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A Computational Analysis of Mental Image Generation: Evidence From Functional Dissociations in Split-Brain Patients

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Recent efforts to build computer simulation models of mental imagery have suggested that imagery is not a unitary phenomenon. Rather, such efforts have led to a modular analysis of the image-generation process, with separate modules that can activate visual memories, inspect parts of imaged patterns, and arrange separate parts into a composite image. This idea was supported by the finding of functional dissociations between the kinds of imagery tasks that could be performed in the left and right cerebral hemispheres of two patients who had previously undergone surgical transection of their corpus callosa. The left hemisphere in both subjects could inspect imaged patterns and could generate single and multipart images. In contrast, although the right hemisphere could inspect imaged patterns and could generate images of overall shape, it had difficulty in generating multipart images. The results suggest a deficit in the module that arranges parts into a composite. The observed pattern of deficits and abilities implied that this module is not used in language, visual perception, or drawing. Furthermore, the results suggest that the basis for this deficit is not a difficulty in simply remembering visual details or engaging in sequential processing.

Visual mental imagery is a transitory event. Images seem to come and go, and for many people only come to mind when they try to answer questions such as, What shape are a beagle's ears? Which is larger, a goat or a hog? Or, how would your sofa look against the opposite wall in your living room? Introspection is adequate to alert one to the fact that an object or scene is present in an image, but falls short of telling one how such images are created. In this article we develop and test a theory of how visual mental images are generated.

One of the major advances of contemporary cognitive psychology is that phenomena previously treated as undifferentiated wholes have been broken into parts. For example, memory is now treated not as a unitary phenomenon, but as consisting of a set of processes that work in concert (encoding, search, comparison, etc.). The parts of such theories often correspond to distinct processing modules, each of which performs a specific set of tasks within the context of the system as a whole.

Kosslyn and Shwartz (1977; see Kosslyn, 1980) proposed a theory of the processing modules used in generating visual mental images. This theory was shaped in large part by three classes of empirical findings: First, although images introspectively may seem to pop into mind all of a piece, we now know that this is not so. In numerous experiments, researchers have found that the time to form an image increases proportionally for each additional part of the imaged object or scene. For example, Beech and Allport (1978), Kosslyn, Reiser, Farah, and Fliegel (1983), and Paivio (1975) found that people

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require an additional increment of time to form images of scenes for each additional object included in the scene. In addition, the complexity of a single imaged object affects image-generation time: Kosslyn et al. found that time to form an image of a geometric pattern increases when the number of units comprising the pattern increases, with units being defined by the Gestalt laws of proximity, similarity, good continuation, and other factors (see Kosslyn, 1980, chap. 4 and 6, for a review of the relevant literature). In short, multipart images are not retrieved all at once, but are built up on the basis of separately stored encodings.

Second, the results of other experiments indicate that people can construct images by making use of descriptions of how parts are to be arranged. For example, subjects in one experiment could imagine a frying pan floating 6 ft. (1.8 m) above a bicycle which is 6 ft. (1.8 m) to the right of a rabbit (see Kosslyn et al., 1983). Once the image was formed, the time to scan between objects in it increased for objects that should be imaged farther apart—providing evidence that people really can use descriptions to guide placement of the parts (see also Beech & Allport, 1978).

Third, Bundesen and Larsen (1975), Farah and Kosslyn (1981), Hayes (1973), and Kosslyn (1975) showed that people can form images at different "subjective sizes" (i.e., so they seem to subtend different visual angles). In general, less time is required to imagine objects at smaller sizes than large sizes, presumably because parts of objects are omitted at smaller sizes because of "grain" constraints (see chap. 5 of Kosslyn, 1980). This interpretation is consistent with the finding that, once an image has been formed, more time is required subsequently to "see" a part of the object if it was imaged at a small size (consistent with subjects' reports of having to "zoom in" to "see" parts at the smaller sizes; see Kosslyn, 1980).

Given these empirical findings, computational considerations place additional constraints on a theory. That is, as a heuristic for formulating a theory of information processing it is useful to consider what one would need to do to program a computer to mimic the effects observed with humans. Given that people can generate images at all, we need a processing mechanism that can locate an encoding of an object's or part's appearance stored in long-term memory, and can use this encoding to generate the corresponding image. Kosslyn and Shwartz call this mechanism the PICTURE processing module. This module is presumably used iteratively when an image is constructed from more than one stored part, with each part being generated separately (and thus image generation times increase with increasingly complex objects or scenes).

In addition, given that people can use descriptions to arrange separately stored encodings (e.g., of a rabbit and a frying pan) into a single imaged scene, we need a processing mechanism that interprets the relations (e.g., "six feet above") and sets the PICTURE processing module so that the objects are imaged in the correct locations. Kosslyn and Shwartz call this the PUT processing module. Given that people can form images of objects (e.g., a car) at different sizes and locations, and that objects or parts are imaged individually, the PUT module cannot simply place parts in absolute locations. Rather, parts (e.g., the wheels of a car) must be placed in a specific relation to other previously imaged parts (e.g., the wheelwells), which themselves may appear at different sizes and locations. The PUT module must first be provided with the location of one object or part before being able to place the next in the correct relative location.

Thus, a third processing mechanism is needed to locate objects or parts already in the image, and then to provide this information to the PUT processing module. Kosslyn and Shwartz call this the FIND processing module. This module identifies spatial patterns as depicting specific parts or objects. That is, the FIND processing module corresponds to an "inspection" routine. The FIND module can only classify patterns correctly when their shapes are discriminable, and if objects are imaged too small they will fail to be "visible" to the FIND processes. This module is presumed to be used not only in locating where to-be-imaged parts belong in relation to previously imaged ones, but also when one inspects an image for a specific property (as in the examples that opened this article) or even when one inspects an actual, visible object during perception. There are ample data supporting the idea that the same visual inspection mechanisms are used in perception and imagery (for reviews see Finke, 1980; Finke & Shepard, in press; Kosslyn, 1980, 1983; Podgorny & Shepard, 1978; Segal, 1971).

In summary, computational considerations formulated in light of empirical findings lead to a theory that posits a PICTURE processing module that activates stored visual information, a PUT processing module that looks up and interprets a description of how parts are to be arranged (e.g., "the front wheel is in-and-under the front wheelwell"), and FIND processing module that locates the foundation part (i.e., the part to which the to-be-imaged part is relative—front wheelwell, in this case). The PUT module uses the location information in conjunction with the description of the relation ("in-and-under") to set the PICTURE processing module so that the two images are correctly juxtaposed.

Functional Dissociations

Although the Kosslyn and Shwartz theory of image generation is consistent with the empirical findings and computational constraints, it is not the only possible theory. For example, the functions carried out by the putative PICTURE and PUT modules might in fact be carried out by one single module, as might the functions putatively carried out by the PICTURE and FIND modules. If the PICTURE, PUT, and FIND processing modules are in fact distinct, we might expect to find evidence of *functional dissociation* following brain damage. That is, we may find cases in which some subset of the modules operates while another subset has been disrupted. In addition, by examining the nature of the deficits, we can begin to discover how the internal workings of the modules actually operate.

This modular approach to theorizing about imagery is especially appealing given Erlichman and Barrett's (1983) recent review of the neuropsychological literature on imagery. They discovered that imagery cannot be consistently identified with one cerebral hemisphere or the other, which is not surprising if the kind of analysis we offer is correct: If imagery in fact consists of a number of separate components, then the nature of the imagery task will be critical because different components will be used in different tasks. Furthermore, the possibility that different components of imagery are localized in different places in the brain receives some support from Farah's (1984) review of the literature on imagery deficits following brain damage. Farah found that image generation (i.e., the combined operation of PICTURE, PUT, and FIND), as distinct from other imagery abilities (e.g., transformation), seems to depend on processes occurring in the posterior region of the left cerebral hemisphere. Thus, the pattern of imagery deficit that follows brain damage will depend on the task, the localization of the relevant processing modules, and the location of the damage.

The split-brain patient offers a unique opportunity to examine many of these issues. It has recently been shown in the special group of split-brain patients with right hemisphere language that the two hemispheres possess strikingly different cognitive capacities. The left hemispheres are essentially normal. In contrast, right hemispheres exhibiting good semantics, and right hemispheres exhibiting both semantic and syntactical skills and speech are still strikingly impaired on carrying out simple cognitive tasks such as elementary math, making inferences, and solving simple geometry problems. Hence, the possession of language ability in a half brain does not imply a concomitant ability to engage in other kinds of cognitive processing (see Gazzaniga & Smylie, 1984). Accordingly, it is of interest to examine whether a hemisphere that has basic language functioning might be impaired in generating mental images.

If the theory outlined above is correct, the PUT processing module involves looking up and using descriptions of how parts are arranged together, which involves the manipulation of symbolic representations. Many of the deficiencies in the right hemisphere can be considered to be deficiencies in manipulation of symbolic representations, and thus it seemed reasonable to ask whether there is a selective deficiency in the PUT module in the right hemispheres of these patients. On the other hand, we had no reason to suspect that the PICTURE or FIND processing modules would be impaired in either isolated hemisphere of our patients. Indeed, given that the perceptual abilities of both hemispheres are essentially normal, we had reason to suspect that the FIND module, which purportedly is also used to categorize perceptual input (see Kosslyn, 1980), would be intact in both hemispheres.

Plan of the Article

This article has three major sections, each of which builds on the preceding ones. In the first section we document that the right hemisphere of one patient has a deficit in performing a task that requires all three imagery-processing modules. We demonstrate that this is an image-generation deficit, and is not due to impairments in other components of the task. In so doing, we provide results that demonstrate a dissociation between the FIND processing module and the PICTURE module and/or the PUT module.

In the second section we implicate the PUT processing module in the right hemisphere's deficit. In so doing, we demonstrate that the patient can form and inspect images very well in his right hemisphere, provided that the images are formed on the basis of only a single part. The deficit, we will argue, is in constructing multipart images.

In the third section we switch to a second patient, whose right hemisphere has abilities different from the first patient's. We now examine the relationship between the imagery deficit and other language and reasoning deficits. In so doing, we consider the implications of this patient's specific deficits for theories of the underlying processing mechanisms.

A Right Hemisphere Imagery Deficit

The first set of experiments reported in this article was designed to discover whether there is an imagery deficit in our first subject's right hemisphere. Discovery of such a deficit would implicate a number of functional dissociations, given the abilities that have already been documented in this patient's right hemisphere. Of particular interest, however, is the fact that this patient's right hemisphere has been found to have intact perceptual abilities. Indeed, it is actually better than the left hemisphere at recognizing faces (Gazzaniga & Smylie, 1983). These results suggest that the FIND processing module is intact in both hemispheres. Thus, as we will argue later in this article, an imagery deficit in the right hemisphere will implicate difficulties in using the PICTURE and/or the PUT module.

Experiment 1

Consider the following task: Which uppercase letters of the alphabet have only straight lines, and which have some curves? This task introspectively seems to require imagery, and in fact was used by Coltheart, Hull, and Slater (1975) in their investigation of sex differences in imagery. In addition, it seems to involve images of a particular sort: When asked to image an uppercase *A*, for example, most people do not image a specific letter (e.g., seen on page 3 of yesterday's *New York Times*). Rather, it seems as if one images a canonical, typical *A*. Our claim here is that because literate adults have seen letters so many thousands (millions?) of times, varying in size, font, weight, and so on, we have come to abstract out and store a "prototypical image" of each letter. According to previous work on image generation, patterns stored in long-term memory are "parsed" according to the Gestalt laws of organization and the like, which leads us to posit that these prototypes are stored as collections of segments with descriptions of how the parts are arranged (see Kosslyn et al., 1983).

If this theory is correct, then all three image-generation processing modules will be used when we image a letter: the PUT module will be necessary to interpret the description of how lines are to be arranged, and it will set the PICTURE module appropriately so that it can activate images of line segments in the correct positions. Furthermore, the PUT module will make use of information delivered by the FIND processing module in the course of computing the correct positions for each succeeding line. For example, in generating an *A* one diagonal line would be imaged by the PICTURE module, the PUT processing module would arrange for a second diagonal line to be placed correctly by using the FIND processing module to locate the top of the first line and then using the description of the relation to set the PICTURE processing module so that the second line is imaged connected to the top, and so on.

Note that we are making two critical assumptions in using the *straight/curved judgment* task to test the theory of image generation: First, we are assuming that imagery is in fact used to perform this task. Second, we are assuming that images of letters are generated a part at a time, requiring the PUT processing module to arrange the parts correctly. Both of these assumptions were tested independently. Briefly, we implicated imagery use in this task via a selective interference task modeled after that of Brooks (1968). We showed that a visual response disrupted making the straight/curved judgments from memory more than did a verbal response, even though the visual response was actually easier to make in isolation. We implicated the sequential generation of separate parts by modifying a task developed by Podgorny and Shepard (1978). Subjects were cued to form an image of a letter in a grid and to indicate whether two *x* marks in the grid would be covered by the letter if it were also in the grid. The *x* marks were presented almost immediately after the cue, so that some of the response time reflected the time to generate the image. (Separate controls were used to implicate imagery in this task.) The time to respond depended on the locations of the *x* marks, with more time being required when marks were more segments further along the letter (following the path by which it was usually drawn). Control experiments demonstrated that these results were not due to scanning along an image after it was generated (see the Appendix of Kosslyn, Holtzman, Farah, & Gazzaniga, 1984, for more details on these validation experiments).

