

## OBSERVATION

# Unexceptional Spatial Memory in an Exceptional Memorist

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Rajan Mahadevan evidences an exceptional memory for arrays of digits. We tested whether Rajan's spatial memory was likewise exceptional. Eight control Ss and Rajan were instructed to remember the position and orientation of 48 images of common objects shown either to the left or the right of fixation and facing either left or right. Rajan's accuracy for judging whether the position and orientation of these pictures had changed when they were shown in a different sequence was lower than that of control Ss for both judgments. Rajan's exceptional memory capacity apparently does not extend to spatial relations.

Rajan S. Mahadevan has demonstrated an exceptional capacity for memorizing digits (Fox, 1989, 1990; Thompson et al., 1991). In the mid 1980s he was listed in the Guinness Book of World Records (McWhirter, 1983) for reciting pi to 31,811 places. Rajan was first tested in the United States by Fox and others at the University of Minnesota for a brief period during 1980. Since 1988, Rajan has been participating in studies of his exceptional memory both at Kansas State University (where he is a graduate student in psychology) and, on occasion, at the University of Minnesota. An extensive background description of Rajan can be obtained from Thompson et al. (1991). On a number of tasks, Rajan rivals or surpasses S (Luria, 1968) and VP (Hunt & Love, 1972) but appears to differ qualitatively in the manner in which he achieves his capacity for recall (Fox, 1989; Thompson et al., 1991). For example, unlike S, Rajan does not appear to use visual imagery.

In general, the Fox (1989, 1990) and Thompson et al. (1991) reports document Rajan's impressive memory for novel arrays of digits. Rajan revealed virtually no forgetting on matrices up to  $20 \times 20$  digits, which he learned quickly and recited quickly, in relation to controls (who can only be tested on smaller sized matrices). With nondigit verbal materials, his advantage over controls is generally small or non-existent in relation to his extraordinary performance with digits. Fox (1990) noted the striking variability of Rajan's memory on tasks that did not involve numerical information. On a nonverbal complex figure recall test (the Rey-Osterrieth Complex Figure Test), Rajan's performance was equivalent to those of control subjects (Thompson et al., 1991).

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At the University of Minnesota, Rajan provided a brief demonstration of his abilities with a 5 row by 10 column matrix (50 items). The matrix was written on the chalk board, and Rajan studied it for approximately 3 min, during which he repeatedly looked at the board and then looked away, as if he were testing himself. He was then able to recall this matrix perfectly, and on request he could recall selected rows, columns, and quadrants, in forward or backward order. There was clearly some additional processing occurring when he recalled items in novel orders or by selected columns in that his performance was slower than when he proceeded through the matrix by rows, left to right, top to bottom. He was readily able to recall the matrix months later.

How Rajan memorizes digits is not clear. He says that he just concentrates on one digit at a time, using no mnemonics or imagery. (Of course, attending to individual digits does not specify their order.) That a general capacity for memory of sequences does not underlie his talent is evidenced by his modest performance on nondigit material. Another representational system that could support sequential reproduction is, of course, spatial memory. Although Rajan says that he does not use visual imagery in performing these tasks and he is slower in recalling matrices in arbitrary orders (e.g., top to bottom or left to right), these phenomena do not necessarily rule out a spatial representation for at least part of his performance. There is evidence that people who do not report using imagery perform in a manner similar to those who do report imagery on visualization tasks (Clark, 1969). Moreover, Rajan's preference for having the digits presented aloud rather than visually is consistent with Brooks's (1968) demonstration of a suppression of visualization by a concurrent reading task.

If Rajan did reveal exceptional spatial memory, it would still remain to be determined why his exceptional performance is limited to digits. Although this issue is beyond the scope of this investigation, there are some neuropsychological observations suggesting that digits may be represented at different cortical sites than those for the representation of words written in an alphabet. Damage to certain cortical loci can produce the phenomenon of *number sparing* in aphasia, in which the individual loses the ability to read words but can still name numbers (Sasanuma & Monoi, 1975). For Japanese readers, who can suffer from selective neurological impairment in

reading either Kana (the alphabetic writing system) or Kanji (the logographic writing system), number sparing is typically associated with a retention in the ability to read Kanji (Sasanuma & Monoi, 1975). This observation is consistent with the idea that numbers are similar to logographs in that they cannot be read through the application of a general grapheme-to-phoneme correspondence system and that they are processed in a manner more related to pictures than to words (Besner & Coltheart, 1979; Biederman & Tsao, 1979).

