Hemispheric Encoding Asymmetry is More Apparent Than Real

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Abstract

■ Previous neuroimaging studies have claimed a left hemisphere specialization for episodic "encoding" and a right hemisphere specialization for episodic "retrieval." Yet studies of split-brain patients indicate relatively minor memory impairment after disconnection of the two hemispheres. This suggests that both hemispheres are capable of encoding and retrieval. In the present experiment, we examined the possible limits on encoding capacity of each hemisphere by manipulating the "depth" of processing during the encoding of unfamiliar faces and familiar words in the left and right hemispheres of two split-brain patients. Results showed that only the left hemisphere benefited from deeper (more elaborate) encoding of familiar words, and only the right hemisphere benefited from deeper encoding of unfamiliar faces. Our findings are consistent with the view that hemispheric asymmetries in episodic encoding are related to hemisphere-specific processing of particular stimuli. Convergent with recent neuroimaging studies, these results with split-brain patients also suggest that these hemispheric differences are not due to unique specializations in each half brain for encoding memories, but rather, are due to preferential recruitment of the synaptically closer prefrontal cortex to posterior regions processing material-specific information. ■

INTRODUCTION

From neuroimaging studies and neuropsychological studies, it is clear that hemispheric asymmetries play a role in episodic memory. The nature of that asymmetry, though, has recently been debated. Some investigators have argued that episodic encoding is predominantly a left prefrontal function while episodic retrieval is predominantly a right prefrontal function (Tulving, Kapur, Craik, Moscovitch, & Houle, 1994). Typically, these neuroimaging studies rely on the encoding and retrieval of familiar verbal material (Cabeza & Nyberg, 2000). Other researchers have suggested that hemispheric asymmetries, particularly episodic encoding, are material specific rather than process specific. For example, recent neuroimaging research has reported right hemisphere activations in the prefrontal cortex during the encoding of unfamiliar faces (Kelley et al., 1998) and textures (Wagner, Poldrack, et al., 1998). Nevertheless, proponents of a lateralized episodic encoding region argue that the propensity of neuroimaging research, including some studies using nonverbal material, suggests that episodic encoding is predominantly a left hemisphere process (Nyberg, Cabeza, & Tulving, 1998; Nyberg et al., 2000).

Despite the functional neuroimaging arguments that episodic encoding is predominantly a left hemisphere function, we propose that each hemisphere is fully capable of encoding and retrieving episodes. This stance is based on studies of "split-brain" patients who have had their hemispheres surgically disconnected as a treatment for intractable epilepsy. If encoding and retrieval are predominantly lateralized processes in opposite hemispheres, then it follows that split-brain patients should have catastrophic memory impairment. Yet these patients demonstrate only minor deficits in episodic memory (Metcalfe, Funnell, & Gazzaniga, 1995; Phelps, Hirst, & Gazzaniga, 1991; LeDoux, Risse, Springer, Wilson, & Gazzaniga, 1977; Zaidel & Sperry, 1974). These findings with split-brain patients suggest that activations seen in neuroimaging studies may indeed be material specific, as suggested by Kelley et al. (1998) and Wagner, Poldrack, et al. (1998). Convergent with this view, other studies suggest that the prefrontal cortex and the medial temporal lobe act interdependently to enable episodic encoding (Wagner, Schacter, et al., 1998; Moscovitch, 1972). That is, the prefrontal cortex is recruited to enable encoding processes (being carried out in more posterior regions) to a greater or lesser extent depending on task demands or stimulus characteristics. For instance, many neuroimaging studies isolate brain activity during episodic encoding by contrasting the shallow encoding of stimuli with deep, more elaborate,