Thus, according to our analysis, the straight/curved imagery task can be decomposed into seven processing stages: (a) The lowercase cue must be *encoded;* (b) The corresponding representation of the uppercase version must be *accessed;* (c) The image must be *generated* (using the three modules discussed earlier); (d) The image must be *retained* long enough to use; (e) The imaged pattern must be *inspected;* (f) The imaged lines must be correctly *classified;* and (g) The subject must *respond* appropriately. A deficit in performing the task could reflect an impairment in any one, or combination, of these stages. Furthermore, even if the subject has no impairment in the individual stages, a deficit in performing the task will arise if the subject does not understand the instructions or is unable to perform multistage tasks.

We were encouraged to use a letter-classification task to study functional decomposition of image generation because of the findings of Farah, Gazzaniga, Holtzman, and Kosslyn (1985). They asked patient J.W., who was tested in the first experiments reported in this article, to evaluate from memory the relative heights of lowercase letters of the alphabet. For example, the lowercase versions of *B, D, F* are relatively high, whereas the lowercase versions of *A, C, E* are relatively low. Weber and Bach (1969) introduced this task and took it to require imagery, although they provided no independent justification for this inference. We found that J.W. could not make the relative height judgments in his right hemisphere. However, this result could indicate a deficit in that hemisphere in the PICTURE, PUT, and/or FIND modules, in a generalized image-generation module (if our breakdown is incorrect), a deficit specific to letters, a deficit for linguistic materials, or a deficit in various other components of the task. In the experiments in this section we whittle away the various alternative explanations and implicate a deficit in image generation per se.

Method

Subject. The subject in the first set of experiments was J.W., who has been extensively described elsewhere (Gazzaniga, 1983; Gazzaniga & Smylie, 1984; Sidtis, Volpe, Wilson, Rayport, & Gazzaniga, 1981). Briefly, J.W. is a right-handed male who was 30 years old at the time of testing. He suffered from intractable epilepsy since the age of 19, and underwent neurosurgical transection of his corpus callosum in 1979. When he was 13 years old he had suffered concussive head trauma, without skull fracture, which led to brief, infrequent absence spells. At age 18 he graduated from high school. At age 19 he had a major motor seizure. An EEG revealed irregular polyspike and high voltage repetitive 3 cps (3 Hz) spike and wave bursts during sleep. These abnormalities had a right anterior temporal lobe prominence. Medication was unable to control his frequent seizures and absence attacks during the ensuing years. He was referred to Dr. D. H. Wilson at the Dartmouth-Hitchcock Medical Center, where he underwent the two stage microneurosurgical section of his corpus callosum over the summer and fall of 1979. The posterior callosum was severed first. The anterior commisure was left intact.

When he was given a neurological examination 8 months after the completed operation, J.W. was found to be normal and of normal IQ. When we tested him he was oriented, alert, and conversed easily about present and past events. Following recovery from surgery, it was demonstrated that his left cerebral hemisphere was for all intents and purposes normal; his right hemisphere could comprehend most statements, but it could not speak. For present purposes, it is important to note that his right hemisphere can comprehend word meanings, and has been shown to be able to understand relatively sophisticated instructions: For example, the right hemisphere can classify named objects in terms of super- and subordination, can judge synonymy and antynomy, and can use a precue to direct his eye movements (see Holtzman & Gazzaniga, 1984; Sidtis et al., 1981).

Materials. Ten letters were selected for use in the straight/curved judgment task: Five had uppercase versions containing only straight lines (*Z, K, M, T, F*), and five had uppercase versions containing some curved lines (*O, J, R, B, D*); these letters were selected at random from the alphabet. The lowercase versions of these letters were used as cues in the imagery task. These letters were randomized such that each one appeared twice to the left and twice to the right of a fixation point, ensuring that each hemisphere received each lowercase cue twice; the order of presentation in the two fields was also randomized.

Procedure. The subject sat before a video display monitor, fixating both eyes on an asterisk located in the center of the screen. A lowercase letter of the alphabet was presented 1.5° to the left or right of fixation for 100 ms, preventing eye movements and ensuring that only one hemisphere could see the stimulus. Two buttons were placed directly in front of him, one 3 in. (7.62 cm) to the left of the other. The subject was to press one button if the *uppercase version* of the letter had only straight lines (this button was labeled by a straight line) and another button if the uppercase version had any curved lines (this button was labeled by a curved line). The subject rested his left hand midway between the buttons and responded by lifting his arm and pressing a button with his left hand. (Ipsilateral and contralateral fibers allow both hemispheres to control gross arm movements, although the right hemisphere has an advantage when the left arm is used). The subject was asked to respond as quickly as possible while being as accurate as possible. No feedback was given about performance in this or in any of the following experiments (unless explicitly noted in the procedure section).

The subject judged three successive blocks of 40 trials each, with approximately 5 min rest between them. The video display monitor was connected to an APPLE II Plus microcomputer, which recorded both responses and response times.

Results

Response time and accuracy data were analyzed in separate analyses of variance. For the accuracy data we pooled the responses for the two replications with the same item and scored each item as 1, .5, or 0, depending on whether it was correct on both, one, or neither trial.

The right hemisphere was significantly less accurate than the left (70% vs. 100% accuracy), $F(1, 8) = 6.48$, $p < .04$. In addition, judgments of curved stimuli were more accurate than judgments of straight stimuli (98% vs. 72%), $F(1, 8) = 5.12$, $p = .054$, but this effect was different for the two hemispheres, as indicated by an interaction between response and hemisphere, $F(1, 8) = 5.12$, $p = .054$. This interaction reflected the fact that the left hemisphere made no errors for either response, whereas the right was accurate 97% versus 43% for curved and straight stimuli, respectively. This difference in accuracy might reflect nothing more than a response bias. No other effect or interaction was significant, $p > .17$ in all cases.

The results from the response times tell a different story. The right hemisphere was significantly faster than the left (1.216 s vs 1.476 s), $F(1, 8) = 7.09$, $p < .05$. This finding may simply reflect the greater control of the right hemisphere for the left-handed motor response required in this task. However, the faster times in the right hemisphere may easily result from a speed–accuracy trade-off: one could argue that the right hemisphere may simply have been guessing on a higher proportion of the trials in order to make rapid responses. In addition, judgments of curved stimuli were faster than judgments of straight ones, $F(1, 8) = 6.79$, $p < .05$, and now there was improvement over the blocks of trials, $F(2, 16) = 6.30$, $p < .01$. There was no difference in times for the first or second replication within a block, $F < 1$. The only significant interaction was between blocks, hemisphere, and stimulus type, $F(2, 16) = 4.19$, $p < .05$. The right hemisphere was faster than the left for both stimulus types in the first two blocks, and for straight stimuli in the third block; the left was faster than the right only for judgments of curved stimuli in the third block. This result is further indication of a speed–accuracy trade-off for the first two blocks and for the straight stimuli in the third block, where the right hemisphere was faster than the left: At the same time the right hemisphere was being faster, it committed more errors for these responses. This pattern of responses was also reflected in a possible trend for an interaction between hemisphere and stimulus type, $F(1, 8) = 3.56, p = .1$. No other interaction approached significance, $p > .2$ in all cases.

Discussion

As expected, then, the right hemisphere was less accurate than the left. However, the relationship between the speed of responding and errors suggested that the right hemisphere may not have been careful in its judgments; in this experiment, it could have been guessing so as to respond faster (although this account will not prove sufficient to explain the right-hemisphere deficit in all subsequent experiments). In addition, there is evidence that the right hemisphere had a bias to respond *curved.* This is not an unreasonable strategy, we realized, given that about 70% of the curved lowercase letters also had curved uppercase versions—which may explain why the right hemisphere performed at better than chance levels.

In Experiments 2–6 we document that J.W.'s right hemisphere has a deficit in performing this task. In addition, we attempt to systematically eliminate the alternative explanations of the failure of J.W.'s right hemisphere to perform the task well, implicating an image-generation deficit. In each case we consider the possibility that the right hemisphere is deficient at carrying out some non-image-generation processing used in the straight/curved task, and we assess the right hemisphere's ability to use such processing in another task.

Experiment 2

In this experiment we asked our subject to perform a perceptual analogue of the imagery task. The subject briefly saw uppercase letters and made the straight/curved judgment on the basis of what he saw. Immediately following this control task we repeated the letter cue task, urging the subject to be accurate and looking to see whether practice at making the judgment improved performance in the imagery task.

This experiment will serve two purposes: First, if J.W.'s right hemisphere can perform the perceptual task, we have demonstrated that it can encode letters, make the classification, and respond correctly. Thus, a deficit in performing the imagery task could not be due to an inability to perform these activities. Second, if we do find that the right hemisphere can perform the perceptual task but not the imagery analogue, this will start us on our way toward discovering functional dissociations among the hypothesized processing modules. That is, according to the theory, the FIND processing module is used when one inspects both images and percepts. Thus, if we find that the subject's right hemisphere can perform the perceptual task but cannot perform the analogous imagery task, we are encouraged to pursue possible dissociations among the image-generation processing modules.

Method

Materials. The uppercase versions of the letters were substituted for the lowercase ones used in the previous experiment. Other than this substitution, the materials were identical to those used earlier.

Procedure. The procedure was identical to that used in the previous experiment except that the subject was asked to judge the letters as they actually appeared, not the other-case versions.

Two blocks of 40 trials were used, with again approximately 5 min rest between blocks.

Following the perceptual classification task, we simply repeated the original letter-classification task, again showing lowercase letters and asking for straight/curved judgments on uppercase versions. The materials were identical to those used in Experiment 1, and the procedure was identical to that used in Experiment 1. One block of 40 trials was administered.

Results

Perceptual classification task. In contrast to the results from the previous experiment, both hemispheres did very well on this task. The left and right hemispheres had 100% and 97.5% accuracy, respectively, $F < 1$, and there were no effects of blocks (100% vs. 97.5% correct for Blocks 1 and 2, respectively) or type of response (100% vs. 97.5% for curved and straight, respectively), $F < 1$ in both cases. No other effects or interactions were significant in the error data, $p > .25$ in all cases.

The response times revealed the same pattern as did the error rates: There was no effect of hemisphere (.877 s vs. .876 s for left vs. right hemisphere) or response type, $F < 1$ in both cases. In fact, the only significant results were due to block (.923 s vs. .830 s for Blocks 1 and 2, respectively, $F(1, 8) = 6.98$, $p < .05$, and the interaction between hemisphere, response and replication was marginally significant, $F(1, 8) = 4.17$, $p < .09$. This trend reflected the fact that only for curved stimuli in the left hemisphere were times on the second replication faster than those on the first replication; in the three other cases, times were slightly slower on the second replication. No other effect or interaction even approached significance, $p > .25$ in all cases.

Lowercase cue task. Again, the left hemisphere performed strikingly better than the right, 100% compared to 65% accuracy, $F(1, 8) = 7.0$, $p < .05$. In addition, there was possibly a tendency for more errors with straight letters (70% vs. 95% for curved letters), $F(1, 8) = 3.57$, $p = .1$, and there was possibly a tendency for especially poor performance for straight letters for the right hemisphere, as witnessed by a marginally significant interaction between stimulus type and hemisphere, $F(1, 8) = 3.57$, $p = .1$: whereas the left hemisphere was perfect, the right was correct on 90% of the curved trials and only 40% of the straight ones. This pattern of responses, which was also apparent in the previous experiment, suggests a bias to respond *curved* in the right hemisphere.

Unlike the error data, there were no differences in any of the comparisons of response times: Times were .973 s and .949 s for the left and right hemisphere, respectively, $F < 1$; .905 s and 1.016 s for curved and straight letters, respectively, $F(1, 8) = 1.99$, $p > .25$; and .948 s and .974 s for Replications 1 and 2, respectively, $F < 1$. No other effect or interaction approached significance, $p > .25$ in all cases.

Discussion

Both hemispheres clearly understood the perceptual control task and clearly could perform it. In fact, both did so well that a ceiling effect occurred, preventing us from making any comparisons about the relative efficacy of the hemispheres on this task. But this was not our purpose: We now had reason to expect that the right hemisphere would understand the classification task. Nevertheless, performance in the imagery task was still very poor in the right hemisphere. And now there was no evidence of a speed–accuracy trade-off.

However, the pattern of errors again suggested that there was a bias to respond *curved.* Most lowercase letters are themselves curved, and it is possible that the subject was basing his judgments in part on the way the actual stimuli appeared. This is in fact not a bad strategy given the straight letters we used, *z, k, m, t,* and *f;* two of these have only straight lines in lowercase, and in fact *z* and *k* were judged correctly on both replications by the right hemisphere. Indeed, all but one of the errors made here (to *d*) can be explained simply by assuming that he was using the lines in the lowercase stimuli as cues. The next experiment eliminates this possible artifact and further documents the right hemisphere deficit in the straight/curved imagery task.

Experiment 3

The pattern of errors in the previous experiment suggests that the curved lines of the lowercase cues may have presented a "Stroop test" situation for the right hemisphere, where what J.W. saw interfered with image generation or response. In this experiment we used auditory presentation of the stimuli, eliminating the possibility of interference from the lowercase visual cue or of his using the shape of the stimuli to help make the judgment. Furthermore, the nature of the response was made compatible with the straight/curved judgment itself, as will be described shortly, which allows us to rule out a Stroop-type response conflict.

Method

Materials. New letters were selected for this task. The letters with some curves in the uppercase versions were *G, J, D, B,* and *Q;* the letters with only straight lines in the uppercase versions were *A, M, H, T,* and *E.* A list of the letters was prepared, with each letter being presented twice on left-hemisphere trials and twice on right-hemisphere trials. The letters and field of presentation were randomly ordered.

