (Coltheart, 1981a,b). For example, if the shape-related pair was PIE–CLOCK, then the shape-unrelated alternative was PIE–CHEEK. Each subject saw 12 shape-related experimental pairs (six presented to the LH and six to the RH) and 12 shape-unrelated experimental pairs (six presented to the LH and six to the LH).

The remaining 48 filler items were not constrained with respect to shape, but were matched on associative relatedness (e.g. elephant and trunk) or lack thereof (e.g. trolley and overcoat). These filler items consisted of 36 semantically related and 12 semantically unrelated word pairs.[1] Thus, 36 stimulus pairs required a "yes" response and 36 a "no" response. The stimulus items are available here: http://www.psy.fsu.edu/~zwaanlab/studies/vf_shape/vf_shape_items.xls.

We used Latent-Semantic-Analysis (LSA) to obtain an independent assessment of their semantic relatedness. LSA (http://lsa.colorado.edu) is a mathematical/statistical technique for extracting and representing the similarity of meanings of words and passages by analysis of large text corpora (Landauer & Dumais, 1997). The degree of semantic relatedness of a word pair is operationalized as the cosine of the contained angle of the vectors representing the meanings of words. We used LSA's pairwise comparison function, the General-Reading-up-to-1st-year-in-college-database, and the default number of factors. The average cosines were 0.11 (SD = 0.10) for the shape-related experimental pairs, 09 (SD = 0.09) for the shape-unrelated experimental pairs, 0.03 (SD = 0.05) for the semantically unrelated filler pairs, and 0.37 (SD = 0.22) for the semantically related filler pairs. Most importantly, the cosine for the shape-related pairs was not significantly different from that of the shape-unrelated pairs [$t(60) = 0.52$, $p > 0.60$]. Furthermore, the cosines for the semantically unrelated conditions together were significantly lower than

[1] Technically, these unrelated filler items are similar to the "shape-unrelated" experimental items. The only difference is that the shape-unrelated pairs contained the same prime or target word (counterbalanced across subjects) as the shape-related pairs, coupled with words that were matched on important psycholinguistic variables with the shape-related words they replaced. The rationale for this is that we wanted appropriate comparison items for the shape-related items. This level of control did not exist in the filler items.

those for the related pairs [$t(39.5)=7.35$], with the number of degrees of freedom being adjusted for the inequality of variances.

2.3. Design and procedure

Two main factors, shape and visual hemifield, were manipulated within subjects and within items. In what follows, we will refer to these as Match and Hemisphere for ease of exposition (despite the fact that visual hemifield rather than hemisphere was the manipulated variable). We created eight lists to counterbalance items and conditions. Each subject was exposed to only one list and equal numbers of subjects were allocated to each list. Each list included one of eight possible versions (2 Shape relatedness × 2 Hemisphere × 2 Word order), producing a 2 (Shape relatedness) by 2 (Hemisphere) by 8 (List) design.

Stimuli were presented by a PC on a 19-in. display using E-prime (2000) stimulus presentation software. Subjects were instructed to judge whether the words that appeared briefly on the screen were semantically related. They were also informed that the relations between the words should be evident. Furthermore, subjects were informed that response times and judgment accuracy were being recorded, and that they should keep their index fingers positioned on the response keys at all times during the experiment to enable quick and accurate responses. Response latencies and semantic-relatedness judgments were recorded via the keyboard using the J-key for "yes" responses and the F-key for "no" responses.[2] Responses not made within 2 s after stimulus presentation were logged as incorrect and the next trial was cued.

The first word in each trial was always presented centrally; the second word was presented either to the left or right of center. The middle of each stimulus word was presented approximately 2.5° of visual angle from the fixation cross. On average, the right-most letter of a rvf presented word or the left-most letter of a lvf presented word subtended 3.7° of visual angle from the fixation cross at a viewing distance of 62 cm. To control head placement and minimize head movement, a table-mounted chinrest was used. Ten practice items occurred at the beginning of the experiment to familiarize the subjects with the task. Half of these items consisted of semantically related and half of semantically unrelated word pairs. Half of these items were presented to the lvf and half to the rvf.