### Spatial Memory: General Theoretical Background

In the past decade evidence has accumulated, primarily from research on primates, that there may be two major cortical visual systems emanating from the primary visual projection area, V1 (Mishkin & Appenzeller, 1987; Ungerleider & Mishkin, 1982). One system, extending ventrally from V1 to V2 to V4 to the inferior temporal region (IT), is believed to subservise object recognition. The other, extending dorsally from V1 to the posterior parietal region (PP), has been identified with the location of objects in the visual field. Removal of IT results in a loss of match-to-sample accuracy; removal of PP results in an inability to use a spatial cue. Mishkin and Appenzeller referred to the dorsal and ventral pathways as the *what* and *where* systems, respectively.

Biederman and Cooper (in press-b) proposed a computational justification for why such different systems would have evolved. In doing so, they refined the earlier functional characterization of the two pathways. They argued that the ventral system subserves shape for the purposes of classification. It would be desirable for such representations to be invariant with respect to translation, size, and orientation (in depth) so that a different representation need not be required for each possible position, size, and orientation in which an object might be encountered. In contrast, the dorsal system represents not only the location of objects in the visual field but, more generally, shape for purposes of motor interaction (including navigation). The attributes that should be ignored for recognition, namely, position, size, and orientation of an object, are critical for motor interaction. Consistent with this characterization (see also Goodale & Milner, in press) is the finding that damage to the posterior parietal region adversely affects motor interaction without affecting object recognition, but the reverse syndrome results from damage to the ventral pathway (Goodale, Milner, Jakobson, & Carey, 1991; Perenin & Vighetto, 1988).

Biederman and Cooper (in press-b) suggested a behavioral means for assessing the functioning of the two systems. The magnitude of visual priming on the latency and accuracy of naming briefly presented object pictures was shown to be unaffected by a change in the position (left-right or upper-lower), mirror reflection, size, and orientation in depth (up to parts occlusion; Gerhardstein & Biederman, 1991) of the picture from the first to a second presentation several minutes later (Biederman & Cooper, 1991, in press-a, in press-b).

In contrast to the results with object naming, the latency and accuracy of episodic recognition, in which the subject judged whether a given shaped object had been presented on the first block, suffered markedly from a change in the size of the image (Biederman & Cooper, in press-b) or its position or orientation (Cooper & Biederman, 1991), even though sub-

jects had been instructed to ignore changes in size, position, and orientation in depth.

Biederman and Cooper (in press-b) argued that the naming task provided a relatively direct measure of ventral system functioning (with allowance for the additional time required to select and produce a response). The episodic recognition task was performed on the basis of feelings of familiarity, which were affected by both dorsal and ventral systems. A change in the size, position, or orientation of a previously presented shape reduced the feeling of familiarity associated with that shape. In general, the memory of the position, size, or orientation of the shape is presumed to be a function of the dorsal system. Thus a change in the position or orientation of a picture on its second presentation was readily detected in an explicit memory test for those changes, but the identical changes failed to produce any effect on visual priming (Biederman & Cooper, in press-a).

It was this explicit test of memory for a picture's position and orientation that we used in testing Rajan's spatial memory. At first it might seem that our spatial memory test would be assessing essentially the same behaviors as the Rey-Osterrieth Complex Figure Test (Rey, 1942; Osterrieth, 1944). Thompson et al. (1991) did assess Rajan's performance on this latter test. In the Thompson et al. study, subjects copied a complex figure and then reproduced it 30 min and 48 hr later. When copying the figure, the subjects knew that they were going to be asked to recall it. For scoring, each figure was regarded as being composed of 18 units, or pieces. The accuracy of reproduction of each unit as well as the accuracy of locating each unit within the figure determined the score. On this accuracy measure, as well as in his production times, Rajan's performance was approximately equal to the means of the controls.

The Rey-Osterrieth test, although it has not been extensively studied, would appear primarily to assess memory for the shape of an object (presumably a ventral system function) rather than viewer-centered relations concerning the location and the left-right orientation of objects in the visual field (presumably a dorsal system function). In the absence of other constraints, if Rajan did depart from the control subjects, it would not be obvious whether his performance would be better or worse than that of the controls. If his memory for numbers was an outgrowth of dorsal system functioning, then his performance would be expected to be superior to that of the controls. Alternatively, if his capacity was at the expense of dorsal system functioning, then his performance should be inferior, assuming, of course, that our test assessed dorsal functioning.