In addition, in this experiment, the cues presented on the video display monitor were the pairs *X O* and *O X.* Each pair was presented 10 times in each visual field (1.5° to either side) for 100 ms, with the presentation order and field being coordinated with the list of letters so that each letter occurred once with each pair in each visual field.

Procedure. The subject again began by staring at the fixation asterisk. Now, however, he heard the name of one of the letters. He was told to make his judgment and then to look for the *X O* or *O X* pair. If the letter had only straight lines, he was to point at the location on the screen where the *X* had appeared; if the letter had curves, he was to point where the *O* had appeared. The cue was presented approximately 2 s after the letter was named, and the subject seemed to have no difficulty in understanding that he was to point to the location of the *X* or *O* as appropriate. All pointing was done with the left arm. Two experimenters watched where the subject pointed and scored his accuracy. Three blocks of trials were conducted, each having 40 trials.

Results

Because of the task used, it was impossible to collect response times (i.e., time to point at a location on the screen). The error rates, however, revealed the now-familiar pattern: The left hemisphere did very well, making correct judgments on 95% of the trials, whereas the right hemisphere did very poorly, making correct judgments on only 52% of the trials, $F(1, 8) = 16.9$, $p < .005$. There also was a significant interaction between block, hemisphere, and response, $F(2, 16) = 6.32$, $p < .01$: In the right hemisphere, increasingly more errors occurred with curved stimuli on the later blocks, whereas increasingly fewer errors occurred with straight stimuli. This interaction reflected a shift from the bias to respond *curved* to a more evenhanded guessing strategy. There was no systematic tendency to respond on the basis of the appearance of the lowercase version of the letter. No other effect approached significance, $p > .11$ in all cases.

Discussion

When the influence of the lowercase cues themselves was eliminated, performance in the right hemisphere dropped to chance. This is just as would be expected if images simply could not be constructed in this hemisphere.

So far we have demonstrated that the right hemisphere cannot perform the imagery task. It can, however, encode the letters, make the classification, and respond. This leaves open the possibilities that it cannot access the other-case representation of the letter, generate the image, retain the image, and/or inspect the image. However, Farah, Gazzaniga, Holtzman, and Kosslyn (1985) showed that both of J.W.'s hemispheres could pick out the corresponding lowercase letter (from a list of all letters) when shown an uppercase letter. Thus, we next sought to demonstrate that the deficit was not due to the right hemisphere's being unable to retain or inspect images.

Experiment 4

An additional weak link preventing us from inferring an image-generation deficit is that we have not demonstrated that the right hemisphere can evaluate an image of uppercase letters. Perhaps the right hemisphere can generate images but cannot maintain them long enough to make the judgment. Or perhaps images are dimmer than percepts, and the FIND module in the right hemisphere has less acuity than in the left hemisphere and so cannot effectively classify these dimmer patterns.

Thus, in this experiment we show that J.W.'s right hemisphere can perform the straight/curved judgment on images, except that the images he uses in this task are not generated from long-term memory, but instead are simply retained from external input. That is, according to the theory, images can be evoked either by generating them from information stored in long-term memory, as has been discussed thus far, or by briefly retaining perceptual input. The theory posits a LOAD module that squelches subsequent sensory input (which usually disrupts prior percepts) so that a perceptual pattern can be retained briefly as an image; it also posits a REGENERATE module that maintains an image in short-term memory for a brief period, keeping it available for further inspection (see Kosslyn, Brunn, Cave, & Wallach, 1984, for a concise summary of the overall imagery theory). In this experiment we use a variant of a task developed by Weber and Harnish (1974), where the shapes of letters in specific locations of words are classified from memory. This task is convenient because Weber and Harnish (1974) provide evidence that imagery is spontaneously used to perform it.

Method

Materials. Twelve three-letter words were created, using only letters tested in Experiment 3 and in the new list used in Experiment 6. The words were constructed so that an uppercase letter with only straight lines or with some curves appeared equally often in the first, second, or third position of the words. One letter was selected from each word to be used as the *target* letter; target letters were identical to those used in Experiment 3. Target letters were presented here in their uppercase versions and occurred equally often in each serial position of the words.

In order to prevent the subject from knowing where to focus on the screen to see a given letter, the words were entered into a computer such that they appeared one, two, or three spaces displaced towards the right from the standard angle of displacement from the fixation point (1.5°). The amount of displacement was varied randomly, except that each amount appeared equally often over trials. Words were presented once to each visual field within a block, for a duration of 150 ms, and order of presentation and field was randomized.

Procedure. Two conditions were tested. The *cue-before* condition was intended as a baseline, given that this task contained all but the imagery components. In this task, the subject was given the cue, *1, 2,* or *3* before a word was presented. This cue told the subject that we wanted him to classify the first, second, or third letter of the word. Approximately 1 s after the cue was given verbally, a word was briefly presented to one visual field or the other. The subject had to pick out the appropriate letter and classify it as having all straight lines or some curved lines, pressing buttons as usual. The *cue-after* condition differed only in that the cue was presented approximately 2 s after the word was presented. Thus, in this case the subject had to maintain an image of the word, which he then used to select the proper letter and make the classification. Note, even though the cues were given aloud, and hence were available to both hemispheres, the fact that the words were lateralized prevents both hemispheres from making the judgment. The experimenter was not aware of the correct response, precluding the operation of experimenter-expectancy effects.

Two blocks of each type of trial were presented, in the following order: cue-before, cue-after, cue-after, and cue-before.

Results

Cue-before. There were no significant differences in accuracies in the analysis of the cue-before data, $p > .18$, for all comparisons. Notably, the left hemisphere was accurate on 95.8% of the trials, compared to 87.5% for the right hemisphere, $F(1, 10) = 2.0$, $p > .18$.

In contrast, the analysis of response times revealed that the right hemisphere was slower than the left (2.265 s vs. 1.646 s), $F(1, 10) = 13.18$, $p < .005$, that there was improvement with successive blocks (2.137 s vs. 1.774 s), $F(1, 10) = 7.33$, $p < .03$, and that the subject again was faster to evaluate curved stimuli (1.772 vs. 2.140 s), $F(1, 10) = 5.73$, $p = .04$. In addition, most of the improvement over blocks was with the straight stimuli, as witnessed by an interaction between block and stimulus type, $F(1, 10) = 5.18$, $p < .05$. No other effects or interactions approached significance, $p > .1$ in all cases.

Cue-after. Again, there were no significant comparisons in the analysis of the accuracy data, $p > .2$ in all cases. For the comparison of hemispheres, there was 95.8% accuracy in the left and 83.3% accuracy in the right, $F(1, 10) = 1.8$, $p > .2$.

The response times again were more sensitive to differences in the different conditions: Less time was required in the left hemisphere (4.018 s vs. 4.769 s), $F(1, 10) = 14.01$, $p < .005$, and times slowed down with block (4.023 s vs. 4.763 s), $F(1, 10) = 9.20$, $p < .02$. No other effect or interaction approached significance, $p > .25$ in all cases.

We also conducted analyses that included both the cue-before and cue-after data. This was desirable because the cue-before task has all processing components in common with the cue-after task except those involved in imagery processing. Thus, the cue-before results provide a baseline against which we can discover the extent to which the ability to maintain or inspect an image might be affecting performance in the straight/curved imagery task. There were no significant differences in the analysis of the accuracy data, but two comparisons came close: Hemisphere, $F(1, 10) = 4.31$, $p < .07$, and the Block × Hemisphere interaction, $F(1, 10) = 4.31$, $p < .07$ (with 100% and 91.7% accuracy for Blocks 1 and 2 for the left hemisphere, and 79% and 91.7% accuracy for Blocks 1 and 2 for the right hemisphere). Most important for present purposes, there was no hint of an interaction between hemisphere and task, $F < 1$, indicating that each hemisphere performed equivalently in the two tasks.

The analysis of response times revealed that times in the cue-before task were in general much faster than in the cue-after task (1.956 s vs. 4.393 s), $F(1, 10) = 406$, $p < .001$, but this result must be interpreted with caution: The times in the cue-after condition include the approximately 2-s delay before the cue was presented and the time to hear and comprehend the cue. In addition, whereas times decreased on the second block of the cue-before task (2.137 s vs. 1.774 s), they increased on the second block for the cue-after task (4.023 vs. 4.763 sec), $F(1, 10) = 16.88$, $p < .003$. For present purposes, however, it is important to note that the hemispheres performed the same way in both tasks, $F < 1$, for the interaction of hemisphere and task. And no other interaction with task was significant, $p > .12$ in all cases.

Thus, relative to the cue-before perceptual baseline, both hemispheres can perform the visual memory task at equivalent levels.

Lowercase cue task. To ensure that the right hemisphere had not suddenly gotten the idea of what we wanted, we administered a block of the lowercase cue task, using the target letters used in the word tasks and the procedure of Experiment 1. The results were as before: The left hemisphere was more accurate than the right (100% vs. 60%), $F(1, 8) = 25.6$, $p < .001$. In addition, straight stimuli were now judged more accurately than curved ones (90% vs. 70% correct), $F(1, 8) = 6.40$, $p < .04$, and this effect was due to the right hemisphere (100% for both types of stimuli for the left, 40 and 80% for curved and straight, respectively, for the right), $F(1, 8) = 6.40$, $p < .04$. Apparently, the right hemisphere now had a bias to respond *straight.*

The only significant effect in the analysis of the response times was due to hemisphere: The left was faster (1.318 vs. 2.032 s), $F(1, 8) = 11.44$, $p < .01$. There was possibly a trend for faster responses for curved stimuli on the second replication and faster responses for straight stimuli on the first replication, $F(1, 8) = 3.76$, $p < .09$, and no other effects or interactions were significant, $p > .35$ in all cases.

Discussion

The right hemisphere does not have a deficit in the visual memory task relative to its perceptual analog. But are we justified in assuming that this task is performed using imagery, thus implicating intact image retention and inspection processes? We have been assuming that imagery was used in the cue-after task largely because of its similarity to a task used by Weber and Harnish (1974). However, Weber and Harnish did not present the words visually. Thus, one could argue that the right hemisphere performed the cue-after condition by classifying all three letters during the stimulus presentation, and retained the three classifications until the position cue was given. This possibility is dispelled by three considerations: First, the response times in the cue-after condition, even after subtracting the approximately 2 s waiting period, were if anything longer than those in the cue-before condition, which is unexpected if the subject was simply scanning a list of classifications. If the subject had the letters classified at the time of probe, he should have been faster than in the cue-before condition, which required him to locate the letter, encode it, and then inspect and classify it. Second, if the three letters were being classified and stored on every trial, we should have found an increase in errors over the perceptual condition, which was not observed. Finally, it is unlikely that 2 s is enough time for the verbally unfacile right hemisphere to encode, classify, and store the letter-classification pairs for the three stimuli being presented at once.

A major distinction between the present task and the lowercase cue task is that an image did not have to be generated here, whereas it did before. Thus, the fact that J.W. can perform this task in his right hemisphere but not the earlier one is strong support for our inference that he has a specific image-generation deficit. When an image had to be maintained and then inspected, both hemispheres performed the task as well, relative to the nonimagery perceptual baseline performance. In addition, even after performing well in this image-inspection task, J.W. still could not perform the image-generation task in his right hemisphere.[1]

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[1] It is of some interest that, for the right hemisphere, the cue-before task was not as easy as was the single-letter perceptual classification task used in Experiment 2. There are at least three possible accounts of this finding: (a) The right hemisphere may have had selective difficulty in picking out the cued positions, perhaps because of the random displacements of the words on the screen; (b) The right hemisphere may have had more difficulty encoding the words because the left-hand portion was less acute (it fell in the extreme left of the visual field); or (c) Perhaps the FIND module in the right hemisphere is less acute—but this deficiency was masked by ceiling effects in Experiment 2. However, previous findings that right hemispheres usually have greater discriminability belie this third possibility (e.g., see Springer & Deutsch, 1981). In any event, the 83.3% accuracy

The results from this image retention task are strong evidence that J.W.'s right hemisphere is not simply having difficulty in performing a multistage imagery task. That is, it is worth noting that the cue-after condition of this task involves not only classifying letters that are not visually present, but also the interpretation of a cue specifying which absent stimulus is to be classified. The ability of J.W.'s right hemisphere to perform this task constitutes evidence that earlier right hemisphere failures on the imagery task were not due to an inability to understand complex instructions.

In short, the comparison between the cue-before and cue-after results allows us to infer that the REGENERATE and LOAD processing modules are intact in J.W.'s right hemisphere; if they were not, we would have found inferior performance in the cue-after task relative to the cue-before task (which required use of all of the same processing modules except those two). Thus, we have shown by process of elimination that J.W.'s right hemisphere can carry out all stages of task performance except those involved in image generation. However, before we can conclude that there is a specific image-generation deficit, we must eliminate two more kinds of alternative accounts, neither of which posits a disruption in one or more processing stages.

Experiment 5

In this experiment we provide additional evidence that J.W.'s right hemisphere is not deficient in combining multiple visual processing stages. We now performed another kind of perceptual control, which required the subject to view lateralized slides of pairs of letters. The upper- and lowercase versions of a letter were tachistoscopically presented side by side to one visual field, and the subject was asked to pick out the uppercase letter and to classify it as having all straight lines or some curves. Both letters were drawn at the same size, so size could not be used as a cue in the selection phase.

This task, then, provided a control for several of the steps in the imagery task and for the right hemisphere's ability to combine them: First, both hemispheres had to understand the task; second, they had to encode both letters (which is more demanding than encoding only a single lowercase cue); third, they had to access the case representations of the stimuli; fourth, they had to select the uppercase version; fifth, they had to evaluate its shape; and finally, a response had to be made. Thus, if the right hemisphere's difficulty in the imagery task is in fact due to difficulties in one or more of these stages, or in combining them, then it should have difficulty in performing this task.