Subjects controlled the inter-trial interval and initiated each trial by pressing the spacebar. At the start of each trial, a centrally located fixation cross was presented for 500 ms. Then the first word was presented for 250 ms in the center of the screen. A second fixation cross was then presented for 250 ms. The second word was then presented for 175 ms to either the left or right of center by approximately 2.75 cm.

[2] The fact that correct ("no") responses were always made with the left hand may make it difficult to examine main effects of hemisphere (although some studies have reported no effect of response hand, e.g. Bowden & Beeman, 1998). However, this presents no serious problem for our analyses, given our prediction of an interaction between hemisphere and referent shape overlap.

Table 1
Semantic-relatedness judgment latencies and accuracy segregated by hemisphere and shape relatedness condition (standard deviations in parentheses)

Experimental items	Shape related		Shape unrelated	
	Latency	Accuracy	Latency	Accuracy
LH/rvf	808 (203)	0.88 (0.16)	727 (202)	0.90 (0.15)
RH/lvf	778 (195)	0.87 (0.17)	783 (250)	0.89 (0.16)
Filler items	**Related**		**Unrelated**	
	Latency	Accuracy	Latency	Accuracy
LH/rvf	607 (145)	0.85 (0.11)	700 (179)	0.88 (0.12)
RH/lvf	653 (147)	0.82 (0.12)	779 (191)	0.88 (0.13)

3. Results

Average response times and accuracy are reported in Table 1.[3] Outliers were removed from the response-time analysis as follows. First, times <150 ms and times >2000 ms were removed. Next, times more than two standard deviations from a subject's condition mean were eliminated. In total, less than 1% of the data were omitted from the analysis. Our main predictions were that (1) subjects should have a more difficult time rejecting shape-related items as unassociated than non-shape related items and (2) that this effect should be strongest in the LH. We tested these predictions by submitting the response times to the experimental items to a 2 (hemisphere) by 2 (shape relatedness) by 8 (list) mixed analysis of variance (ANOVA), with the first two factors manipulated within, and list manipulated between subjects. In all analyses reported below, the alpha level was set at $p=0.05$. The subscripts 1 and 2 refer to analyses conducted with subjects as the random factor and with items as the random factor, respectively.

Consistent with our first prediction, there was a main effect of shape relatedness, with subjects rejecting shape-related items more slowly than non-shape related items [$F1(1,48)=8.23$, MSe = 9628; $F2(1,24)=3.66$, $p<0.07$, MSe = 10066]. Consistent with our second prediction, there was an interaction between hemisphere and shape relatedness [$F1(1,48)=5.28$, MSe = 19177; $F2(1,24)=6.55$, MSe = 10100], with shape relatedness having a 91 ms effect in the LH [$F1(1,48)=14.73$, MSe = 12211; $F2(1, 24)=7.16$, MSe = 14094], whereas the 5 ms difference in the RH was not significant [both $Fs<1$].

[3] Reviewers of a previous version of this article pointed out that some of the shape-related word pairs seemed associated, despite their low LSA cosines (e.g. CARD-PHOTO). We concur. If these items are associated, despite their low LSA ratings, then they would create some noise in our data. The RH is known to be more sensitive to remote associations than the LH (Beeman, 1998), and would thus be more likely to yield "yes" responses to these stimuli than the LH. For these reasons, we reduced the number of experimental items to 16 (six per list), eliminating the pairs identified by the reviewers, plus an additional four pairs to obtain equal numbers per list. Thus, the analyses reported below are based on 16 experimental pairs (see http://www.psy.fsu.edu/~zwaanlab/studies/vf_shape/vf_shape_items.xls). It is important to note, however, that the analysis of the full set of items yields a qualitatively identical pattern of results (i.e. the same effects are significant). The results of this analysis can be obtained from the first author.