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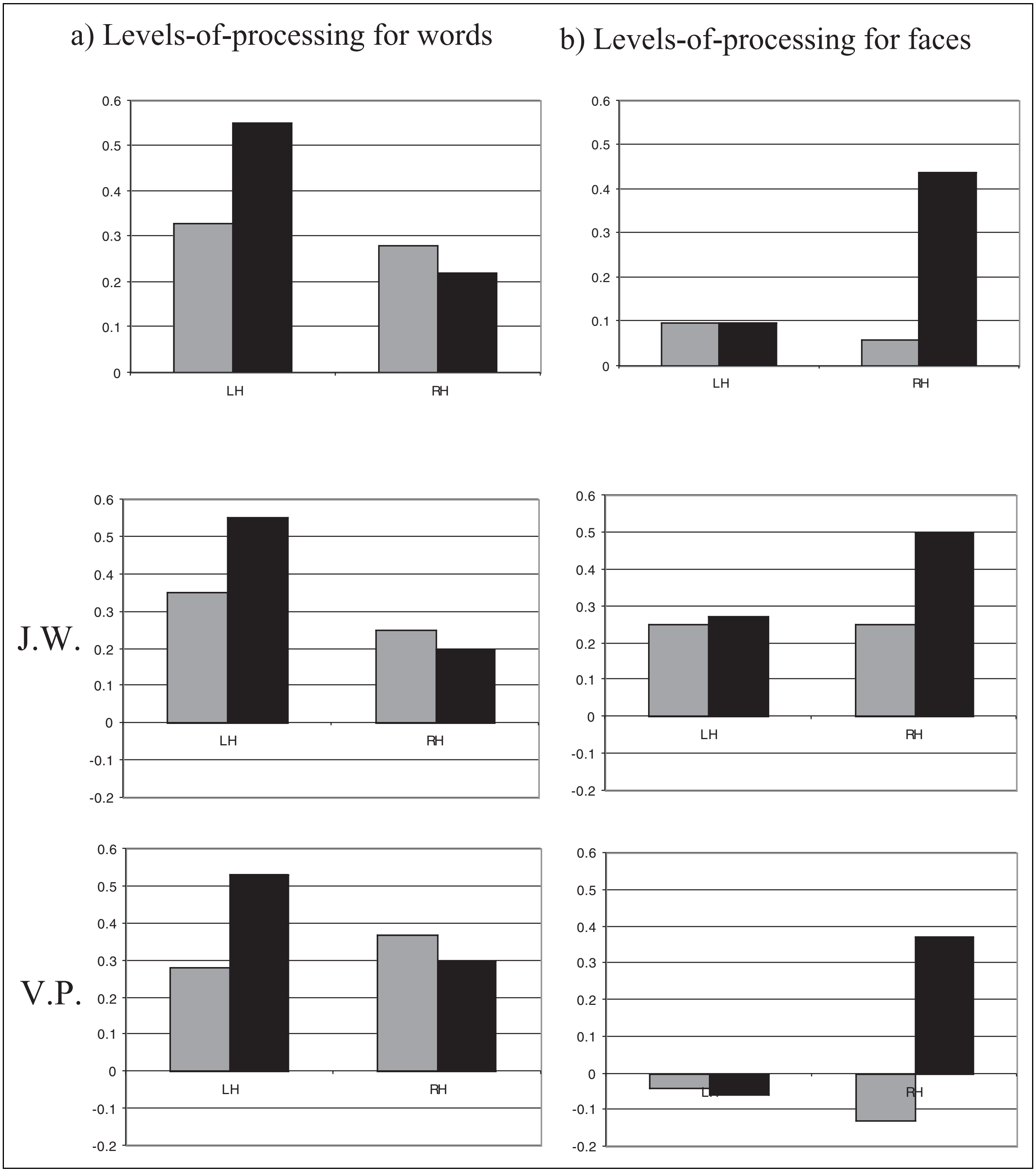

Figure 1. (a) This column represents recognition performance using words for the left and right hemispheres of split-brain patients. The first row is the average of both patients, while the second row is Patient J. W. and the third row is Patient V. P. Gray bars represent a shallow level-of-processing during encoding, and black bars represent a deep level-of-processing. The left hemispheres' recognition performance improved significantly after deep processing of words as compared to shallow processing, while the right hemisphere showed no improvement. (b) This column represents recognition performance using faces for both hemispheres of both patients. In contrast to word processing, the right hemispheres' recognition performance improved significantly after deep processing, but the hemisphere's recognition performance did not.

