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Visual word stem completion priming within and across modalities: a PET study

Daniel L. Schacter,[1,CA]
Rajendra D. Badgaiyan[1,2] and
Nathaniel M. Alpert[2]

[1]Department of Psychology, William James Hall, 33, Kirkland Street, Cambridge, MA 02138; [2]PET Imaging Laboratory, Massachusetts General Hospital, Boston, MA 02114, USA

[CA]Corresponding Author

USING positron emission tomography, we studied changes in the regional cerebral blood flow (rCBF) associated with cross modality (auditory to visual) and within modality visual priming in a word stem completion task. Compared to baseline completion performance and to within modality visual priming, cross modality priming was associated with increased rCBF in prefrontal cortex and decreased rCBF in the left angular gyrus. The results confirm and complement trends observed in a previous study concerning visual to auditory cross modality priming, and suggest that distinct cortical mechanisms may mediate within- and cross modality priming on the stem completion task. The findings are consistent with the neuropsychological data concerning auditory to visual cross modality priming, and indicate involvement of aspects of explicit retrieval and lexical processes in cross modality priming. *NeuroReport* 10:2061–2065 © 1999 Lippincott Williams & Wilkins.

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Introduction

Priming refers to changes in the ability to identify or produce an object or word as a result of a specific prior encounter with the item. Studies of healthy volunteers and amnesic patients have shown that priming does not require conscious or explicit recollection of a prior encounter with an object, and is thus considered a form of implicit memory [1]. Experiments using such neuroimaging techniques as PET and fMRI have consistently revealed that priming is accompanied by decreased activity in a variety of cortical regions [2,3] (for reviews see [4,5]).

Most theoretical accounts of priming distinguish between two basic forms of the phenomenon. Within modality priming occurs when target stimuli are presented and tested in the same sensory modality, and is thought to involve changes in modality-specific perceptual processes [1,6,7]. By contrast, cross modality priming occurs when stimuli are presented in one modality and are tested in another (e.g. visual study followed by auditory test, or *vice versa*), and is thought to involve modality-non-specific conceptual or lexical processes. Several lines of evidence suggest that cross modality priming is mediated by some form of abstract lexical representation involved in phonological input or output processing [6,8,9]. An alternative perspective holds that cross modality priming involves explicit retrieval processes (i.e. conscious or intentional recollection) that do not occur during within-modality priming [10,11].

Although neuroimaging studies have focused on within modality priming, we recently reported PET data concerning cross modality priming [12]. In this study, participants either heard or saw words during the study phase of the experiment, and were then scanned while performing an auditory word stem completion test that included studied and non-studied words. Within modality priming was accompanied by decreased regional cerebral blood flow (rCBF) in several cortical regions (extrastriate cortex, precuneus, medial/right anterior prefrontal, right angular gyrus). By contrast, cross modality priming was accompanied by trends for rCBF increases in the right anterior prefrontal area previously implicated in explicit memory retrieval [2,3,13–16]. Further, cross modality priming was also associated with trends for rCBF decrease in a region of left posterior parietal cortex previously implicated in phonological storage processes [17,18]. Thus, the results of Badgaiyan *et al.* [12], though preliminary, raise the possibility that cross modality priming on the word stem completion task might involve both activation of explicit retrieval processes on the one hand, and decreases in phonological or lexical processes on the other. However, the generality of these conclusions is uncertain because Badgaiyan *et al.* focused exclusively on cross modality priming involving visual study and auditory test. It is thus unknown whether the same pattern of results holds for cross modality priming from auditory study to visual test. This point is particularly important because prior ideas about cross modal priming are based mainly on experiments involving auditory study and visual test (but see [9]). For example, behavioral evidence suggesting a role for explicit retrieval in cross modality priming of word stem completion comes from studies using auditory study and visual test [10,11,19]. We hypothesized that the trends previously associated with cross modal word stem completion priming using visual study and auditory test (blood flow increases in anterior prefrontal cortex and decreases in left posterior parietal cortex) will also be observed with auditory study and visual test. The purpose of the present experiment was to test this hypothesis.

Materials and Methods

The experimental protocol was approved by the institutional review boards of Harvard University and Massachusetts General Hospital. Informed written consent was obtained from all participants prior to the study. Subjects were selected according to the same criteria as in our previous study, including age and gender ratio [12]. The experiment was conducted with eight English speaking Harvard undergraduates (three females, five males, age 18–29 years; mean 20.6 years) who were right handed and had normal or corrected to normal vision and hearing. They were screened to rule out neurological or psychiatric conditions. A history of prolonged use of a prescription or recreational drug was also an exclusion criterion. They were advised to remain alcohol free for at least 24 h prior to the scan and tobacco free for at least 2 h prior to the scan.