Method

Materials. Twenty letters of the alphabet were selected, half having uppercase versions with only straight lines and half having uppercase versions with some curved lines. We did not use any letter that had the same-shaped upper- and lowercase versions. We prepared two slides for each letter, one with the lowercase version to the left of the uppercase version, and one with the lowercase version to the right of the uppercase version. The slides were prepared by drawing directly on acetate with a black felt pen, and the two letters on each slide were drawn at the same height and approximately at the same width. Slides were presented using a rear-projection screen, and the duration of exposure was controlled by a tachistoscopic shutter on the projector.

Procedure. Each slide was presented twice, once in each visual field. The slides were presented in a random order and field of presentation was randomized. As usual, the slides were 1.5° to the left or right of a fixation point and were exposed for 100 ms. The subject was told to point to the area on the rear-projection screen where the uppercase version of the letter had appeared (the time to point was not recorded), and then to press one button (the one labeled by a straight line) if the letter had only straight lines and the other button (labeled by an arc) if the letter had any curved lines. As usual, all responses were made with the left arm. Three blocks of trials were presented.

Results and Discussion

In no case did J.W. incorrectly point at a letter and then correctly classify it. Thus, we analyzed only the button-push responses. The analysis of these accuracy rates revealed that the right hemisphere was more accurate than the left (93% vs. 80%), $F(1, 8) = 5.57$, $p < .05$, that responses to curved letters were more accurate than responses to straight ones (100% vs. 73%), $F(1, 8) = 7.64$, $p < .03$, and that these two effects interacted, $F(1, 8) =$

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observed for the right hemisphere in the cue-after task of the present experiment is strikingly better than the 60% accuracy observed in the lowercase cue task, even though this task used the same target items as the cue-after task and followed immediately after that task.

5.57, $p < .05$ (100% accuracy in both hemispheres with curved stimuli, compared to 60% and 86.7% accuracy in the left and right, respectively, for straight stimuli). In addition, there was a tendency for the left hemisphere to do progressively worse over blocks, whereas the right was relatively constant, $F(1, 16) = 3.37$, $p = .06$, and for this interaction to depend on the response, $F(1, 16) = 3.37$, $p = .06$. No other effect or interaction was significant, $p > .2$ in all cases.

The analysis of response times revealed a slightly different pattern: There was no effect of hemisphere (2.439 s vs. 2.238 s for left vs. right, respectively), $F(1, 18) = 1.14$, $p > .25$, nor of stimulus type, $F(1, 18) = 1.14$, $p > .25$. However, times were slowest on the second block, $F(2, 36) = 39.27$, $p < .001$, and times were faster for the second replication of a letter within a block, $F(1, 8) = 8.03$, $p < .03$. The interaction between block, replication, and stimulus type was also significant, $F(2, 16) = 3.54$, $p = .05$. Although the time to judge both types of stimuli decreased with successive blocks, straight stimuli showed more improvement over blocks. There was also a trend towards an interaction between block and stimulus type, $F(2, 36) = 2.55$, $p < .1$, suggesting a tendency for relatively faster responses to the straight stimuli in Block 2, whereas responses were faster to the curved stimuli in Blocks 1 and 3. No other effect or interaction was significant, $p > .15$ in all cases.

In short, these results demonstrate that J.W.'s right hemisphere is capable of selecting the proper letter, evaluating it, and putting the two steps together. Indeed, the right hemisphere actually did better in this task, which may reflect its superior ability to make subtle perceptual discriminations (which was important here because so much information was presented at once).

Experiment 6

In the final experiment in this series with patient J.W. we considered yet another way in which his right hemisphere could fail to perform the task but not because of an image-generation deficit. Perhaps the right hemisphere does not perform the straight/curved imagery task well simply because it does not understand what it is supposed to do when given the lowercase cue in that task. Perhaps it needs examples of correct and incorrect responses before it can comprehend the instructions. Thus, in this experiment we first establish baseline performance in the lowercase cue task. We then urge the subject to be cautious in responding and to consider his decisions carefully; following this, we provide feedback about accuracy of performance. The use of feedback is a way to provide the right hemisphere with examples of what we want, which in conjunction with the instructions should make the nature of the task as clear as possible. Finally, after we have the right hemisphere performing well, we switch to a new set of letters. If the improved performance following feedback is due to his finally understanding what to image, and this was the only problem all along, then we expect that his ability to perform the task will transfer to the new letters. However, if the improved performance is merely the result of the right hemisphere's memorizing stimulus–response pairs, then we would not expect transfer to new letters.

Method

Materials. The letters used in Experiment 3 were also used here. Now, however, the lowercase versions of the letters were presented on the video display monitor. Each letter appeared twice in each visual field, with the order of presentation and field being randomized.

For the second set of trials, the *transfer trials*, five new letters were selected that had uppercase versions containing only straight lines: *V, K, F, Y*, and *N*. Five new letters were selected that had lowercase versions containing some curved lines: *U, O, C, R*, and *S*. These letters also were used as fillers in Experiment 4. (Due to the limited number of letters of the alphabet, some of these lowercase cues resembled the uppercase ones; the possible effects of this factor can be examined directly in the data, however.) As usual, each lowercase version was presented to each visual field twice, and the order of presentation and field was randomized. Three blocks of 40 trials were administered.

Procedure. The procedure for the first four blocks was identical to that of Experiment 1 in all respects but two: First, during the second block we cautioned the subject to be careful and to review the judgment in his head before actually making a response. We reminded the subject of the need to be careful about five times during the session, but did not make this reminding contingent on correct or incorrect performance on the trial preceding the admonition. Second, in the third and fourth blocks of trials, we provided the subject with feedback after each trial simply by saying *right* or *wrong* aloud.

The procedure for the three transfer blocks, using the new letters, was identical to that of the first block, with no feedback or special encouragement. The subject was tested on the transfer task immediately following the previous one (separated only by a rest period of approximately 15 min).

Results

Initial trials. Figure 1 presents the results of primary interest from this experiment. We began by analyzing the first two blocks, where no feedback was provided. We again found that there was greater accuracy in the left hemisphere, $F(1, 8) = 11.25$, $p = .01$, and that there was possibly a tendency for greater accuracy with curved stimuli, $F(1, 8) = 3.86$, $p < .1$. To our surprise, there was a significant interaction between block, hemisphere, and stimulus $F(1, 8) = 8.33$, $p < .03$. This interaction seems to reflect primarily the degraded performance for curved stimuli in the right hemisphere during the second block, and may indicate a gradual abandoning of his response bias in favor of a simple guessing strategy. No other effects or interactions were significant in this analysis, $p > .25$ in all cases.

A slightly different pattern is evident in the response times: There was a distinct increase in time on the second block, $F(1, 8) = 42.46$, $p < .001$, which probably reflects our urgings to be careful; there was no effect of hemisphere, $F(1, 8) = 2.24$, $p > .1$; there was no effect of stimulus type, $F < 1$, or of replication, $F(1, 8) = 2.38$, $p > .1$. In fact, the only other significant comparison was an interaction between hemisphere and block: the right hemisphere began by being faster than the left, and exhibiting the kind of speed–accuracy trade-off we saw in Experiment 1. But by the second block, the right hemisphere was taking longer than the left—but was still committing more errors than the left hemisphere. No other effect or interaction was significant, $p > .25$ in all cases.

The effects of feedback were apparent in Blocks 3 and 4. By Block 4, there was no significant difference in accuracy between the hemispheres, 100% for the left and 90% for the right, $F(1, 8) = 1.0$, $p > .25$, and there was no significant difference in response times, 1.172 s for the left and 1.248 s for the right, $F < 1$. However, although the left hemisphere was faster on Replication 1 than on Replication 2, the right hemisphere was faster on Replication 2, $F(1, 8) = 5.83$, $p < .05$ for the interaction of replication and hemisphere; in addition, curved stimuli were judged faster on Replication 1 than on Replication 2, but vice versa for straight stimuli, $F(1, 8) = 5.25$, $p = .05$ for the interaction between replication and stimulus. Finally, there was possibly a tendency for responses to curved stimuli to be faster than responses to straight ones, $F(1, 8) = 3.48$, $p = .1$, and no other effect or interaction approached significance, $p > .2$ in all cases.

An analysis of all four blocks together revealed that accuracy improved over the blocks, $F(3, 24) = 3.27$, $p < .05$, that the left hemisphere was more accurate than the right, $F(1, 8) = 17.6$, $p < .01$, and that over successive blocks responses to straight stimuli tended to improve more than those to curved stimuli, $F(3, 24) = 2.76$, $p = .06$ (this may simply reflect a ceiling effect for curved stimuli, however).

In addition, considering all of the data together revealed that there were differences in the overall time per block, $F(3, 24) = 59.9$, $p < .001$ (the subject slowed down on Block 2, then sped up on each block thereafter); that the left hemisphere was generally faster than the right, $F(1, 8) = 6.69$, $p < .05$, and that there was a significant interaction between the difference in the response times for the two hemispheres over blocks, $F(3, 24) = 3.97$, $p < .03$. No other effect or interaction was significant, $p > .25$ in all cases.

Transfer trials. The most relevant results from this condition are also presented in Figure 1. As is evident, there was virtually no savings in the right hemisphere in terms of accuracy: The overall accuracy of the two hemispheres was 95% and 66.7%, for the left and right, respectively, $F(1, 8) = 4.90$, $p = .058$. There was possibly a tendency for improved performance in later blocks, $F(2, 16) = 2.80$, $p < .1$, but no other effect or interaction approached significance, $p > .25$ in all cases.

As is also apparent in Figure 1, there was no overall difference in the response times for the two hemispheres, $F < 1$. In addition, not illustrated in the figure, times again varied with block, $F(2, 16) = 3.81$, $p < .05$. Again, there was an apparent speed–accuracy trade-

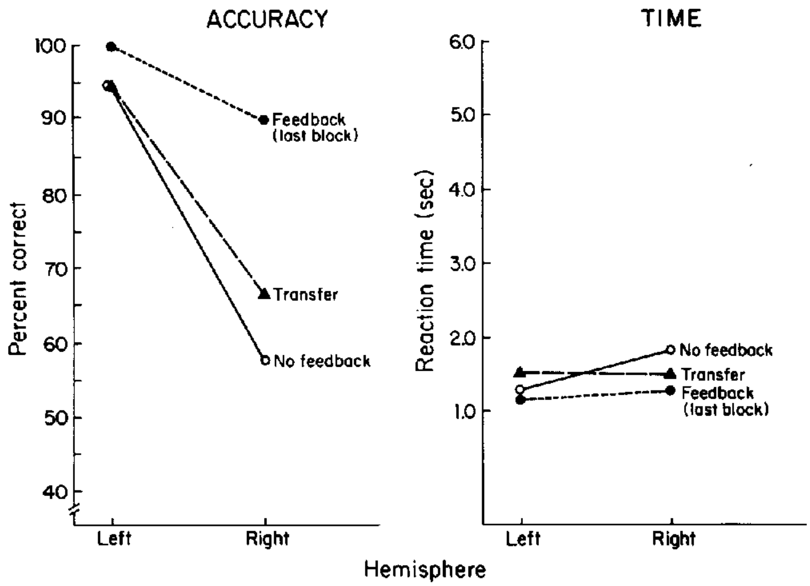

Figure 1. Results from the no feedback, feedback, and transfer trials for J.W.

off on Block 2, and there was a marginal trend for faster responses for the second replication (1.672 s vs. 1.427 s), $F(1, 8) = 4.19$, $p < .08$. No other effect or interaction was significant in this analysis, $p > .25$ in all cases.

To better assess possible savings on the transfer trials, we directly compared performance on the last three blocks of the transfer trials with performance in the first three blocks of the initial trials. Analysis of the accuracy data indicated that there was no overall savings on the transfer trials, $F < 1$, and that the relative difference in the performance of the hemispheres was the same in the two conditions, $F < 1$. In fact, the only difference between the conditions was that accuracy improved with successive blocks in the initial trials (due to the feedback), whereas it improved only marginally with successive blocks in the transfer condition, $F(2, 32) = 3.30$, $p < .05$. For all other interactions involving condition, $p > .25$.

The analysis of all of the response times indicated that there was only a marginal difference between the overall times for the two conditions, $F(1, 16) = 3.88$, $p < .08$, and revealed only two significant effects of condition: the effects of block were different in the two conditions, $F(2, 32) = 44.39$, $p < .001$; in addition, this interaction itself was different in the two hemispheres, $F(2, 32) = 3.29$, $p = .05$. The difference between the hemispheres steadily decreased in the initial trials, whereas it was largest in the second block for the transfer trials, and actually reversed (with the right hemisphere becoming faster) for the third block (this indicates a speed–accuracy trade-off). Apparently, the right hemisphere realized the increased difficulty on the second block of the transfer trials, but then did not try very hard on the third block. No other interactions involving condition approached significance, $p > .25$.

Discussion

In the initial blocks of trials, the subject's right hemisphere again was unable to make the shape judgments from memory. However, when given feedback about accuracy, this hemisphere quickly learned to perform the task. Given this evidence that the right hemisphere had finally understood what we wanted it to do, the question became whether it could generate the images to perform the task or had simply memorized the responses to the letters. The transfer task addressed this question. The results of this task were clear-cut:

the right hemisphere of this patient had not learned to perform the imagery task. Indeed, the slightly better than chance performance could be attributed to the letters *c, o,* and *s,* which have similar-shaped upper- and lowercase versions.