There was no main effect of hemisphere [both $Fs < 1$]. The accuracy scores for the experimental items were also submitted to a 2×2×8 mixed ANOVA. None of the effects were significant [all $Fs < 1.27$].[4]

4. Discussion

We hypothesized that shape information would be activated during a semantic-relatedness judgment task. Moreover, we hypothesized that this would result in an interference effect primarily in the LH, given that neurological and behavioral evidence suggests that shape information about concrete objects at the category level is represented by the LH. The results are consistent with these hypotheses. In terms of reaction times, only the LH showed evidence of shape-based interference in semantic judgments. The RH, however, showed some sensitivity to shape information in terms of response accuracy.

A question we did not seek to address in the present experiment, but which might be worth discussing is whether our effects are the result of automatic or strategic processes. It has been argued that subjects may generate expectancies about the target when presented with the prime (Neely, 1977; Posner & Snyder, 1975), leading to facilitation if the expectancies are matched by the target and to inhibition if they are not matched. However, such an expectancy strategy is considered possible only at long SOAs (den Heyer, Briand, & Dannenbring, 1983; Neely, 1977). The ISI in our experiment was 250 ms, the prime word remained on the screen for 250 ms, resulting in an SOA of 500 ms, and the target was presented for only 175 ms. Whereas we do not necessarily want to claim that shape information is activated automatically, our data do show that shape information is activated rather rapidly, suggesting it is not the result of strategic processing. Moreover, it is important to note that activating shape information actually is detrimental to task performance in our experiment, yielding responses that are both slower and less accurate than those in a control condition. Furthermore, it has been observed (Kellenbach et al., 2000; Pecher et al., 1998), and it is also our experience, that subjects rarely notice the shape overlap among items, especially if the frequency of these items in the total stimulus set is low. In our experiment, only 1/3 of all items had referents with similar shapes. Finally, it has been noted (Kellenbach et al., 2000; Pecher et al., 1998) that the presence of associated items will promote relatedness checking, which may mask shape-based priming effects. Half of our stimulus pairs were associatively related. Thus, we found effects of

[4] We also analyzed the data for the filler items, using a 2 (hemisphere) by 2 (semantic associatedness) by 8 (list) ANOVA. There was a large main effect of hemisphere [$F1(1,48)=43.16$, MSe = 5085; $F2(1,22)=8.44$, MSe = 4202], showing the commonly observed pattern of the LH being faster in lexical-semantic tasks than the RH (but see footnote 1). There also was a large effect of semantic relatedness, showing that subjects responded "yes" more quickly to associated items than they responded "no" to unassociated items [$F1(1,48)=66.71$, MSe = 10081; $F2(1,22)=13.03$, MSe = 6544]. Finally, the interaction between these two factors was not significant [$F1(1,48)=4.06$, $p=0.05$, MSe = 3708; $F2 < 1$]. In the analysis of response accuracy, the only significant effect (by subjects) was a main effect of semantic associatedness, with subjects responding "yes" more accurately to associated items than they responded "no" to unassociated items [$F1(1,48)=7.87$, MSe = 0.0168; $F2 < 1$].

shape-based priming (in the LH) despite the presence of factors that arguably work against a conscious strategy focusing on shape overlap.

Our results are consistent with recent behavioral studies showing that visual representations are rapidly activated by words either presented in isolation or in sentences (Dahan & Tanenhaus, 2002; Potter, Kroll, Yachzel, Carpenter, & Sherman, 1986; Richardson, Spivey, MacRea, & Barsalou, 2003; Stanfield & Zwaan, 2001; Zwaan, Madden, Yaxley, & Aveyard, 2004; Zwaan, Stanfield, & Yaxley, 2002) and with studies showing priming or interference between visual and linguistic stimuli (Boroditsky, 2000; Fincher-Kiefer, 2001; Kaschak et al., in press). Moreover, our results show that visual information is activated, even with exclusively verbal stimuli (see also Zwaan & Yaxley, 2003a,b). This ensemble of findings is consistent with theories that assume that verbal processing activates distributed visual representations (Barsalou, 1999; Damasio et al., 2004; Zwaan, 2004) outside of the classical language areas, which are subsequently used in mental simulations of the described situation.

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