

following way. During active exploration, participants studied novel, three-dimensional objects (see Figure 1) by rotating the objects on a computer screen by means of a track ball. The objects could be rotated 360° about any axis. During passive observation, each participant viewed recorded rotations of objects that had been carried out by the preceding participant. Later recognition was tested with an explicit old-new task in which participants had to indicate for every test object whether or not they had seen it before (Harman et al., 1999). Participants were faster at making this decision with objects that they had actively explored as compared with those they had viewed passively.

We speculated that active control allowed participants to test predictions about how changes in viewpoint might affect the appearance of the object. That is, participants could “hypothesize” about how an object might look from different views and then store the trajectories that link one view to another. Although this kind of strategy might also work with passive observation, we argued that the links between views might be stored more effectively when the participants rotated the object from one view to another.

There could be another factor at work as well. It is possible that when the different views are stored under active exploration, later access to those views is accomplished by transforming an internal representation in much the same way as the real object was transformed on the computer screen. In other words, active exploration could make it easier to carry out “mental rotation” of stored object representations. The idea that motor processes and mental rotation are tightly linked has been proposed before. For example, Wolhslager and Wolhslager (1998) showed that “manipulations” of mental representations of visual stimuli can be equated with actual manipulations of visual stimuli. In their research Wolhslager and Wolhslager used a mental rotation task modeled after that originally used by Shepard and Metzler (1971). In such a task, participants are required to decide if a given object is the same as a rotated version of itself or not (for review see Shepard & Cooper, 1982). During this task, response times increase as a function of the angular difference between the two objects. Wolhslager and Wolhslager found that if participants physically rotated one object to match it to the other during their decision, response times increased at the same rate as they do in mental rotation (Wohlslager & Wohlslager, 1998). In addition, when translational hand movements were performed during the mental rotation task, these actions interfered with mental rotation – but only if the hand movements were along a different axis from that required during the mental rotation task. Wexler, Kosslyn, and Berthoz (1998) have also provided evi-

dence that motor processes influence transformations of mental representations. In their studies, they required participants to perform a typical mental rotation task using Shepard-Metzler figures while at the same time executing an unseen motor rotation with the hand. They found that motor rotation that was in the same direction as the required mental rotation resulted in faster response times for the mental rotation task than motor rotation in the opposite direction. In addition, they found that the speed of the motor rotation also affected the ease with which participants could perform the mental rotation task (Wexler et al., 1998). These researchers concluded that motor processes are not simply an end product of cognitive processes, but may be an integral part of cognitive operations in general.

Experiment 1

This evidence suggests that motor programs are invoked during the performance of tasks requiring mental rotation. It is not clear, however, whether or not the motor processes invoked during the encoding of an object representation can aid mental rotation at a later time. It was this question that motivated the present study. In other words, we investigated whether or not active exploration of a three-dimensional object would facilitate performance in a subsequent “perceptual match” task that is thought to involve mental rotation. In addition, the use of a perceptual match task provided a measure of how previous experience with an object affects performance without the need to recall specific encounters with that object. Finally, we attempted to replicate an earlier finding showing that participants explored objects in a somewhat stereotyped way, focusing their attention on particular views.

METHOD

Participants. Twenty-four right-handed students volunteered to participate in the present experiment, and were given course credit for their participation. =rir atHpresc
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DISCUSSION

When participants studied novel three-dimensional objects actively by rotating them on a computer screen, they performed faster on a later perceptual matching task with the same objects than they did with objects they had simply studied passively. This result replicates our earlier findings using a related paradigm (Harman et al., 1999), but suggests further that encoding an object via active exploration can facilitate performance on a task that is thought to involve mental rotation. The facilitation observed in the present experiment was evident, however, only when the test stimuli were 90° apart.