Dissociations Among Processing Modules

We have thus far demonstrated that J.W.'s right cerebral hemisphere has an image-generation deficit: It cannot generate images of letters of the alphabet. In addition, however, we have shown that there is a dissociation between at least two of the processing modules putatively used in imaging letters, namely the FIND "inspection" module and the PUT and/or PICTURE modules. That is, in Experiments 2, 4, and 5 we showed that the right hemisphere can perform perceptual analogues of the straight/curved image-generation task. Recall that the FIND module is putatively used both in perception and in imagery. In addition, in Experiment 4 we showed that when image generation is not involved, the right hemisphere could inspect images about as well as it could inspect the actual words, when, if anything, only a brief iconic memory was used.

However, we do not know which of the other two modules is responsible for the observed generation deficit in the right hemisphere. It could be that the PICTURE module produces only very faint, weak images, which cannot be used effectively. Or it could be that the PUT module is defective, preventing the segments of a letter from being arranged to form an image of the pattern. Or, perhaps both modules are deficient. In addition, we do not know if the deficit is particular to images of letters and words, or is more general. The experiments in this section address these concerns.

Experiment 7

Our hypothesis is that J.W.'s right hemisphere cannot form images of letters of the alphabet because these images must be formed by composing together distinct parts. If so, then we have no reason to expect a deficit when images having only one part must be formed. The next question we asked was whether both cerebral hemispheres in our first patient could in fact generate images of global shapes. If so, we have evidence that the PICTURE processing module operates in both hemispheres of this subject.

The predictions of the following experiments are based on the idea that vision uses different "spatial frequency" channels (see Marr, 1982). These channels operate at different levels of resolution. At high levels of resolution, the individual parts of an object (e.g., fingers on a hand) are distinct, and are perceptually parsed and stored individually. At very low levels of resolution, only a rather blurred, general shape outline will be encoded (e.g., a blob for a hand). Kosslyn (1980) assumed that images of objects typically are constructed by first activating a general shape envelope, corresponding to an encoding from a low-spatial frequency channel. This shape served as as *skeletal image* which could be "fleshed out" by adding additional details. These details were encoded from high-spatial frequency channels, and must be added if the task requires "seeing" details on an imaged object. In the straight/curved imagery task, the skeletal image of an uppercase letter will not be sufficient to "see" the shapes of individual segments. To get this kind of resolution, high-spatial frequency encodings must be used, which requires amalgamating together individual segments.

The first task we used in this experiment required the subject J.W. to decide which of two similar-sized objects, such as a goat and a hog, was the larger. This task was chosen for two reasons: First, it could be performed on the basis of skeletal images of the animals' general forms, with no added details being necessary. Second, Kosslyn, Murphy, Bemesderfer, and Feinstein (1977) and Kosslyn (1980, chap. 9) had shown that images of the two shapes were used to make the judgment. They asked people to start off with a tiny image or a normal-sized image of one object, and then to decide if another named object was larger than the first. Subjects were told that they did not have to use the image of the first object, but were simply to decide as quickly as possible. If the objects were similar in size, more time was taken if the first was imaged at a tiny size: Subjects claimed that they had to "zoom in" on this object before they could compare it to the second one; if the first object was imaged at a normal size, no such zooming in was necessary, and hence less time was taken. For objects not similar in size, such as an elephant versus a rabbit, there was no effect of the size of the initial image, and subjects claimed not to use imagery. These results make sense if objects are labeled in memory in terms of size categories: An elephant is *large* and a rabbit is *small;* knowing this is enough to make the judgment. But two similar-sized objects are likely to be classified in the same category: A goat is *medium* and so is a hog; knowing the size categories does not help, and one is forced to use imagery to make the comparison (see Kosslyn, 1980, for a discussion of various theories of processing in this task).

In addition, we also tested J.W. in a second task that required subtle spatial distinctions, and hence was likely to evoke imagery: We gave him the names of common objects, and asked whether they are higher than they are wide.

Method: Task 1

Materials. The following animal names were used as stimuli: *mouse, bat, rat, cat, dachshund, beagle, spaniel, beaver, lamb, hog, goat, wolf, tiger, deer, bear, donkey, horse, zebra, moose,* and *elephant.* These animals were to be compared to *goat,* with 10 being smaller and 9 being larger. Our subject lived on a farm and was interested in animals; as the data attest, he had little difficulty with these judgments. The subject saw each comparison name lateralized once to the left and once to the right, resulting in a total of 38 trials.

Procedure. As before, the subject sat in front of a video display monitor, a CRT screen, with two buttons before him. One button was labeled *goat* and the other was labeled *other.* The subject was told that he soon would see the names of animals. When he saw a name, he was to press the *goat* button if a goat was larger than that animal, and the *other* button if the named animal was larger than a goat. Before each trial he fixated on an asterisk in the center of the screen. The stimulus word was presented 1.5° to the left or the right of the asterisk. Stimuli were presented in a random order, each word was presented once in each visual field, but the order of the field of presentation was varied randomly. The subject always responded using his left hand.

Results

First, and most basic, both hemispheres could perform this task. Only one error was committed in the entire experiment (for *moose,* which he apparently misread as *mouse*), resulting in 100% accuracy in all but the right hemisphere large condition, which had 89% accuracy. Not surprisingly, there were no significant differences in the comparisons of error rates, $p > .25$ in all cases.

Next, we examined the response times. Again, there was no difference between the hemispheres (1.203 vs. 1.264 s for the left and right, respectively), $F < 1$. Nor was there an effect of the size of the objects, $F(1, 17) = 1.65$, $p > .20$. However, the pattern of times was different for the two sizes for each hemisphere, as witnessed by a significant interaction between size and hemisphere, $F(1, 17) = 5.69$, $p < .03$. For the small animals times were 1.178 s and 1.482 s, whereas for the large ones times were 1.227 and 1.047 s for the left and right hemispheres, respectively. This result is a puzzle, but is very fortunate in a way: It demonstrates that our failure to find effects of hemisphere are not simply a reflection of noisy data or insensitive statistical procedures.

We were concerned that perhaps some of the comparison objects were too disparate in size, allowing the judgment to be made without imagery. Thus, we examined only the 5 objects just larger than a goat and the 5 just smaller than a goat. All of these items were evaluated correctly in both hemispheres. The response times were 1.318 s and 1.319 s for the left and right hemispheres, respectively, $F < 1$. No other effect or interaction approached significance in this analysis, $p > .14$ in all cases.

In short, then, these data provide evidence that both hemispheres can form images of general shapes, as is required to evaluate the relative sizes of similar-sized objects.

Method: Task 2

In the previous task, both hemispheres were essentially perfect; this ceiling effect prevents us from discovering whether one hemisphere is in fact better at generating skeletal images of the overall shapes. This task was intended to require only a skeletal image, but to be more difficult than was the first one—which should prevent a ceiling effect and allow a meaningful comparison of the hemispheres' performance.

Materials. Twelve imageable objects were selected that are higher than they are wide: *nose, book, ape, ear, mug, boot, jar, coat, chair, barrel, pear,* and *vase;* an additional 12 were selected that are wider than they are high: *flag, cake, eye, bike, buckle, dollar, sofa, bow, soap, crate, tomato,* and *bowl*. In addition, a professional artist drew a canonical black-and-white line drawing of each object, and these drawings were photographed and made into slides. Finally, the names of the objects were typed in a random order on a sheet of paper.

Procedure. The subject again sat before the screen, fixated on the asterisk, and viewed lateralized stimuli. Now, however, there were three experimental conditions: The *imagery* condition consisted of his seeing the names of the objects, presented in a random order, with each word being presented once in each field with the order of the field of presentation also being randomized. One button was labeled *higher,* and the other *wider.* He pressed the appropriate button if the named object was higher than it is wide or wider than it is high.

The *picture* condition consisted of his seeing the slides of the objects, presented in a random order with the field of presentation also being randomized. He made the same judgment as in the imagery condition, but now on the basis of what he saw. This condition was included to provide a baseline for perceptual performance of the task.

Finally, the *picture-name association* task consisted of his seeing the pictures as in the previous condition, but now he simply pointed to the appropriate name on the sheet in front of him. This task was included as a baseline against which to compare performance in the imagery task; if he cannot read certain names, he clearly will not be able to image and evaluate the corresponding objects.

The subject was tested in the imagery task first, then the pictures task, then the picture-name association task. This order ensured that he could not be memorizing the responses to the actual pictures and using them in the imagery task. The subject had approximately 10 min rest between tasks.

Results

The imagery task. There was no significant difference in the accuracy of the two hemispheres in performing this task (70.8% vs. 66.7% for left and right, respectively), $F < 1$. Nor was there an effect of response category, $F < 1$ (66.7 vs. 70.8 for taller and wider, respectively). However, there was a marginal trend for the left hemisphere to be more accurate with the wider stimuli (79.2 vs. 62.5%), whereas the right was more accurate with the taller stimuli (70.8% vs. 62.5%), $F(1, 22) = 3.19$, $p < .09$. This marginal trend reflected a more complicated interaction between hemisphere, response category, and block, $F(1, 22) = 6.82$, $p < .02$. The interaction between hemisphere and response category was dramatic for the first block (33.3% vs. 83.3% for taller and wider for the left hemisphere, and 83.3% vs. 50% for taller and wider for the right hemisphere), whereas the interaction was diluted by the second block. There were no other significant effects or interactions in this analysis, $p > .14$ in all cases.

A closer examination of the data revealed that almost half of the errors were committed in the first 10 trials. This was not surprising, given that the task was novel and the subject had had only a few practice trials. Thus, it was of interest to examine the data excluding the first 10 trials. Now the left hemisphere was accurate 81% versus 70% for the right hemisphere, $t < 1$.

The same story emerges when we examine the response times: There was no systematic effect of hemisphere (2.266 s vs. 2.318 s for left and right), $F < 1$, nor were there any interactions involving hemisphere, $F < 1$ in all cases. In fact, the only significant effect reflected faster times on the second block (2.908 s vs. 1.675 s), $F(1, 22) = 36.18$, $p < .001$. For all other effects and interactions, $p < .19$.

When we excluded the first 10 trials, the two hemispheres took virtually the identical amount of time to make the judgments, 2.018 s versus 2.013 s for the left and right, respectively, $t < 1$.

The pictures task. Both hemispheres again could perform the task, 85% and 91.7% accuracy for the left and right, respectively, $F < 1$. Similarly, there was no difference in accuracy for the different response categories (91.7% vs. 85.4% for taller and wider, respectively), $F(1, 22) = 1.48$, $p > .23$. In fact, there were no significant comparisons in the accuracy data, $p > .13$ in all cases.

The analysis of the response times revealed that responses were faster on the second block (2.229 vs. 1.501 s), $F(1, 22) = 8.59$, $p < .01$. Although the right hemisphere appeared slightly better at this perceptual discrimination task (1.971 s vs. 1.759 s for left and right, respectively), this difference was not significant, $F < 1$. No other comparisons were significant, $p > .4$ in all cases.

We also performed analyses that included data from both the imagery task and the pictures task, considering whether the hemispheres differed in their imagery ability relative to the perceptual baseline. First, there was no difference in the relative accuracies of the hemispheres in the two tasks, $F(1,$

22) = 1.23, $p > .25$., nor was there a general difference in the accuracy of the two hemispheres, $F < 1$. However, the relative accuracy of the hemispheres appeared to differ for the different stimulus types in the different tasks, $F(1, 22) = 4.00$, $p < .06$. The interaction involving response category and hemisphere, noted earlier, only occurred in the imagery task. In addition, there was a marginal interaction between task, block, hemisphere, and response, which again reflected the interaction noted earlier, $F(1, 22) = 3.21$, $p < .09$. Furthermore, the pictures task was in general easier than the imagery task, $F(1, 22) = 14.44$, $p < .001$. No other interaction involving task was significant, $p > .15$ in all cases.

The analysis of response times from both tasks was consistent with the foregoing analysis: Not only was there no difference in times for the two hemispheres, $F < 1$, but the relative latencies were the same in both tasks, $F < 1$. There was a marginally significant interaction between task and block, with greater improvement in the imagery task, $F(1, 22) = 4.04$, $p < .06$. In fact, by the second block of trials the overall times were quite similar (1.675 s and 1.501 s for imagery and perception vs. 2.908 s and 2.229 s for the two tasks on the first block). No other interaction involving task was significant, $p > .14$ in all cases.

The picture-name association task. Finally, the left hemisphere performed with 100% accuracy in the picture-name association task, and the right hemisphere performed with 92% accuracy. Thus, the difference in accuracy found between the tasks, although not significant, is about what could have occurred due to factors having nothing to do with imagery.

Discussion

The left and right hemisphere clearly could perform two imagery tasks that do not involve generating multipart images. Only a skeletal image (a general outline) is necessary to decide if one object is larger than another or to determine the height/width shape envelope of a single object. Thus, we have reason to believe that the PICTURE processing module operates effectively in both hemispheres. In addition, in order to "inspect" the images to perform the task, the FIND module had to be effective, and thus these results are consistent with the previous ones, indicating that the right hemisphere's imagery problem is not due to a faulty FIND module.

The next question, then, is whether both hemispheres can perform as well when images of nonlinguistic stimuli must be formed from separate parts.