encoding of stimuli. Word processing and encoding of verbal stimuli is known to involve structures posterior to the prefrontal cortex in the left hemisphere of most subjects (Milner, Corkin, & Tueber, 1968; Milner, 1972). These structures are often not evident in these neuro-imaging contrasts presumably because they operate to the same extent in both the shallow and deep conditions (see Schacter & Wagner, 1999 for discussion). However, this contrast does typically produce strong activations in the left dorsolateral prefrontal cortex associated with more elaborate encoding. It may be that the left prefrontal cortex is recruited to a greater extent in the elaborate condition compared to the shallow condition, and that it is lateralized to the left hemisphere due to its proximity to more posterior hemisphere-specific processing of particular verbal stimuli.

The present study tested these ideas by manipulating the encoding of words and faces in each hemisphere of two split-brain patients. If episodic encoding is predominantly a left hemisphere function despite the type of material, then only the left hemisphere in these patients should benefit from more elaborate encoding of words and faces. However, because language is preferentially lateralized to the left hemisphere and face processing to the right hemisphere in these patients (Gazzaniga, 2000), we hypothesized that the left hemisphere would benefit from the deeper encoding of familiar words but not the right, and that the right hemisphere would benefit from the deeper encoding of unfamiliar faces but not the left.

RESULTS

Results from Split-Brain Patients on Manipulating the Encoding of Words

In this experiment, we directly manipulated the level of encoding of word stimuli in each isolated hemisphere of two split-brain patients, J. W. and V. P., using a lateralized procedure for both the study and test phases. First, it is important to note that both hemispheres for both patients had no difficulty in performing the shallow and deep encoding tasks. The shallow task required the patient to determine whether the letter "a" appeared in the word. The deep encoding task required the patient to determine whether the word represents a living object or not.

Table 2. Levels-of-Processing for Faces in Normal Subjects

	Hit Rate	*False Alarm Rate*	*Corrected Recognition*	d'
Shallow	69%	34%	35%	0.91
Deep	82%	30%	52%	1.45

In the recognition task, both split-brain patients showed a significant benefit in the left hemisphere for deeper encoding of words, but showed no benefit in the right hemisphere. Figure 1a illustrates the recognition performance across several sessions for both split-brain patients using corrected recognition scores, while Table 1 shows all the hit rates, false alarm rates, corrected recognition scores, and d' for each hemisphere of both patients. J. W.'s recognition performance in the left hemisphere increased significantly from the shallow condition (35%) to the deep condition (56%), while his performance in the right hemisphere did not improve (shallow 24%, deep 20%). Similarly, V. P.'s performance in the left hemisphere increased from the shallow condition (28%) to the deep condition (53%), while her performance in the right hemisphere also did not improve (shallow 37%; deep 29%). In a repeated-measures ANOVA, there was a significant two-way interaction between hemisphere and level-of-processing [$F(1,14) = 14.31$, $p = .002$]. (Each patient's session was considered a case with proportion correct as the dependent measure. Patient was considered a between-subjects variable, while hemisphere [left or right] and level-of-processing [shallow or deep] were considered within-subjects variables.) Overall, there was a significant difference between the left hemisphere and the right hemisphere [$F(1,14) = 7.66$, $p = .015$], but no significant difference between patients [$F(1,14) = .24$, $p = .631$], nor did patient interact significantly with other variables (all F's < 2.15; all p's $> .16$). As for the depth of processing, overall, there was no significant difference between deep encoding

Table 1. Levels-of-Processing for Words in Each Hemisphere of Two Split-Brain Patients

Patient	*Hemisphere*	*Condition*	*Hit Rate*	*False Alarm Rate*	*Corrected Recognition*	d'^{a}
J. W.	Left	Shallow	73%	38%	35%	0.92
		Deep	84%	28%	56%	1.55
	Right	Shallow	65%	41%	24%	0.63
		Deep	67%	47%	20%	0.51
V. P.	Left	Shallow	60%	32%	28%	0.72
		Deep	72%	19%	53%	1.46
	Right	Shallow	78%	41%	37%	1.01
		Deep	86%	57%	29%	0.92