We had some anticipation that the latter outcome would obtain. This expectation was not based on theory but on the observation of Paul W. Fox: In Rajan's 10 years of visiting Elliott Hall, where Fox tested him during a number of 2- or 3-day visits, Rajan revealed consistent spatial confusion as to the locations of the laboratories, faculty offices, bathroom, and other such places.<sup>1</sup>

<sup>1</sup> In fairness to Rajan, we should point out that Elliott Hall, with its various interconnected sections, poses a bit of a challenge to its spatial mastery, though most people appear to learn the layout well within the time frame afforded Rajan.

## Method

### Subjects

The 8 control subjects' performance, against which Rajan's performance was evaluated, were, like Rajan, graduate students in psychology (although at the University of Minnesota rather than Kansas State University). All were native English speakers with normal or corrected-to-normal vision who performed a version of Experiment 3 of Biederman and Cooper (in press-a). They participated for payment (\$5 per session).

### Stimuli and Procedure

Each subject viewed 48 briefly presented (150 ms) pictures of objects in each of two blocks of trials. Each picture was a simple line drawing of a common object with a readily available basic level name. The pictures were created through Cricket Draw (Cricket Software, Malvern, PA) and shown on a high-resolution (1024 × 768) monitor (Mitsubishi Model HL6605) controlled by a Macintosh II.

The subject pressed a mouse button to start each trial. A central fixation dot would then be presented for 500 ms, followed by the 150-ms presentation of the object picture (a duration too brief to make a second eye fixation). The picture was, in turn, followed by a 500-ms mask, a random-appearing arrangement of straight and curved lines. The images were centered 2.4° to the left or to the right of fixation. The maximum extent of each image could be contained in a circle the diameter of which subtended a visual angle of 4°, so the closest possible point of any picture was 0.4° from fixation.

The positions (left or right) and orientations (facing left or facing right) were presented in random sequence (subject to constraints for balancing positions) so that the subject could not accurately anticipate the position or orientation of the image. The subjects had also been instructed to maintain fixation, which was undoubtedly facilitated by the natural tendency of visual capture by the presentation of the fixation point 500 ms prior to the presentation of the picture.

Prior to the first block, the subject was instructed to look at the picture and to try to remember its position and orientation. (In Experiment 3 of Biederman & Cooper, in press-a, subjects were not instructed to expect a subsequent memory test.) On the second block a given picture could appear either in the same position it held on the first block or on the other side of fixation. For each position type (same or different), half the images were in their original orientation, and the other half were in mirror-image reversed orientation. Thus on the second block, one quarter of the objects viewed by each subject were in one of the four position and orientation conditions. The sequences of images were balanced across the 8 control subjects so that the mean serial position of every object in every condition of position and orientation was equal, with all objects appearing equally often in the four conditions of position and orientation variation. For each object, left and right positions and orientations were also balanced across subjects. Approximately 7 min intervened between the first and second presentations of an object.

On the second block of trials the subjects had to judge whether the position and orientation of each object were the same or different from what they were on the first block. After they saw each image on the second trial block, subjects made two verbal judgments as to whether the object's position and left-right orientation were the same as or different from those on the first block. Object presentation in both blocks was subject paced.

### Second Testing

Ten weeks later, Rajan was again trained and tested with the same set of pictures, although their order, positions, and orientations were randomized from what he had viewed the first time he performed the task. On this occasion he was encouraged to take his time and to use

any strategy that would help him perform the task. Two graduate students were subsequently trained and tested with the strategy devised by Rajan. As a follow-up test, in a telephone conversation with Fox 22 weeks later, Rajan was asked to recall the object names.

## Results

### First Testing

The accuracy of these judgments for the control subjects was well above the 50% level expected by chance. Mean percentage correct for the controls was 83.8% for position judgments and 71.0% correct for orientation judgments ( $p < .001$  for both judgments). The accuracy of Rajan's judgments was considerably lower than was that for the control subjects. Rajan was correct on 72.9% of his position judgments and 62.5% of his orientation judgments. In fact, his position score was lowest of the 8 participants in this experiment. A single sample  $t$  test revealed that the difference between Rajan and the mean of controls for position was significant,  $t(7) = 4.65$ ,  $p < .005$ , and the difference for orientation was just short of significance,  $t(7) = 2.21$ ,  $p < .07$ .