The experiment included within modality visual priming and auditory to visual cross modality priming conditions. In the within modality condition, during the study phase a list of 60 upper case words (30 target and 30 filler words, presented in random order) was shown on a computer monitor. Each word (new gothic MT, 24 point, bold) was presented for 2000 ms (ISI 150 ms) and subjects were instructed to rate the pleasantness of the meaning of each word on a 1–3 scale using a numeric keypad and responding with the right hand. Approximately 2 min after presentation of the study list, participants were scanned. During the scan blocks, they provided completions to three-letter word stems (same font and size as study words) that could be completed with previously studied words (priming blocks) or could not be completed with previously studied words (baseline blocks). Thirty word stems were presented (2200 ms; ISI 800 ms) in each block and subjects were asked to speak aloud the first word that came to mind beginning with each stem. The first nine stems in each block were derived from both studied and non-studied words. The final 21 stems in the priming block all came from the studied list, whereas in baseline blocks none of the final 21 stems could be completed with a studied word. PET scans were obtained during completion of the final 20 word stems.

In the cross modality condition, auditory study words (recorded in a single female voice) were presented through a headphone. In this condition, the length of the study list was reduced to 45 words (30 target and 15 filler) to equate levels of priming in comparison to within modality priming, as discussed earlier by Badgaiyan *et al.* [12]. Word stem completion blocks were constructed in the same manner for the within- and cross modality conditions.

Target materials consisted of a list of common English words, each having a unique stem (first three letters) and were selected according to the criteria set in our earlier study [12]. Words were counterbalanced across subjects in such a way that each word occurred equally often in the within and cross modality condition, priming and baseline, and in each scan sequence.

Each subject underwent eight scans, two in each of the four main conditions (i.e. within modality priming and baseline, cross modality priming and baseline). During the word stem completion test, responses and response latencies were recorded.

PET data acquisition and treatment were as described earlier [12]. During the priming and baseline conditions head scans were obtained using a General Electric Scanditronix (Uppsala) model PC4096 15-slice whole body tomograph. An individually molded plastic face mask was used to minimize head motion during the experiment. At time zero, the word stem completion task was started along with the PET camera and continued for 90 s. At 30 s radioactive tracer inhalation (^{15}O labeled carbon dioxide) and emission data acquisition began. Tracer inhalation and data acquisition lasted for 60 s. A washout period of ~10 min was allowed between successive scans. The data were analyzed with SPM95 (from the Wellcome Dept. of Cognitive Neurology, London, UK) according to the theory of statistical parametric mapping [20]. To set the threshold of significance we followed the criteria of Badgaiyan *et al.* [12]. Accordingly, when no localizing hypothesis or prior experimental data were available, a threshold of $z = 4.2$ was considered significant. When an *a priori* hypothesis localized the putative activation to a specific anatomic region, a score of $z \geqslant 3.09$ was considered significant and a score of $z \geqslant 1.96$ was considered a trend effect.

Results

Behavioral data: As indicated in Table 1, the proportion of word stems completed with target words, in both the visual and auditory study conditions, was higher than in the corresponding baseline conditions for both the first and second study/test blocks. As compared to the appropriate baseline, participants completed more stems with target words following both visual study ($t(15) = 7.81$, $p < 0.0001$) and auditory study ($t(15) = 11.27$, $p < 0.0001$). An ANOVA was performed on priming scores that were obtained by subtracting the proportion of target words provided in the baseline conditions from the proportion of target words provided in the corresponding priming conditions. The ANOVA showed a non-significant effect of study modality ($F(1,14) < 1$), indicating that, as intended, comparable levels of priming were attained in the within- and cross modality conditions. There was a non-significant effect of study/test block ($F(1,14) = 1.97$) and a non-significant study modality × test block interaction ($F(1,14) = 1.27$).

rCBF data: Cortical areas showing significant rCBF changes were localized using the conventional Talairach coordinate system [21]. Within modality priming was accompanied by rCBF decreases in extrastriate visual cortex (Fig. 1; Table 2), replicating previous studies of priming on the visual stem completion task [2–5]. Although the peak of the priming-related decrease was localized in the lingual gyrus, anterior and medial to comparable peaks reported in earlier studies, the decrease extended into regions of BA 19 that have shown priming-related rCBF decreases in these studies (24,−88,−8, z-score = 2.19; −14,−88,−12, z-score = 2.31). Within modality priming was also accompanied by a blood flow decrease in the precuneus (BA 7). There were no significant rCBF increases associated with within modality priming. Cross modality priming was accompanied by a different pattern of rCBF changes than that seen with within modality priming (Fig. 1; Table 2). Consistent with our hypotheses and replicating the results of Badgaiyan *et al.* [12], there was a significant rCBF increase in right anterior prefrontal cortex (BA 10). There was also an rCBF increase, not observed by Badgaiyan *et al.* [12], in a slightly