[a]Average d' across testing sessions.

and shallow encoding [$F(1,14) = 1.35$, $p = .265$]. However, critical to our hypothesis was the difference in depth of encoding for each hemisphere. Therefore, each hemisphere was analyzed separately. Indeed, there was a significant difference between deep encoding and shallow encoding in the left hemisphere [$F(1,14) = 6.24$, $p = .026$], but not in the right hemisphere [$F(1,14) = .88$, $p = .363$].

Results from Normal Subjects on Manipulating the Encoding of Faces

Levels-of-processing effects are normally thought to occur only with familiar word stimuli, although Bower & Karlin (1974) published a study showing increased recognition performance following a deep level of encoding faces (is the face likeable/honest?) compared with a shallow level of encoding (is the face male?). Before we tested the separate hemispheres of split-brain patients, we wanted to ensure that our methods for manipulating the level of encoding unfamiliar faces could produce improved recognition in normal subjects using a full-field presentation. The shallow encoding task required subjects to determine whether a face was female or not. The deep encoding task required subjects to determine whether a face was the face of a healthy person or not. As shown in Table 2, normal subjects' recognition performance increased significantly from the shallow condition (35%) to the deep condition (52%) [$F(1,16) = 10.31$, $p = .005$] using corrected recognition scores in a repeated-measures ANOVA.

Results from Split-Brain Patients on Manipulating the Encoding of Faces

Since face processing is known to be lateralized to the right hemispheres in these patients, we hypothesized that the right hemisphere would benefit from the elaborate encoding of unfamiliar faces, but not the left. The left and right hemispheres for both patients did not make any mistakes in determining whether the face was female or male. The deep encoding task (is the face the face of a healthy person?) was subjective, but neither hemisphere appeared to have difficulty in making the judgment.

In contrast to the left hemisphere benefit for words, the right hemisphere of both patients showed a significant benefit for deeper encoding of unfamiliar faces, but not the left (Figure 1b and Table 3). There was no improvement from the shallow condition (25%) to the deep condition (27%) in the left hemisphere of Patient J. W. Yet there was a significant improvement from the shallow condition (24%) to the deep condition (50%) in the right hemisphere. Similarly, in the left hemisphere of V. P., there was no improvement from the shallow condition (−4%) to the deep condition (−6%). Yet, in the right hemisphere there was a significant improvement from the shallow condition (−12%) to the deep condition (37%). (Interestingly, Patient V. P. was at chance in recognizing faces in all the conditions except the deep condition in the right hemisphere, despite the fact that she did not have any trouble with the encoding tasks.) As indicated by these results, there was a significant two-way interaction in a repeated-measures ANOVA between hemisphere and level-of-processing [$F(1,4) = 11.46$, $p = .028$]. Overall, there was a significant main effect for hemispheres [$F(1,4) = 13.11$, $p = .022$] and levels-of-processing [$F(1,4) = 47.22$, $p = .002$]. Although there was also a significant difference between patients [$F(1,4) = 48.33$, $p = .002$], patient did not interact significantly with hemisphere [$F(1,4) = 0.56$, *ns*] or level-of-processing [$F(1,4) = 3.33$, *ns*]. As with the words, each hemisphere was analyzed separately. In the left hemisphere, there was no difference between the shallow condition and the deep condition across patients ($F < 1$) and there was no significant interaction between patient and level-of-processing [$F(1,4) = 0.107$, *ns*]. However, in the right hemisphere, there was a

Table 3. Levels-of-Processing for Faces in Each Hemisphere of Two Split-Brain Patients

Patient	*Hemisphere*	*Condition*	*Hit Rate*	*False Alarm Rate*	*Corrected Recognition*	d'^{a}
J. W.	Left	Shallow	71%	46%	25%	0.64
		Deep	81%	54%	27%	0.78
	Right	Shallow	83%	59%	24%	0.75
		Deep	88%	38%	50%	1.47
V. P.	Left	Shallow	46%	50%	−4%	−0.10
		Deep	36%	42%	−6%	−0.17
	Right	Shallow	38%	50%	−12%	−0.32
		Deep	52%	15%	37%	1.09