Caution is warranted in assessing Rajan's abilities in relation to the abilities of the controls in that it is possible that differences in performance between Rajan and controls (in any experiment) could represent population differences. In particular, University of Minnesota graduate students performed our spatial memory task, and Kansas State University undergraduates performed the Rey-Osterrieth test in the study by Thompson et al. (1991).

Minnesota undergraduates were the subjects in Experiment 3 of Biederman and Cooper (in press-a), who used the same stimuli and presentation conditions used in the current experiment. However, the Block 1 task in that experiment was one in which the subjects were merely instructed to name the pictures as quickly as possible. They were not instructed, nor did they have any reason to believe, that a subsequent test of recognition memory for position and orientation was going to be provided. These subjects performed more similarly to Rajan: Position was judged correctly on 70% of the trials (vs. 72.9% for Rajan), and orientation was correct on 59.6% of the trials (vs. 62.5% for Rajan).

We suspect that most of the differences between the two sets of controls likely represent instructional differences, and Rajan's spatial memory is below what would be expected of someone with his intelligence.

### Second Testing

Rajan was 100% correct on position but only 41.6% correct on orientation. He adopted a strategy in which he looked only at the pictures to the left of fixation. After each image on the left, he would pause for a considerable period of time—between 10 and 30 s (by informal estimate of the experimenter). If the image was on the right, he would immediately press the mouse key to go on to the next image. When it was announced during the interval between the two blocks that the testing phase would begin, he said "just a minute" and proceeded to rock back and forth in his chair—a behavior he illustrates when he rehearses—for 1 or 2 min. Using Rajan's strategy of only looking at the pictures in the left hemifield,

the 2 graduate students achieved 97.9% and 91.7% accuracy on position and 60.4% and 56.2% accuracy on orientation. The combined position and orientation scores of each of the graduate students were thus above those of Rajan's. Moreover, these students only took 3 or 4 s after each picture on the left and did not rehearse during the interval between blocks.

In the subsequent follow-up test, Rajan was able to recall the names of 12 of the 48 objects which he thought had appeared in the experiment approximately 5 months before. Of these 12 objects, 6 were on the left side of the screen during presentation, 4 were on the right, and 2 of the objects he recalled were not present in the experiment at all. Rajan reported that to aid his recall during the follow-up test, he used common objects around him as cues (thus, perhaps, explaining his erroneous recall of 2 objects not present in the experiment). Rajan's poor memory for the objects used in the study is striking given that his retention of digit stimuli is extremely persistent. He typically can recall digit matrices a year or more after their initial study (e.g., Fox, 1990).

### General Discussion

Memory for position and orientation is much closer to the kinds of viewer-centered spatial memory presumed to be localized in the dorsal visual system than the object-centered relations assessed by the Rey-Osterrieth Complex Figure Test. Although Rajan was average on the Rey-Osterrieth test, his performance was noticeably and reliably lower than that of the control subjects on our viewer-centered spatial memory test for left-right position and orientation of object pictures. Perhaps his sensitivity to his own lack of ability to store viewer-centered relations was his opting to circumvent spatial memory in his second testing by using an item rehearsal strategy for the pictures on one side and ignoring the other side. If a picture was familiar, he could infer that it was on the left side. If the picture was not familiar, then it must have been presented on the right. This strategy allowed him to be perfect on position but could not yield encoding of orientation (for which he performed at chance). The difference in Rajan's performance on the Rey-Osterrieth test and our spatial tests is suggestive of the dissociation between storage of object-centered and viewer-centered relations suggested by Biederman and Cooper (in press-b).

Our results are consistent with, but by no means prove, the hypothesis that Rajan's remarkable abilities with digit memory may be at the expense of an apparent reduced capacity for spatial memory. It is an open question as to whether the striking difference in Rajan's memory for digits in comparison with his memory for other types of nonspatial materials, such as words, is related to the phenomenon of number sparing described in the introduction. More generally, these results are consistent with the variability of memory viewpoint expressed by Fox (1990) and with the proposition that spatial memory may be subserved by a system that works independently of the memory for other kinds of information.

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