Experiment 8

The materials and task used in the foregoing experiments were considerably different from those used in the experiments with letters of the alphabet. Perhaps we have found a deficit for letters per se, and not for multipart images. To rule out this possibility, in this experiment we used materials used in the previous experiment to demonstrate an image-generation deficit when parts had to be arranged correctly in an image in order to perform a task. In this experiment we asked our subject whether an animal's ears protrude above the top of its skull or whether they flop down along the side side of its skull. Which is the case for a beagle? a mouse? a wolf? Earlier experiments indicated that people use imagery in making just this sort of judgment (see Kosslyn & Jolicoeur, 1980; Jolicoeur & Kosslyn, in press), and fortunately our subject's interest in animals had led him to have ample exposure to these sorts of stimuli. In addition, because this judgment requires relating two parts—the ears and the skull—we had reason to expect that the right hemisphere would have difficulty. Thus, in this experiment the subject saw animals' names lateralized, and simply judged the relationship between the ears and skull.

Method

Materials. The same stimuli used in the size comparison experiment were used here. As before, 20 animal names were presented in a random order, with the field of presentation also being randomized, and each name was presented once in each field. Ten of the animals had ears that protruded above the skull, and 10 had ears that flopped down alongside it.

Procedure. The two keys were now marked with small drawings, one showing a stylized skull with an ear sticking up (a small triangle above a semicircle) and the other showing a stylized skull with an ear hanging down (a *U* hanging within a semicircle). The subject was told that he would see the names of animals and would be asked to judge whether each animal's ears protruded above the top of the head or hung down. Drawings were shown, and the subject correctly classified the drawings. He was told which key to press for each judgment, and again fixated on the asterisk before each trial. Two blocks of trials were administered.

Results

The most striking aspect of the results is the relative accuracies of the two hemispheres: 87.5% versus 45% for the left and right hemispheres, respectively, $F(1, 18) = 18.45$, $p < .001$. In addition, protruding ears were judged more accurately than nonprotruding ears (80% vs. 52.5%), $F(1, 18) = 5.89$, $p < .03$, but this may simply reflect a response bias. And the effects of type of stimulus were different for the two hemispheres (85% and 90% for protruding and nonprotruding in the left, and 75% and 15% for protruding and nonprotruding in the right), $F(1, 18) = 10.79$, $p < .005$. No other effects or interactions were significant, $p > .2$ in all cases.

The analysis of response times revealed improvement with block, $F(1, 18) = 55.6$, $p < .001$ (2.923 s vs. 1.530 s for the first and second blocks, respectively). There was no effect of hemisphere (2.139 s, and 2.315 s for the left and right, respectively), $F < 1$, nor was there any other effect or interaction, $p > .2$ in all cases.

Discussion

The results from this task are in sharp contrast to those from the two previous ones, even though exactly the same stimuli were presented to the subject here and in the size-comparison task. Indeed, the present results are quite similar to those from the lowercase cue imagery task. Unlike the case for letters, however, one could argue that the right hemisphere was simply unfamiliar with the shape of ears. However, given the hemispheres' comparable knowledge of subtle size differences among animals, and the left hemisphere's knowledge of ears, there is no clear reason why the right hemisphere should have a selective deficit for knowledge about ears.

In order to perform the ears-judgment task, the subject must coordinate an image of the ears with an image of the head, which we claim requires the PUT processing module to access and use a stored description of the relation. Thus, the failure of the right hemisphere to perform this task converges nicely with our earlier results in a very different task. Furthermore, the results of the experiments reported so far in this article converge in demonstrating that the FIND, PICTURE, LOAD, and REGENERATE processing modules operate effectively in both hemispheres. These data taken as a whole are consistent with our claim that the PUT module is a distinct entity, and J.W.'s right hemisphere has a deficit in using this module to generate multipart images.

Experiment 9

Have we really identified a deficit in a particular processing module, or something more general? In this last set of experiments with J.W. we show that we have discovered something more specific than a deficit in memory for details or in serial processing. We do so by showing that an alternative retrieval strategy can allow J.W. to perform the task. Specifically, neuropsychological data on the apraxias and the visual agnosias show that motor and visual memories can be separately spared or destroyed after brain damage, and the existence of alexia (inability to read) without agraphia (inability to write) and vice versa makes this point especially strongly for letters (see Geschwind, 1965). We have shown that J.W. can recognize letters, and so he must have their representations stored in long-term memory; in addition, J.W. is an excellent artist, able to produce highly realistic drawings of cars and other objects from memory. Thus, we attempted to lead J.W. to perform the task by asking him to draw (print) the uppercase versions of letters. If he can perform the task using a drawing strategy, but not an imagery one, we can argue that his deficit is not in memory for details, in serial processing, or in a processing module used to perform both activities.

Method

This experiment was conducted about 3 months after the previous one. Thus, we began by replicating our original findings, using the second set of letters (from Experiment 3). After this, we administered training trials, and then looked for transfer to the third set of letters.

Materials. The materials were the same as those used in Experiment 6.

Procedure. The experiment had three phases: The first phase was a simple replication of our original findings. The procedure here was identical to that used in Experiment 1. One block of 40 trials was administered. The second phase had multiple components, described later, which were used to train J.W. to form images by "mentally drawing" the letters. The final phase was identical to that of Experiment 6, where we simply switched him to the new set of letters. The details of each procedure will be described as they become relevant.

Results

Lowercase cue task. The results from the basic imagery task replicated our previous findings; indeed, the right hemisphere performed more poorly than we had found before: The left hemisphere was accurate 95% of the time and the right was accurate only 30% of the time, $F(1, 8) = 67.6$, $p < .001$. In addition, there was no improvement with the second block, $F < 1$, or any other effect, $p > .19$. There was no effect of hemisphere in the analysis of the response times (1.316 s for the left hemisphere compared with 1.342 s for the right), $F < 1$, and no other effects or interactions were significant, $p > .2$ in all cases.

Mental drawing trials. There were three phases of these trials. We began by simply asking J.W. to draw (i.e., print) the uppercase versions of the letters, with his left hand and his eyes closed. He could do this perfectly when the cues were presented to the right hemisphere. Clearly, visual and motor representations need not be related in the brain; this finding is consistent with reports of alexia without agraphia (and vice versa). We next asked him to "draw the letters in your head" before making a decision and pressing the appropriate button during the basic lowercase cue imagery task. These instructions had no effects whatsoever, as witnessed by the left hemisphere's being accurate 100% of the time and the right hemisphere's being accurate only 20% of the time, $F(1, 8) = 51.2$, $p < .001$. There was no evidence of a response bias or consistent guessing strategy in the right hemisphere, with errors being distributed relatively evenly for the different stimulus types (10% vs. 30% accuracy for curved and straight, respectively), $F < 1$. No interactions were significant, $p > .25$. There were no significant differences in the analysis of response times, although there was a marginal trend for the left hemisphere to be faster (2.086 s vs. 2.830 s), $F(1, 8) = 3.84$, $p < .09$; no other effect or interaction approached significance in this analysis, $p > .16$ in all cases.

In the final procedure, we asked him to draw the uppercase versions of the first three lowercase cues shown to the right hemisphere, and then to classify the uppercase version as straight or curved. He was successful on these initial trials. After the first three letters we told him to "do the same thing, but without actually drawing the letters; draw them in your mind." And this proved to be a successful strategy. His arm was prevented from moving in an attempt to preclude solution by proprioception or gross cross-cuing and to force him to consider his response before pressing a button. His arm was held by an experimenter who was not watching the lowercase stimuli (and hence could not provide nonverbal cues on how to respond correctly). J.W. was allowed to press a button only after saying he was ready. Three blocks of trials were conducted. As is evident in Figure 2, on these trials, there was no difference in the accuracy of the two hemispheres, $F(1, 8) = 1.0$, $p > .34$. However, the left hemisphere was perfect by the second block, whereas the right was perfect only on the third block, resulting in a marginally significant interaction between hemisphere and blocks, $F(2, 15) = 3.50$, $p < .06$. In addition, the improved accuracy in the right hemisphere with successive blocks lagged for the straight stimuli, whereas the improved accuracy in the left hemisphere was equivalent with both types of stimuli, resulting in a marginally significant interaction between hemisphere, block, and stimulus type, $F(2, 16) = 3.50$, $p <. 06$. In general, there was improvement over blocks, $F(2, 16) = 3.70$, $p < .05$. No other comparisons were significant, $p > .13$ in all cases.

The analysis of response times painted a more complex picture. The most important finding is that although the right hemisphere developed the ability to perform the task, it was still slower than the left (6.054 s vs. 4.351 s), $F(1, 8) = 19.45$, $p < .005$. (Note that the absolute times are inflated because his arm was held until after the stimuli were presented

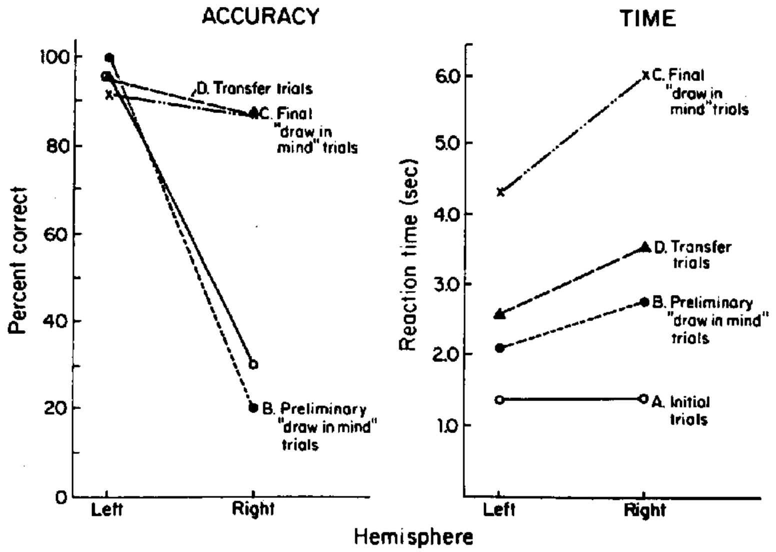

Figure 2. Results from the lowercase cue task in Experiment 9, with and without "mental drawing" instructions.

and he was ready to respond, forcing him to be careful.) In addition, there was an interaction between block and replication, *F*(2, 16) = 3.65, $p < .05$, and a marginal interaction between hemisphere, block, and replication, *F*(2, 16) = 3.34, $p = .061$. But these interactions reflected a four-way interaction between hemisphere, block, stimulus type, and replication, *F*(2, 16) = 6.56, $p < .009$, indicating that the data became more systematic with successive blocks; on the first block, different patterns of responses occurred on the different replications for the different types of stimuli, whereas by the third block the data were quite regular. Other than the finding that times generally decreased on the final block, *F*(2, 16) = 7.01, $p < .01$, there were no other significant comparisons, $p > .11$ in all cases.

Transfer trials. Finally, we simply switched the stimuli to the third set of letters. This was done to determine whether the right hemisphere had developed a general strategy or somehow had memorized the individual responses. Two blocks of trials were administered. The most important results are illustrated in Figure 2. The analysis of accuracy data revealed no significant effects or interactions, and only the effect of stimulus type was marginal, *F*(1, 8) = 3.5, $p < .1$. In particular, there was no difference between the hemispheres (95% vs. 87.5%), $F < 1$, and $p > .3$ for all other comparisons.

The analysis of the response time data again revealed that the left hemisphere was faster than the right, *F*(1, 8) = 11.16, $p < .01$. In addition, there were faster responses on the second block, *F*(1, 8) = 67.04, $p < .001$, marginally faster responses to curved stimuli (2.817 s vs. 3.299 s), *F*(1, 8) = 4.07, $p < .08$, and faster responses on the second replication of a letter (3.454 s vs. 2.662 s), *F*(1, 8) = 36.6, $p < .001$. None of the interactions was significant, $p > .14$ in all cases.

To examine the degree of transfer from the first set of letters we analyzed together the data from the final two blocks of the previous condition with the two blocks of transfer trials. The accuracy rates were equivalent in the two conditions in all respects. Not only was there no difference in overall accuracies, $F < 1$, but no interaction with condition was significant, $p > .12$ in all cases. In particular, the difference in accuracies for the two hemispheres was the same in both conditions, $F < 1$ for the appropriate interaction.

The analysis of the response times indicated that times were faster with the new items (4.904 s vs. 3.058 s), *F*(1, 16) = 26.3, $p < .001$. No other factors interacted with condition, however, $p > .11$ in all cases.

Discussion

These results are in sharp contrast to those found earlier with J.W.: he now can do the task in his right hemisphere. Clearly, the impairment observed before does not reflect a deficit in memory for the form of letters or in serial processing in general. However, he still is taking more time in the right hemisphere. Apparently, we helped J.W. discover an alternate access route to the stored information about the letters' forms. But even so, this access route was not as efficient as that used in the left hemisphere.

Although the success of J.W.'s right hemisphere after motor practice puts to rest any nagging doubt left by the previous visual imagery experiments as to whether or not the right hemisphere could understand the goal of the task, it raises a host of new questions: Was imagery of some sort involved here? Did J.W. acquire an ability to use the PUT processing module to access the stored representations in a new way? Or has an altogether different system of motor imagery been marshaled by the right hemisphere? To what extent are visual and motor imagery separable? That is, it is possible that J.W. performed this task using not visual, but motoric imagery. The idea of motoric imagery has been discussed at least since the time of Piaget's seminal writings (for an overview see Piaget & Inhelder, 1971). Furthermore, numerous researchers have informally noted that there seems to be a motoric component to mental rotation. For example, Shepard and Metzler (1971) asked people to decide whether two blocklike forms had the same shape, irrespective of the orientation of the forms. The decision times increased linearly with increases in the angular disparity in the forms' orientations. Many people report the introspection of "mentally holding" the forms and "twisting" them into congruence. Such introspections are consistent with Parsons' (1983) demonstrations that the ease of mentally rotating a body part is related to the ease of actually performing that movement.