[a]Average d' across testing sessions.

significant difference between deep encoding and shallow encoding [$F(1,4) = 54.34$, $p = .002$]. Clearly, there was a difference between patients in overall recognition performance in the right hemisphere but the interaction did not reach significance [$F(1,4) = 5.83$, $p = .073$]. These results confirmed our hypothesis that only the right hemisphere benefits from more elaborate encoding of unfamiliar faces.

DISCUSSION

The foregoing results with split-brain patients add to the growing volume of neuroimaging studies on the hemispheric asymmetries of episodic encoding, and allow for a new perspective on the Hemispheric Encoding/Retrieval Asymmetry (HERA) model that episodic encoding is predominantly a left prefrontal activity while episodic retrieval is predominantly a right prefrontal activity (Tulving et al., 1994). The HERA model, unique in that it was based solely on functional neuroimaging data, has made important contributions to the field of cognitive neuroscience in realizing the role of the prefrontal cortex in episodic encoding and retrieval. At the same time, the present study suggests that recent formulations of the HERA model, which argue for the notion that across stimulus domains encoding is a left hemisphere process, are not correct (Nyberg, Cabeza, & Tulving, 1996, 1998; Nyberg et al., 2000). The data also invalidate the less extreme view that while both hemispheres are capable of encoding and retrieval, across stimulus domains encoding is predominately a left hemisphere process. Neither of these stances can be reconciled with our finding that the effects of stimulus encoding differed in their lateralization based on the nature of the stimulus, with the encoding effects for word stimuli preferentially lateralized to the left hemisphere and the encoding effects for face stimuli preferentially lateralized to the right hemisphere.

Our data, however, are entirely consistent with the formulation of HERA as originally put forward by Tulving et al. (1994). Here, Tulving's model was limited solely to the encoding and retrieval effects of word stimuli. Our finding that the levels-of-processing effects for words stimuli were lateralized to the left hemisphere agrees with the HERA model as it was conceived initially.

An important contribution of the HERA model, and subsequent neuroimaging studies, is the emphasis on the involvement of the prefrontal cortex in memorial processes. The prefrontal cortex appears to be recruited to "elaborate on material" or to "work with" information in order to enhance its memoriability. Our data with split-brain patients suggest that which prefrontal cortex is recruited may depend on the lateralization of more posterior processing. In recent years, it has been argued that fewer synaptic connections are important in enhancing the timing and efficiency of processing (Cherniak, 1994). In this regard, not only is there a significant wiring cost as one ascends the phylogenetic scale (Allman, 1999), but there is a decrease in interhemispheric connections as compared to intrahemispheric connections (Rilling & Insel, 1999). This perspective on cerebral processes could mean that encoding and retrieving hemispheric-specific information might call upon hemisphere-specific memory systems. Of course, split-brain patients have disconnected hemispheres and are, therefore, limited to which prefrontal cortex can be recruited for additional processing. Importantly, however, we have conducted neuroimaging studies that suggest that recruitment by proximity happens in the normal brain as well (Miller, Kingstone, Corballis, Groh, & Gazzaniga, 1999). These findings are consistent with the view that each hemisphere manages locally the extended processes associated with its specialized skills.

Conclusion

The prefrontal cortex may be a component of a larger network supporting episodic memory (Nyberg et al., 2000; Milner, Squire, & Kandel, 1998; Wagner, Schacter, et al., 1998; Moscovitch, 1972). The unique benefit of studying split-brain patients to test competing hypotheses of prefrontal asymmetries is that this approach provides behavioral measures from the isolated hemispheres. Our results indicate that manipulations of episodic encoding differentially affect the performance of the hemispheres depending on the type of material being processed. We maintain that each hemisphere is fully capable of supporting episodic memory, and that the recruitment of a system is based on the type of material being processed.