Table 1: Percentage of target words used to complete word stems in the studied (priming) and non-studied (baseline) conditions

	Block 1	Block 2	Mean
Within modality priming			
priming	45.0 ± 4.5	52.5 ± 4.5	48.7 ± 3.2
baseline	17.5 ± 2.5	12.5 ± 2.3	15.0 ± 1.8
Cross modality priming			
priming	43.1 ± 3.6	46.8 ± 2.5	45.0 ± 2.2
baseline	13.7 ± 3.6	16.2 ± 1.2	15.0 ± 1.1

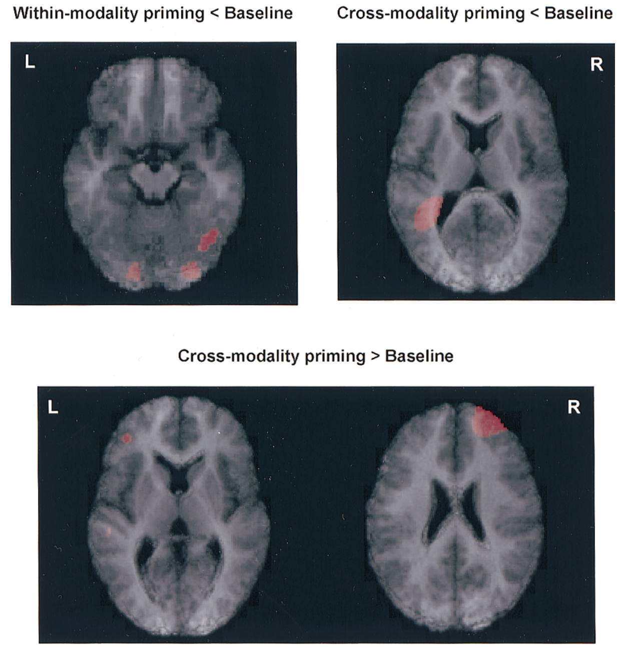

FIG. 1. Statistical parametric maps showing rCBF changes in within modality visual priming and auditory to visual cross modality priming on the word stem completion task, compared to the baseline (unprimed) word stem completion task. rCBF decreases were observed in extrastriate cortex during within modality priming, and in the left angular gyrus during cross modality condition. Compared to the baseline, there were rCBF increases in prefrontal cortex in the cross modality condition. The maps are superimposed over averaged structural SPGR/MRI images that were transformed to Talairach space.

Table 2: Regions showing significant changes in rCBF in the main experimental comparisons

Condition and cortical area	Talairach coordinates x	y	z	z-score
Within modality priming < baseline				
extrastriate cortex (BA 19/37)	42	−58	−8	3.38
precuneus (BA 7)	6	−64	32	3.13
Cross modality priming > baseline				
anterior prefrontal (BA 10)	28	50	24	3.32
Cross modality priming < baseline				
superior/middle temporal gyrus (BA 39/22)	−34	−46	12	3.44
Cross modality priming > within modality priming				
precuneus/extrastriate cortex (BA 19)	2	−66	32	3.31
Cross modality priming < within modality priming				
superior/middle temporal gyrus (BA 39/22)	−32	−48	16	3.44

more ventral and posterior left prefrontal region (−26,22,−12, z-score = 3.38). In addition, cross modality priming was associated with an rCBF decrease in the vicinity of the left superior/middle temporal gyrus (BA 39/22), close to that previously observed by Badgaiyan *et al.* [12]. There was also a bilateral decrease in parahippocampal cortex, extending into extrastriate cortex (18,−50,−4 and −18,−68,−8). The z-score (2.94) of this deactivation, however, was below the statistical threshold for non-planned comparisons.

Direct comparisons between the two priming conditions (Table 2) revealed significant differences in a region involving extrastriate visual cortex (BA 19) extending to precuneus (cross modality > within modality), as well as the left superior/middle temporal gyrus (within modality > cross modality). There were also more modest trends in bilateral anterior prefrontal cortex (cross modality > within modality; 36,44,−4, z-score = 2.31; 26,44,−4, z-score = 2.19).