In the absence of EMG data during our testing sessions, we cannot know whether the task was performed by accessing motor representations ("motor images") or by a purely motor strategy, consisting of his making movements imperceptible to the experimenters. The straight/curved judgment would certainly lend itself to performance by motor feedback. However, if we assume that motor imagery was used in this task, it is important to note that the motor imagery and visual imagery systems themselves need not be integral (i.e., share representations or processes). Indeed, the present results underscore the existence of at least some distinct processing modules used by the two systems. The precise mechanisms of coordination of visual and motor image generation are by no means clear, but certainly seem worthy of further investigation.

Variations in Disconnected Right Hemispheres

We tested a second subject, V.P., in our tasks with an eye toward discovering whether a different pattern of deficits would emerge. We originally decided to test split-brain patients in these tasks because we suspected that the PUT processing module used some of the same computational machinery used in other sorts of symbol-manipulation tasks, and we knew something about the general deficits of J.W.'s right hemisphere. Our second subject, V.P., has an exceptional degree of reasoning and linguistic ability in her right hemisphere, which led us to examine whether she could use the PUT module to form multipart images. Thus, another avenue for evaluating the theory is to compare the deficits in V.P.'s processing with those in J.W.'s processing, looking for a single underlying pattern cutting across different deficits. In addition, by comparing subtle differences in the nature of the functional dissociations in the two subjects, we hoped to learn something about the mechanisms used by the processing modules.

Experiment 10

We started our investigation of V.P.'s imagery abilities with the same basic lowercase cue straight/curved imagery task and the same perceptual analogue control task used in Experiment 2.

Method

Subject. V.P. is a right-handed female who was 32 years old at the time of testing. At age 9, following febrile illnesses (including measles and scarlet fever), she began having recurrent seizures. The initial seizures were infrequent and were controlled by anticonvulsant drugs until after she graduated from high school. By 1976 she was experiencing episodes of blank staring several times a day that would last for seconds. The EEG indicated bilateral 4 cps (4 Hz) spike and slow wave activity, and sharp activity with left temporal predominance. In 1979 she was being administered multiple anticonvulsant drugs, which failed to control generalized, major motor seizures, absence, and myoclonic seizures. She was referred to Dr. M. Rayport at the Medical College of Ohio. In early April 1979 she underwent partial anterior callosal section, and the resection was completed in a second operation 7 weeks later.

A neurological exam following the operation revealed no evidence of focal activity, and her IQ scores were in the normal range. When we tested her she was alert and thoughtful, carrying on normal conversation and fully oriented. V.P. could comprehend language in her right hemisphere immediately after surgery. Unlike the vast majority of split-brain patients, within 1 year after the operation she was actually able to produce speech from her right hemisphere (see Gazzaniga, 1983; Sidtis et al., 1981, for additional details).

Materials. The lowercase cue task used the same letters used in Experiment 3, and the upper case control used the uppercase versions of these letters.

Procedure. The procedure used in Experiment 1 was also used here. However, four blocks of trials of the lowercase cue task were used initially.

Immediately following the four blocks of imagery trials two blocks of the uppercase controls were administered, using the procedure of Experiment 2. The uppercase versions of the letters used in the previous task were shown in the same random order used previously.

Finally, following the uppercase controls were two more blocks of imagery trials with the lowercase stimuli.

Results

Initial imagery trials. The analysis of the accuracy data revealed that there was improvement with successive blocks, $F(3, 24) = 4.0$, $p < .03$, and better performance in the left hemisphere (95% vs. 67.5%), $F(1, 8) = 6.45$, $p < .04$. No other effects or interactions were significant, $p > .4$ in all cases.

The analysis of the response times revealed an interesting, unexpected effect: Although there was no effect of hemisphere in general, $F(1, 8) = 2.17$, $p > .17$, there was an effect of hemisphere for the first replication: For Replication 1 (i.e., the first time a letter was presented in a block), the left and right hemispheres required 4.319 s and 6.839 s, respectively, $F(1, 8) = 14.93$, $p < .01$; for Replication 2, the left and right hemispheres required 5.1901 s and 5.135 s, $F < 1$. This pattern of means produced an interaction between replication and hemisphere, $F(1, 8) = 11.01$, $p < .02$. There was also improvement with successive blocks, $F(3, 24) = 8.97$, $p < .001$, and a marginally significant tendency for faster times for judgments of straight stimuli (6.275 s vs. 4.467 s for curved and straight, respectively), $F(1, 8) = 4.11$, $p < .08$. The means suggested a trend for increasingly faster times on the first replication of each successive block (7.147, 6.652, 4.876, and 3.642 s) compared to little speeding up on the second replication after the first block (7.097, 4.314, 4.983, and 4.257 s), but this was not borne out by the analysis, $F(3, 24) = 2.13$, $p = .12$, for the interaction between replication and block. Finally, there was no overall effect of replication, $F < 1$, nor of any other interaction, $p > .25$ in all cases.

Perceptual control. There were no significant differences in the accuracy data, $p > .3$ in all cases. In particular, the two hemispheres were very accurate, 100% and 97.5% for the left and right, respectively, $F = 1.0$.

The response times revealed improvement with the second block (3.369 s vs. 1.990 s), $F(1, 8) = 10.99$, $p < .01$, and a marginal trend for a smaller effect of block in the left hemisphere, $F(1, 8) = 3.73$, $p < .09$. There was no systematic difference in the speed of responding from the two hemispheres (2.409 s vs. 2.950 s for the left and right, respectively), $F < 1$. No other effects or interactions were significant, $p > .1$ in all cases.

Final two imagery blocks. V.P.'s performance on the final two blocks of trials was very different from her performance earlier. Accuracy improved dramatically in the right hemisphere (87.5%, compared to 100% for the left), but the difference between the hemispheres was still marginally significant, $F(1, 8) = 4.55$, $p < .08$. By the final block, however, there was no effect of hemisphere (95% vs. 100% for the right and left, respectively), $F < 1$. No other effect or interaction was significant in this analysis, $p > .3$ in all cases.

The response times revealed a similar pattern: There was no effect of hemisphere, $F < 1$; block, $F(1, 8) = 1.77$, $p > .2$; or any other effect or interaction, $p > .25$ in all cases.

Discussion

As was found with J.W., V.P.'s right hemisphere began by having great difficulty in performing the imagery task. However, there was a clear initial difference between the pattern of response times found with V.P. and that found with J.W.: Unlike J.W., V.P.'s right hemisphere response times were slower only on the first replication within a block. This practice effect seemed quite transient, however, occurring on each block, although there seemed to be a tendency for the effect to accumulate gradually. We will consider the implications of these data in more detail after discussing the results of the following experiments.

The results from the perceptual control task were also like those from J.W.: Both of V.P.'s hemispheres clearly understood the basic task, and could evaluate the uppercase letters when they were actually presented.

Finally, after participating in the perceptual control task, V.P. clearly was able to perform the basic imagery task in both hemispheres. These results are in sharp contrast to J.W. This finding is not surprising, as these patients have different neurological histories and V.P.'s right hemisphere has shown itself to be exceptional in other ways, most notably in its ability to access speech. For this reason, we would argue for caution in generalizing from the hemispheric localization of imagery abilities in these patients to localization in normal individuals. Our primary objective is to find dissociations among processing modules, providing evidence that the theory has correctly organized these functional units.

We next asked whether the right hemisphere of V.P. could indeed generate images of the letters, or whether she somehow learned the correct responses (even though no feedback had been given).

Experiment 11

In this experiment we used a different task: We now asked V.P. to decide whether there is a vertical line at the far left of the uppercase letter. If she merely learned the responses to the letters, she should perform at close to chance in this task. On the other hand, if she learned to generate images of the letters, there should be considerable transfer even though the new task requires a different judgment—and this judgment conflicts on about half of the trials with the responses made in the straight/curved task.

Testing V.P. on this new task is particularly important here because in Experiment 12 we will look for transfer of a different kind, and argue that failure to transfer implicates a specific type of computational mechanism; thus, it is important to demonstrate that she does not have difficulty in transfering to a new task per se.

Method

Materials. The same letters used in the previous experiment were used here. Three of the straight letters (*M*, *H*, and *E*) and two of the curved letters (*B* and *D*) had straight vertical lines on the left; the other five letters did not have a vertical line on the left. The same order of presentation used in the previous experiment was used here.

Procedure. The procedure was the same as in the previous experiment, except that the subject was now instructed in the new task: Instead of indicating whether the uppercase letter was composed of only straight lines or some curved lines, she was now to indicate whether or not there was a vertical line on the far left. Examples were given using nonstimulus letters until her left hemisphere, at least, clearly understood the task. Two blocks of trials were given.

After the imagery task, we conducted a perceptual control task like that used before (Experiment 2). We again showed the uppercase letters themselves. Now, however, we asked the subject to make the vertical-line judgment, not the straight/curved one used before. Again, two blocks of trials were administered. This control task was conducted after the imagery trials to obtain a baseline; this ordering of the task prevents her from memorizing the responses during the control and using this information to perform the imagery task.

Results

Imagery task. As usual, accuracy was superior in the left hemisphere, $F(1, 8) = 9.52$, $p < .03$, and there was a marginal trend toward improved performance with successive blocks, $F(1, 8) = 4.24$, $p < .08$. However, by the second block of trials performance was markedly improved in the right hemisphere (95% vs. 80% for the left and right, respectively), $F(1, 8) = 2.57$, $p > .1$.

There was only one significant difference in the comparisons of response times, reflecting improvement on the second block of trials, $F(1, 8) = 12.72$, $p < .01$. Notably, there was no effect of hemisphere, $F < 1$, stimulus type, $F(1, 8) = 1.41$, $p > .25$, or replication, $F < 1$. Nor were any interactions significant, $p > .18$ in all cases.

The fact that there was some savings in this task over the initial one was revealed in analyses that included the first two straight/curved imagery blocks and these two blocks. Whereas the original blocks required a mean of 6.302 s, these required only 4.300 s, $F(1, 16) = 8.62$, $p < .01$. In addition, whereas there was a marginally significant difference in the left versus right hemisphere in the original task, 5.444 versus 7.161 s, $F(1, 8) = 4.78$, $p = .06$, there was absolutely no difference here, 4.238 versus 4.362 s, $F < 1$ [this interaction was not significant in our analysis, however, $F(1, 16) = 2.16$, $p > .15$]. The only other effect of interest here was an interaction between hemisphere and replication, $F(1, 16) = 8.70$, $p < .01$, revealing the now-familiar effect of practice in the right hemisphere.

Perceptual control. There were no significant effects in the analysis of accuracy rates. However, there was a marginal tendency for improved performance on the second block, $F(1, 8) = 3.6$, $p < .1$, and there was a marginal tendency for an interaction between block and hemisphere, $F(1, 8) = 3.6$, $p < .1$, reflecting slightly superior performance in the right hemisphere on Block 1 (90% vs. 95% for the left and right hemisphere, respectively) compared to slightly inferior performance in the right hemisphere on Block 2 (90% vs. 80%).

There were no differences in response times for the different blocks or hemispheres, $F < 1$ in both cases. However, responses to vertical-line-on-left stimuli were faster than the others (2.116 s vs. 3.583 s), $F(1, 8) = 5.52$, $p < .05$, and there was an interaction between hemisphere and replication, $F(1, 8) = 5.12$, $p = .054$. This interaction documented an increase in time over replications for the left hemisphere (2.413 s and 3.062 s for Replications 1 and 2, respectively) but a decrease in time over replications for the right hemisphere (3.877 s and 2.045 s for Replications 1 and 2, respectively). There was a marginal trend for faster times on the second replication in general, $F(1, 8) = 3.65$, $p < .1$. No other interaction was significant, $p > .25$ in all cases.

Another way to assess the performance of the right hemisphere in the imagery task is by comparison to performance in the perceptual baseline task. Thus, we included both sets of data in a single analysis. In general, there was no difference in the accuracy of the two hemispheres, $F(1, 16) = 2.75$, $p > .1$, and their relative performance was equivalent in the two tasks, $F(1, 16) = 1.84$, $p > .19$. And in fact, in the analysis of the accuracy data there were only two significant comparisons that involved effects of task: Performance improved more sharply with successive blocks in the imagery condition, $F(1, 16) = 7.36$, $p < .02$, and judgments of vertical-line-on-left stimuli were relatively more accurate than the others in the perceptual condition, but vice versa in the imagery condition, $F(1, 16) = 5.45$, $p < .04$. For all other comparisons involving task, $p > .1$.

The analysis of response times indicated that responses were generally faster in the perceptual task, $F(1, 16) = 7.77$, $p < .02$, and that times tended to decrease more sharply on the second block in the imagery condition, $F(1, 16) = 4.28$, $p < .06$. As before, there was no difference between the hemispheres, $F < 1$, and the hemispheres performed equivalently in the two tasks, $F < 1$. For all other comparisons involving task, $p > .12$.

Discussion

The results from this experiment give us good reason to believe that V.P. could form images of the letters. By the second block of trials her right hemisphere was performing the new task about as well as it performed the original task on the fifth block. In addition, there was clear savings in the overall time. Furthermore, performance in the imagery task did not differ for the two hemispheres relative to performance in the perceptual control task. These findings are especially impressive because the responses required here often conflicted with those required for the straight/curved task, and thus there is the possibility of proactive interference.