The difference in performance on the more difficult match task following active exploration vs. passive viewing could have occurred for two reasons. One possibility is that because the angular difference between the side view and the front views of an object was relatively large, the “mental rotation” necessary to match the two views was more demanding. But if the participants had the experience of physically rotating the same object (in the active exploration condition), then this experience could have facilitated a later mental rotation between the relevant views. Certainly, there is evidence that mental rotation might involve some of the same neural machinery as actual physical rotation (Wexler et al., 1998). In short, the early active rotation of the object could have “primed” the later mental rotation.

But there is a second possibility as well. Perhaps the particular views of the objects to be matched were both recognized more readily after active exploration than after passive viewing – and as a consequence were associated more readily with the same object representation. Our earlier report showed that both side and front views of objects were certainly recognized more quickly after active exploration than after passive viewing, whereas for the three-quarter view of the object that was most similar to the one used in the present experiment there was no effect of study condition on recognition latency (Harman et al., 1999). Thus, rather than facilitating mental rotation from one view to another, the active exploration condition may have created stronger associations between some sort of object template and different views of that same object.

Of course, these two explanations are not mutually exclusive. It could be the case that mental rotation is enhanced by virtue of the fact that different views of the object are “linked” more efficiently when the objects are actively rotated from one view to another. Mental rotation then would re-activate the same links between that which had been set up earlier when the object had been physically rotated. The participants who simply looked at the object rotation passively

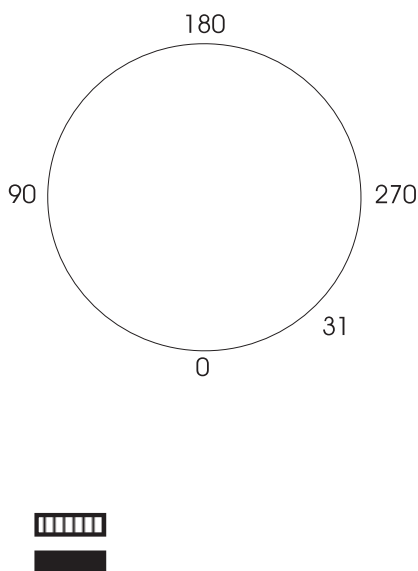
would not have had this opportunity to set up these links. This idea is reminiscent of an earlier proposal about mental rotation put forward by Edelman and Weinshall (1991).

The idea that the front and side views of the object might be directly linked by active exploration is reinforced by patterns of exploration exhibited by the participants. In both the present experiment and the earlier study, participants spent more time studying the front and side views than they did the intermediate or three-quarter views. All of this begs the question as to why participants used this particular strategy; in other words, why did they spend more time exploring the “plan” views than they did the intermediate views? As a first step towards answering this question we carried out another experiment.

Experiment 2

Perrett and his colleagues (1992) have proposed that when observers explore objects they concentrate on “plan” views, like the front and side views, because these views are “unstable” and can be thought of as singularities in the viewing space of an object. In other words, these are the views where there is the greatest amount of change in the visibility of the object features as the object is rotated by a small amount. Inspection strategies that concentrate on such views might facilitate the encoding of the object’s three-dimensional structure. We can see now why observers would not dwell on any particular intermediate views. The intermediate views are all perceptually similar: all the major features of the objects are visible over a wide range of image projections. Thus, observers do not need to concentrate on one particular intermediate angle because of the high similarity among many of the successive images. This might explain why, in the present experiment and our earlier study, the participants deviated only a little from side to side when exploring a plan view; larger excursions would not have produced much more information than was already available.

Perrett and his colleagues (1988; Harries, Perrett, & Lavender, 1991) tested whether or not preferential inspection of the plan views of three-dimensional objects correlates with later recognition. They found that even though participants inspected plan views more than intermediate views, the amount of time spent on these views did not predict later performance on a test of recognition. But in these experiments, the emphasis was on how people inspected objects rather than on how different inspection strategies would affect later recognition. In our previous study, we also found no correlation between the time spent inspecting the plan views and the reaction time in the recognition test (Harman et al., 1999), but again the experiment was



not designed to pull out the effects of inspection strategies on later recognition. Rather than relying on individual differences in the time spent on particular views to explore the relationship between viewing strategies and later recognition, we decided to examine quite directly whether or not limiting the availability of particular views would affect later recognition of the objects. In Experiment 2 then, we limited the views that participants were able to explore to either only plan views or only intermediate views of the study objects. We then tested their recognition of both plan and intermediate views of these objects.