METHODS

Subjects

Two callosotomy patients (J. W. and V. P.) participated in Experiments 1 and 3. Both patients underwent full-stage callosotomy surgery approximately 20 years ago. Patient V. P. does have some sparing in the rostrum and splenium of the corpus callosum, although no transfer of information was evident in these experiments. Both patients have average intelligence and score within the normal range on standard memory tests. For more descriptive information on these patients, see Gazzaniga, Nass, Reeves, & Roberts (1984).

Seventeen Dartmouth College undergraduate students participated in Experiment 2 in exchange for course credit in an Introductory Psychology class. Their ages ranged from 18 to 22 years old. Subjects gave informed consent in accordance with guidelines set by the Human Subjects Review Committee at Dartmouth College.

Experiment 1

Twelve sessions for Patient J. W. and 4 sessions for Patient V. P. were run in a 2-year period. All words used in the experiment were concrete nouns, for which J. W. and V. P. have previously demonstrated left and right hemisphere comprehension. Each study/test session consisted of a study phase in which 16 words were presented to the left visual field (LVF) and 16 words were presented to the right visual field (RVF). During the test phase, 24 words were presented to the LVF and 24 words were presented to the RVF. Each set of 24 words was composed of 16 old words and 8 new words. Words were presented tachistoscopically for 150 msec, randomly to the left or right of a fixation point, in order to maintain lateralization. There was a 10-min interval between study and test during which the patients were engaged in an unrelated cognitive task. There were two study/test blocks for each session. During one study phase, the patients were engaged in a shallow, perceptual task during encoding (does the word contain the letter "a"?). During the other study phase, they were engaged in a deep, semantic task during encoding (does the word represent a living object?). The order of the study conditions alternated between sessions. The test in both cases was a yes/no recognition test. In both the study and test phases, the patients responded by pointing with their hand ipsilaterally to the visual field of the presentation. They pointed to either "yes" or "no," also presented tachistoscopically, with "yes" appearing randomly in the upper field on half the trials and in the lower field on the other half.

Experiment 2

Prior to testing split-brain patients on a levels-of-processing for unfamiliar faces, we tested normal subjects using the same stimuli and procedures (except full field) to ensure that we could get a levels-of-processing effect. These data were not used as a control for Experiment 3 since the more appropriate control of the right hemisphere of a split-brain patient is the patient's left hemisphere. The procedures were identical to the ones used in Experiment 1 (and Experiment 3) except in the following ways. The faces were not lateralized. They were presented at the center of the computer screen. There were 32 faces presented during the study phase, and 48 faces presented during the test phase (32 old and 16 new). The encoding tasks were identical to Experiment 3. Nine of the subjects engaged in the shallow encoding block first, and 8 subjects engaged in the deep encoding block first. Instead of responding by pointing to "yes" or "no" on the screen, the subjects responded by pressing designated keys on the keyboard.

Experiment 3

This experiment was comprised of 3 sessions with J. W. and 3 sessions with V. P. The procedures were identical to Experiment 1 except that unfamiliar faces were used instead of words. The faces were photographs of Dartmouth undergraduate students from the shoulder up and with a neutral facial expression. The encoding tasks were also different from the ones with words. For the shallow condition, the patients' task was to answer whether the face was female. For the deep condition, their task was to respond whether the face was the face of a healthy person.

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REFERENCES

Allman, J. M. (1999). Evolving brains. *Scientific American Library Series,* No. 68, New York: Scientific American Library.

Bower, G. H., & Karlin, M. B. (1974). Depth of processing pictures of faces and recognition memory. *Journal of Experimental Psychology, 103,* 751–757.

Cabeza, R., & Nyberg, L. (2000). Imaging cognition: II. An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience, 12,* 1–47.

Cherniak, C. (1994). Component placement optimization in the brain. *Journal of Neuroscience, 14,* 2418–2427.

Gazzaniga, M. S. (2000). Cerebral specialization and interhemispheric communication: Does the corpus callosum enable the human condition? *Brain, 123,* 1293–1326.