Discussion

Cross modality priming on a visual word stem completion test was accompanied by significant increases in right anterior prefrontal cortex, and by significant decreases in left middle/superior temporal gyrus. These results thus complement and extend trends in our previous study [12], suggesting that cross modality priming on an auditory word stem completion test is accompanied by rCBF increases in right anterior prefrontal cortex and by decreases in left posterior parietal cortex near the angular gyrus. The peak of this latter decrease in the study of Badgaiyan *et al.* [12] (−40,−46,28) was in the vicinity of, though slightly inferior to, the peak of the left superior temporal decrease observed in the present experiment (−34,−46,12). Moreover, in both studies, patterns of rCBF increases and decreases during cross modality priming were markedly different from those observed during within modality priming even though the overall degree of priming observed in the within- and cross modality conditions was indistinguishable.

Our findings provide further evidence concerning the possible contributions of explicit retrieval and lexical processes to cross modality priming. Specifically, the right anterior prefrontal region that was activated during cross- but not within modality priming has been implicated previously in aspects of explicit retrieval [15,16].

Based on the present results and those of Badgaiyan *et al.* [12], we cannot be certain about the exact nature of the explicit retrieval processes that are associated with cross modality priming. Badgaiyan *et al.* [12] reviewed evidence suggesting that cross modality priming does not involve intentional or voluntary attempts to retrieve studied items [22]. Anterior prefrontal activation might instead reflect involuntary conscious memory or postretrieval monitoring of primed responses [15]. Clearly, further research will be needed to explore this issue.

As noted earlier, evidence from our previous study suggested that cross modality priming is accompanied by rCBF decreases in left posterior parietal cortex [12]. In the present experiment, cross modality priming was accompanied by an rCBF decrease in a nearby region of superior/middle temporal gyrus (−40,−46,28 in Badgaiyan *et al.* [12] compared with −34,−46,12 in the present study). Decreased activity in left posterior parietal cortex during cross modality priming could reflect a priming-related reduction in some aspect of phonological or lexical processing [6,9]. Given the relative proximity of the left superior/middle temporal region that showed decreased rCBF in the present study to the left posterior parietal region observed in the Badgaiyan *et al.* [12] study, a similar account may be warranted. It is also possible that small differences in the exact location of the two regions could reflect differences associated with transfer from visual study to auditory test [12] *vs* auditory study to visual test (present experiment).

Taken together, our results and those of Badgaiyan *et al.* [12] converge nicely with cognitive studies indicating that cross modality priming can involve both explicit retrieval and changes in phonological or lexical processing [6,9]. These findings could also help to resolve an apparent inconsistency between data indicating a role for explicit retrieval in cross modality priming [10,11] and evidence from amnesic patients indicating normal cross modality priming on the visual word stem completion test [23,24]. Specifically, cross modality priming of word stem completion may be based either on explicit retrieval or on changes in lexical processing. When only explicit retrieval is impaired, as in the amnesic patients studied by Carlesimo *et al.* [23] and Graf *et al.* [24], cross modality priming can be accomplished by changes in lexical processing. When both explicit retrieval and lexical processing are impaired, however, cross-modality priming on the stem completion test should be abolished. Consistent with this idea, Curran *et al.* [8] found that patients with lesions to left frontal and temporo-parietal regions, who exhibited both verbal production deficits and explicit memory deficits, showed impaired cross modality priming on a visual word stem completion task although they exhibited intact within modality priming.

In contrast to the foregoing, Vaidya *et al.* [25]

found that a group of amnesics showed normal within modality priming, but only a non-significant trend for cross modality priming in a word fragment completion test. Kohler *et al.* [19] reported that a patient with severe amnesia showed within- but not cross modality priming on a similar test. It is thus conceivable that in contrast to cross modality priming of visual word stem completion performance, cross modality priming on the visual fragment completion test might rely entirely on explicit retrieval and not on changes in lexical processing, which are probably crucial for cross modality word stem completion performance. These observations would lead to a novel prediction: patterns of rCBF during cross modality priming of visual fragment completion should yield evidence of the involvement of some aspect of explicit retrieval (i.e. anterior prefrontal increases), but will not yield evidence of changes in lexical processing (i.e. left posterior parietal/superior temporal decreases). A direct comparison of rCBF during within- and cross modality priming on the visual fragment completion task should further extend our understanding of cross-modality priming and strengthen the links between neuropsychological and neuroimaging studies.

Conclusions

The present study complements and extends trends observed in visual to auditory cross modality priming in a previous study by Badgaiyan *et al.* [12], and suggests that within modality and cross modality priming are supported by distinct cortical mechanisms. Activation of right anterior prefrontal cortex and deactivation of left angular gyrus observed in the cross modality condition suggests involvement of both explicit retrieval and lexical processes in the expression of cross modality priming, at least in a word stem completion task. These findings are consistent with neuropsychological data on auditory to visual cross modality priming.

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