METHOD

Participants. Participants were 24 undergraduate students (16 females, 8 males) who participated for course credit. Ages ranged from 18 to 28 with a mean age of 20. All participants reported normal or corrected-to-normal visual acuity and were naïve to the research design and to the appearance of the objects.

Materials. The stimuli used in the present experiment were the same three-dimensional images that were used in our previous studies. The experimental equipment and setup were identical to those used in

Experiment 1. In this experiment, however, the views that participants studied were limited. For half of the study objects, participants moved the objects on a computer screen around the vertical axis only and were able to explore only the intermediate views of the objects. For the other half of the objects, participants again rotated the objects about the vertical axis, but were able to explore only the plan views of the objects. The plan views were the 0°, 90°, 180°, and the 270° views (see Figure 6); however, we allowed 10° of movement around each of these views. Therefore, the visible angles became 350-10°, 80-100°, 170-190°, and 260-280°. When exploring the objects' intermediate views (see Figure 6), participants were able to explore views between 35-55°, 125-145°, 215-235°, and 305-320°. When the end of any range of movement was exceeded, the view of the object "jumped" to the closer angle of the neighbouring range. Image size and virtual lighting were the same as those used in Experiment 1. The plan and intermediate views study sessions were blocked and their order of presentation was counter-balanced, but stimuli within each block were presented in a different random order for each participant.

The test stimuli were four static views, each presented in isolation, of all 20 previously studied or "old" objects and four static views of 20 distracter or "new" objects. The four test angles in both cases were a front (0°) view, a side (90°) view, and two intermediate views, a 45° and a 225° view. Therefore, a total of 160 test images were presented in random order. Again, image size and virtual lighting were the same as those used in Experiment 1. Thus, for the objects that were studied by rotating to the plan views, the front and side test views were studied, but the two intermediate test views were not studied. Conversely, for the objects that were studied by rotating to the intermediate views, the two intermediate test views were studied, and the front and side test views were not studied.

Procedure. After instructions and a practice session, participants were presented with the first object to explore. Depending on the condition, participants would rotate either the plan-view objects in the first block, or the intermediate-view objects in the first block. Participants were able to rotate each object about the vertical axis for 20 s. After a 5-s intertrial interval, a new exploration trial was begun. Note that all objects were studied actively; there was no passive observation condition in the present study. There was no break between the two blocks, and participants were not told that the viewing conditions differed. After studying all 20 objects, the test session began.

During the test session, an image of an object would appear and participants were required to decide

whether or not they had seen the object during the study session. They indicated their “old-new” decision by pressing one of two keys on a keyboard. Following their response, a fixation-cross appeared for 500 ms followed by the next test image. An image remained on the screen until participants made a response. Participants were instructed to respond as quickly and accurately as possible.

RESULTS

Two separate 2 X 4 (Exploration Condition: plan views or intermediate views and Test Angle: front, side, intermediate front, and intermediate back) repeated-measures ANOVAs were run on the resultant data, one for response latency scores and one for accuracy scores. Data from one participant was removed because he scored less than 60% in total correct decisions.

Response latency. The ANOVA revealed a significant main effect of Exploration Condition. Objects whose exploration had been limited to plan views were recognized faster than objects whose exploration had been limited to intermediate views, $F(1,22) = 8.78$, $p < .01$ (Figure 7). There was no main effect of test angle, nor was there an interaction between Exploration Condition and Test Angle.

Accuracy. The overall mean accuracy was 70.7%. There were no significant effects of Exploration Condition or Test Angle on accuracy. Sensitivity (d') was also calculated and found to be not significantly different for the two study groups.