Gazzaniga, M. S., Nass, R., Reeves, A., & Roberts, D. (1984). Neurologic perspectives on right hemisphere language following surgical section of the corpus callosum. *Seminars in Neurology, 4,* 126–135.

Kelley, W. M., Miezin, F. M., McDermott, K. B., Buckner, R. L., Raichle, M. E., Cohen, N. J., Ollinger, J. M., Akbudak, E., Conturo, T. E., Snyder, A. Z., & Petersen, S. E. (1998). Hemispheric specialization in human dorsal frontal cortex and medial temporal lobe for verbal and nonverbal memory encoding. *Neuron, 20,* 927–936.

LeDoux, J. E., Risse, G., Springer, S., Wilson, D. H., & Gazzaniga, M. S. (1977). Cognition and commissurotomy. *Brain, 110,* 87–104.

Metcalfe, J., Funnell, M., & Gazzaniga, M. S. (1995). Right-hemisphere superiority: Studies of a split-brain patient. *Psychological Science, 6,* 157–163.

Miller, M. B., Kingstone, A., Corballis, P. M, Groh, J. M., &

Gazzaniga, M. S. (1999). Manipulating encoding of faces and associated brain regions. *Society for Neuroscience Abstracts, 25,* 646.
Milner, B. (1972). Disorders of learning and memory after temporal lobe lesions in man. *Clinical Neurosurgery, 19,* 421–446.
Milner, B., Corkin, S., & Teuber, H. L. (1968). Further analysis of the hippocampal amnesic syndrome: 14-year follow-up study of H. M. *Neuropsychologia, 6,* 215–234.
Milner, B., Squire, L. R., & Kandel, E. R. (1998). Cognitive neuroscience and the study of memory. *Neuron, 20,* 445–468.
Moscovitch, M. (1972). Memory and working-with-memory: A component process model based on modules and central systems. *Journal of Cognitive Neuroscience, 4,* 257–267.
Nyberg, L., Cabeza, R., & Tulving, E. (1996). PET studies of encoding and retrieval: The HERA model. *Psychonomic Bulletin and Review, 3,* 135–148.
Nyberg, L., Cabeza, R., & Tulving, E. (1998). Asymmetric frontal activation during episodic memory: What kind of specificity? *Trends in Cognitive Sciences, 2,* 419–420.
Nyberg, L., Habib, R., Tulving, E., Cabeza, R., Houle, S., Persson, J., & McIntosh, A. R. (2000). Large scale neurocognitive networks underlying episodic memory. *Journal of Cognitive Neuroscience, 12,* 163–173.
Phelps, E. A., Hirst, W., & Gazzaniga, M. S. (1991). Deficits in recall following partial and complete commissurotomy. *Cerebral Cortex, 1,* 492–498.
Rilling, J. K., & Insel, T. R. (1999). Differential expansion of neural projection systems in primate brain evolution. *NeuroReport, 10,* 1453–1459.
Schacter, D. L., & Wagner, A. D. (1999). Medial temporal-lobe activations in fMRI and PET studies of episodic encoding and retrieval. *Hippocampus, 9,* 7–24.
Tulving, E., Kapur, S., Craik, F. I. M., Moscovitch, M., & Houle, S. (1994). Hemispheric encoding/retrieval asymmetry in episodic memory: Positron emission tomography findings. *Proceedings of the National Academy of Sciences, U.S.A., 91,* 2016–2020.
Wagner, A. D., Poldrack, R. A., Eldridge, L. L., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. E. (1998). Material-specific lateralization of prefrontal activation during episodic encoding and retrieval. *NeuroReport, 9,* 3711–3717.
Wagner, A. D., Schacter, D. L., Rotte, M., Koutstaal, W., Maril, A., Dale, A. M., Rosen, B. R., & Buckner, R. L. (1998). Building memories: Remembering and forgetting of verbal experiences as predicted by brain activity. *Science, 281,* 1188–1191.
Zaidel, D., & Sperry, R. W. (1974). Memory impairment after commissurotomy in man. *Brain, 97,* 263–272.