Experiment 12

The results of the previous two experiments demonstrate that V.P.'s right hemisphere can generate images of letters with practice; but practice is definitely required. The pattern of practice effects was unexpected, appearing on the first replication in a block and gradually

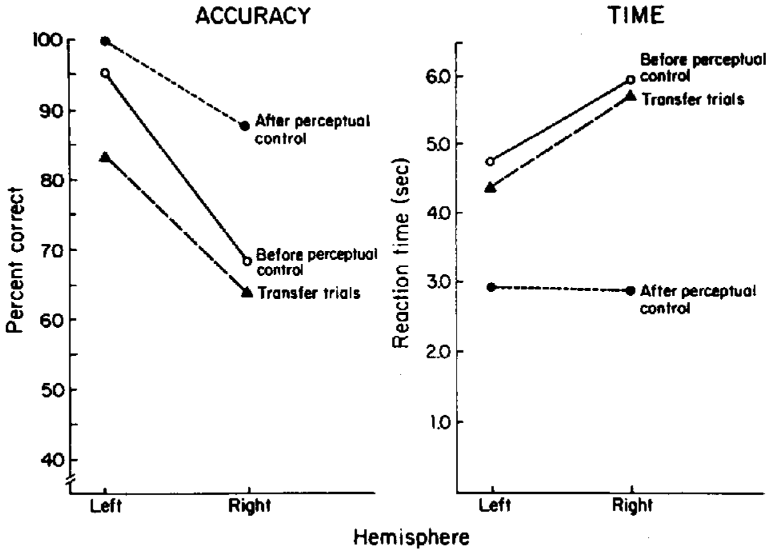

Figure 3. Results from the initial, postperception, and transfer imagery trials for V.P.

resulting in the ability to form images of the letters. This sort of effect may indicate that one or more of the processing modules simply took time to "warm up". If so, then once the modules are all operating, V.P. should be able to transfer to a new set of letters in her right hemisphere. In this experiment we asked her to perform the basic lowercase cue task with a new set of letters.

Method

Materials. The final (transfer) set of letters used in Experiment 6 was also used here.

Procedure. The procedure was identical to that used in Experiment 1. Three blocks of trials were administered.

Results

The left hemisphere again appeared to be more accurate than the right (83.3% vs. 63.3%), although this effect was now only marginally significant, $F(1, 8) = 4.8, p < .06$. Responses to curved stimuli were more accurate than to straight stimuli (86.7% vs. 60%), $F(1, 8) = 10.24, p < .02$, suggesting that there was a slight response bias. In addition, the effects of stimulus type were marginally different over successive blocks (with no change for curved, but steady improvement for straight), $F(1, 16) = 3.38, p < .06$, and the effects of stimulus type were different in the two hemispheres (83.3% and 90% for curved letters compared with 83.3% and 36.7% for straight letters in the left and right hemispheres, respectively), $F(1, 8) = 8.53, p < .02$. No other effects or interactions were significant, $p > .2$ in all cases.

The only effect in the response time results that was even marginally significant was due to hemisphere, $F(1, 8) = 4.16, p < .08$, with the left hemisphere being faster (4.409 s vs. 5.812 s). No other effect or interaction was significant, $p > .18$ in all cases. The performance of the two hemispheres in the three imagery conditions is illustrated in Figure 3.

In order to examine possible transfer more carefully, we performed analyses including these data and those from the first three blocks of trials administered in Experiment 10. The analysis of the accuracy data revealed that not only was there no overall savings from the initial to the transfer trials (79.2% vs. 73.3% for the initial and transfer trials, respectively), $F < 1$, but there was no difference in the accuracy of the two hemispheres in the two conditions, $F < 1$. In fact, no interactions with condition were significant, $p > .2$, indicating that the intervening trials had no effects at all (salutory or otherwise) on the later performance.

The analysis of all of the response times revealed the same pattern. Probably the most telling results were the lack of even a hint of a difference in the relative performance of the two hemispheres in the two conditions, $F < 1$, and the failure to find savings in overall times (5.845 s vs. 5.110 s for the original and new trials, respectively), $F(1, 16) = 1.38$, $p > .25$. However, there was an interaction between experiments and blocks, $F(2, 32) = 6.80$, $p < .01$. This interaction was due to especially slow times on the very first block in the first experiment (7.123, 5.483, and 4.930 s for the three blocks) and relatively fast times on the first block in the new experiment (4.329, 5.730, and 5.272 s for the three blocks). The slow times for the first set of trials ever received are not surprising, and the relatively high error rates for the first block in the new experiment suggest that she was not expecting new letters and was not carefully considering her decisions before responding.

Two other interactions with condition proved significant in the analysis of the original and new data: A Condition × Stimulus Type interaction reflected her being faster for curved letters originally but faster for straight letters in the new data, $F(1, 16) = 5.08$, $p < .05$. A three-way interaction between condition, hemisphere, and replication, $F(1, 16) = 7.70$, $p < .02$, reflected the fact that in the new data times increased slightly for both hemispheres from Replication 1 to Replication 2 (.189 s for the left, .333 s for the right), whereas in the original data they increased for the left hemisphere (.970 s) while they decreased dramatically for the right hemisphere (2.491 s); this finding may indicate that there was a speed–accuracy trade-off in the second replication in the original experiment.

Discussion

There was virtually no transfer of V.P.'s ability to generate images of the previous set of letters to the new set. V.P. became able to form images of the first set of letters only with practice. However, the practice apparently was *representation specific:* it did not generalize to images of other letters. Thus, she apparently did not become better at using the processing modules in general.

These unexpected findings are particularly interesting because they highlight one of the core assumptions of the information-processing paradigm in cognitive psychology—by appearing to violate it! "Computation as symbol manipulation" presupposes a distinction between instructions for manipulating symbols and the symbols being manipulated, as occurs in computer programming. This distinction corresponds to the difference between cognitive processes (such as those used in image generation) and representations (such as the long-term memory representation of a letter's appearance). Given this traditional view, we would expect to find either deficits in memory for individual letters as a result of destruction of their long-term memory representations, or an across-the-board deficit in image generation as a result of a deficit in one or more of the processing modules. In contrast to these possible findings, V.P.'s right hemisphere displays intact long-term memories for the appearances of letters (as evidenced in its reading ability and its letter-naming ability), yet after becoming adept at generating images of a subset of the alphabet still showed a deficit for another subset. Although this result could certainly be accommodated within a traditional information-processing theory, for example by postulating individual representation-specific processes, it violates the spirit of such theories. It is worth noting, however, that V.P.'s failure to transfer imagery practice to new letters is quite compatible with recent models of "massively parallel" computational networks, in which the distinction between representations and processes is eliminated (see Hinton & Anderson, 1981). This observation is of interest because such models have been explicitly based on considerations of neural functioning.[2]

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[2] After this article went to press it was discovered that V.P. did not in fact have a complete transection of her corpus callosum. Nuclear Magnetic Resonance scanning has revealed that some of the fibers in her splenium and rostrum were inadvertently spared; the splenium is part of the callosum known to convey visual information between the two hemispheres and the rostrum, in these special patients with right hemisphere language, may convey semantic information. In contrast, J.W. was found to have a complete transection. Thus, the interpretation of our results from V.P. has become more difficult; it is possible that the differences between J.W. and V.P. reflect in part intact functioning of the splenium. However, it is important to note that even with these fibers intact, V.P. is not able to pass high-resolution visual information between her hemispheres.

General Discussion

J.W.'s right hemisphere could encode cues, access case representations, generate images of single forms ("skeletal images"), retain images, inspect images, make classifications of imaged patterns, and respond appropriately. Furthermore, it could combine separate stages together and understood the instructions well enough to use a different strategy to perform the task. Nevertheless, we found dissociations between the right hemisphere's ability to perform imagery tasks that require integration of parts during image generation versus tasks that require imagery but that do not require integration of parts. This pattern of results is as expected if the FIND and PICTURE processing modules can operate effectively in both hemispheres, but the PUT processing module has selective difficulty in operating in the right hemisphere. We also found a dissociation between the PUT module and the LOAD and REGENERATE modules, which have the effect of forming an image from immediate visual input and maintaining that image, respectively. We showed that the deficit was not due to some more general problem in remembering visual details or engaging in sequential processing. Imagery seems to involve at least one processing module that is not used in visual perception, reading, or printing.

But do the present findings really implicate a distinct PUT processing module? One might try to claim that the right hemisphere merely fails when it is confronted with "harder" tasks. That is, the letter task and animal–ears judgment task may simply be more difficult than the animal-size comparison task. This argument was, however, the motivation for Experiment 7, Task 2. In this experiment we used a higher-than-wide judgment, which was quite difficult for the stimuli tested. Indeed, the left hemisphere performed more poorly on this task than on any of the others. Nevertheless, the right hemisphere was as good as the left, as predicted by the claim that it had a selective deficit in performing imagery tasks requiring the integration of parts (no separate parts need be composed together to perform this task).

Taking another tack, one could argue that the right hemisphere of J.W. has a "visual deficit" because of the right temporal lobe locus of his original EEG abnormality. However, J.W.'s right hemisphere has been shown to be better than his left at some visual tasks, such as the recognition of faces (Gazzaniga & Smylie, 1983; see also the results from the perceptual conditions in Experiments 5 and 7 of the present article). In addition, V.P.'s initial imagery deficit cannot be attributed to right-hemisphere dysfunction; the initial focus of her abnormal EEG activity was on the left side.

One could also argue that J.W.'s deficit, and V.P.'s initial deficit, merely indicate that their right hemispheres had vague images. However, "vague" is ambiguous. On the one hand, it could mean fuzzy. But the right hemisphere was able to make assessments of the relative sizes of very similar-sized objects, and was no worse at examining an image of a word—relative to the word itself—than was the left hemisphere. On the other hand, "vague" could mean lacking in details. This is, of course, our point: The right hemisphere is deficient in the processing necessary to add details to an image. Our theory of processing modules quite naturally allows for a dissociation between detailed and undetailed images, because of the existence of a separate PUT module. Although we cannot claim that there is no conceivable way to account for a dissociation between detailed and undetailed image generation other than by using our theory, to our knowledge no alternatives have been proposed. Thus, our findings do not rule out alternative models (because there are not any), but we have found a previously unexpected dissociation that is consistent with a prediction of the theory—and therefore can be taken as empirical support for it.

The results supporting the psychological reality of the PUT processing module are appealing in part because they suggest a previously unconsidered connection between visual imagery and visual perception. Consider a basic aspect of the problem of recognizing objects in perception: many objects are subject to nonrigid transformations. For example, a person can hold up both arms, squat, stand on one leg, and so on. One of the only invariants in the shape are the topological relations among parts, what is connected to what and what is inside or outside of what. This sort of relation is abstract; "connectivity" per se cannot be represented in an image (either perceptual or mental). Rather, a description of the relations among parts would seem to be necessary in order to represent a prototypical object. Thus, it is of interest that just this sort of representation seems to be used when one generates images of (presumably) prototypical forms.

This notion introduces a puzzle, however: the right hemisphere is—if anything—better than the left in visual recognition. How can this be if descriptions are primarily left-hemisphere based and are used to relate parts together? There would seem to be two kinds of answers: First, in most cases where the right hemisphere is better, the stimuli are individual faces or objects, not members of classes of objects. Abstracting out a prototype will not be helpful in recognizing an individual case. Rather, one may want to remember the particular exemplars just as they appeared, nonrigid distortions and all. And this sort of memory may be best carried out by the right hemisphere. Second, most objects can be recognized simply by identifying their parts, ignoring the relationships among them. Indeed, letters of the alphabet are one of the few classes of patterns where the precise spatial relations among parts are important in identifying members of a category (i.e., letter), which may be why the left hemisphere is better at recognizing letters.

When we leave the relatively abstract level of description of processing modules, and turn to the specifics of the mechanisms that underlie the modules, the results from V.P. are intriguing: Her right hemisphere acquired the ability to generate images of letters with practice, but the effects of practice did not generalize to the imaging of other letters. This result does not fit in neatly with the Kosslyn and Shwartz theory, nor, indeed, with the standard form of cognitive information-processing theories in general. In such theories, processes, such as are carried out by the PICTURE, PUT, and FIND modules, are akin to distinct subroutines. However, improvement or damage to a subroutine should make itself evident whenever that subroutine is used, which was not the case here. Some sort of representation-specific processing seems more compatible with the data, but the details of such a model are yet to be developed.

In conclusion, two general points have been driven home by the results of the experiments reported in this article. First, imagery is not a simple event and it does not take place entirely within a single part of the brain. Attempts to localize the imagery system, as an undifferentiated whole, to one neural locus have not been successful (see Erlichman & Barrett, 1983). More recent attempts to bring order to the effects of brain damage on visual imagery have been more successful by breaking imagery down into component imagery abilities, such as image generation (see Farah, 1984). In this article we demonstrate the usefulness of a still more fine-grained analysis, taking seriously the notion of "natural computation" (Marr, 1982). Using a theory of imagery that was developed on the basis of behavioral data from normal subjects and computational constraints, we looked for functional dissociations among processing modules posited by the theory. The discovery of such dissociations suggests that the theoretical analysis is in fact a description of how functions are actually organized in the brain.

The second general point made by our results is that neuropsychological data can be useful in testing and developing computational theories. In particular, the modular composition of such theories can be tested by looking for evidence of dissociations among the modules in the behavior of subjects who have had brain damage (including brain bisection). In addition, some characteristics of the natural computations underlying our cognitive processes may be more obvious through neuropsychological investigation than through the traditional cognitive methodologies. This observation was brought home in the present article by the apparent failure of the "subroutine" theory of the mechanisms to explain V.P.'s ability to generate images with practice. Neuropsychological data clearly can do more than simply provide a way of testing computational theories: they can provide the motivation for formulating and developing such theories.

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