DISCUSSION

By limiting the views of objects that participants could explore, we were able to demonstrate that studying only plan views of objects results in better learning

than studying only intermediate views. Thus, when participants studied the plan views of objects they showed faster recognition of test objects than they did when they studied intermediate views of objects. This difference was found with all test views of the objects – no matter whether those test views were plan views or intermediate views, as reflected by the lack of interaction between study condition and test view (see Figure 7). In other words, studying only the plan views of an object appears to lead to a better representation of the three-dimensional structure of the object than does studying only the intermediate views.

As we discussed earlier, Perrett and his colleagues (1988, 1992) have proposed that the reason observers concentrate on “plan” views is because these views offer the greatest amount of change in the visibility of the object features as the object is rotated by a small amount. Inspection strategies that concentrate on such views would be important in the encoding of these particular views. In contrast, moving around the intermediate views would provide little new information about object features. The results of the present study support Perrett’s conjecture and show that this “natural” viewing strategy is an efficient way of encoding the important object features. In other words, when viewing is artificially limited to the plan views, observers perform better on later discrimination tasks.

General Discussion

The results of Experiment 1 again show, like our earlier study (Harman et al., 1999), that active exploration of novel objects leads to better performance on later tests of object recognition. But Experiment 1 is the first study to demonstrate that active exploration can improve performance on a task thought to involve “mental rotation” of object representations. This perhaps is not surprising given recent research suggesting that mental rotation may involve motor processes (Wexler et al., 1998; Wohlshlager & Wohlshlager, 1998). Our results, however, extend this idea of a motor theory of mental rotation by suggesting that earlier experience manipulating objects that one is actually viewing may facilitate later mental rotation of representations of the objects in the “mind’s eye.”

These findings may have important implications for

classic paper on “active touch” (Gibson, 1962). The present study underscores Gibson’s original notion but shows that active control over the different views of an object that one is learning about can also improve later recognition. Thus, with the development of computer-based virtual displays of organic molecules, anatomical structures, architectural models, and other complex three-dimensional forms used for training and education, it might be useful to allow the student to control the rotation of these objects on the computer screen. Indeed, it has been claimed, albeit anecdotally, that having control over the way in which a four-dimensional object, such as a hypercube, is presented in a three-dimensional display allows a mathematician to develop a strong intuition about the structure of the hypercube (Davis & Hersh, 1981; Kellert, 1994).

The results of Experiment 2 show that the exploration strategies used by observers to study novel objects (i.e., concentrating on the plan views) in fact leads to better learning. When participants were limited to exploring only certain views of novel objects, they did better on later tests of recognition for objects that they had explored around the plan views than for objects that they had explored around the intermediate views. This result supports Perrett’s suggestion that movement around plan views offers the most salient information about object features. But there is an apparent paradox here. One might have predicted, based on the research of Palmer, Rosch, and Chase (1981), that observers would have done better with the intermediate views than with the plan views. After all, there is a large body of research showing that individuals find it easiest to recognize the intermediate or “canonical” views of familiar objects that have a principal axis of elongation (e.g., Humphrey & Jolicoeur, 1993; Palmer et al., 1981; Warrington & Taylor, 1978; for review, see Jolicoeur & Humphrey, 1998). It is important to keep in mind, however, that in all those studies that have shown an advantage with canonical views, common objects have been used and the observers were presumably already familiar with their structure. In Experiment 2 in our study, participants were still learning about the object and their knowledge about the object’s structure was being assembled from either a set of plan views or a set of intermediate views. It appears that having access to the plan views leads to a better representation of the object than having access to only the intermediate views. This perhaps explains why all the studies that have examined the way in which observers explore objects have shown that observers concentrate on the plan views (Harman et al., 1999; Locher, Vos, Stappers, & Overbeeke, 2000; Perrett & Harries, 1988; Perrett et al., 1991, 1992).

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