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Orientation Priming of Novel Shapes in the Context of Viewpoint-Dependent Recognition

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Can visual similarity between shapes facilitate orientation priming? We report five experiments that explored this possibility using novel two-dimensional shapes that formed homogeneous stimulus classes. Following training on individual shapes in a canonical view, we tested the recognition of these shapes in several picture-plane orientations. Experiments 1 and 2 used an identification task to replicate the classic finding obtained with the mirror-judgment task (Cooper & Shepard, 1973) – that prior orientation cueing does not reduce the magnitude of orientation dependence in processing rotated shapes. Experiment 3, however, indicates that blocking trials by orientation is one condition in which orientation priming may be obtained. Experiment 4 builds on this result, suggesting that awareness of the blocking manipulation is not required to obtain orientation priming. Experiment 5 explores the mechanisms underlying this finding, offering evidence that orientation priming is a consequence of representations that encode both shape and orientation. Such results may be considered as an extension to the "image-based" approach to object recognition, demonstrating that generalization across exemplars may occur within recognition mechanisms that are viewpoint dependent.

The study of the perceptual reference frames used in object perception owes much to the pioneering work of R. N. Shepard and his colleagues (for a review, see Shepard & Cooper, 1982). In so-called "mental rotation" tasks, Shepard had subjects judge whether two differently oriented objects were identical or mirror-reversed versions (Shepard & Metzler, 1971) or whether a single misoriented shape was a standard or mirror-reversed version (Cooper & Shepard, 1973). Such studies have repeatedly found that perceivers seem to use viewer-centered processes to make these judgments. Apparently, at least in some tasks, visual object representations include some information about the specific viewpoints or orientations of objects. This point was reinforced by the finding that some viewpoints of familiar objects are more recognizable than others (Palmer, Rosch, & Chase, 1981). Since that time, a host of theories have attempted to extend the viewer-centered framework to a variety of other tasks and conditions – for ease of referral, these may be grouped under the term "image-based" theories (Bülthoff & Edelman, 1992; Bülthoff, Edelman, & Tarr, 1995; Edelman & Weinshall, 1991; Poggio & Edelman, 1990; Tarr, 1995). Such theories posit that orientation, as well as many other properties present in the original image, are encoded in shape representations. With regard to orientation, these theories predict that recognition performance, as measured by response time and/or accuracy, will be dependent on the difference in orientation between the input shape and a stored representation. As an alternative to image-based theories, several researchers have proposed that shape representations do *not* by default encode information about orientation (Biederman, 1987; Cooper & Schacter, 1992; Corballis, 1988; Marr & Nishihara, 1978). The majority of such theories propose that object representations are "structural-descriptions," and that, for many tasks, shapes are represented in an abstract form in which much of the image information has been discarded. In contrast to image-based theories, structural-description theories typically predict that recognition performance, as measured by response time and/or accuracy, will *not* be dependent on the difference in orientation between the input shape and a stored representation of the object (as long as the same structural description is recovered, see Biederman & Gerhardstein, 1993).

Regardless of one's theoretical position on this topic, one unequivocal fact is that empirical studies have yielded both orientation-dependent and orientation-invariant patterns of performance, depending on the type of stimuli, the homogeneity of the targets, the task, etc. (see Tarr & Bülthoff, 1995). Therefore, any comprehensive theory of object recognition should be able to account for and predict both types

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of effects (Jolicoeur, 1990). For instance, proponents of the image-based approach have suggested that orientation-invariant patterns may result from familiarity with an object in multiple orientations (Jolicoeur, 1985; Tarr & Pinker, 1989). In contrast, proponents of the structural-description approach have suggested that orientation-dependent patterns may result from perturbance of top-bottom relations (Hummel & Biederman, 1992) or viewpoint-dependent feature searches (Biederman & Gerhardstein, 1995). In light of the considerable creativity researchers have exhibited in accounting for results that are inconsistent with their theories (Biederman & Gerhardstein, 1995; Tarr & Bülthoff, 1995), perhaps a more effective approach would be to take a phenomenon that has been used as evidence for one class of theories and ask whether it is obtainable in the context of effects predicted by the other class of theories.

In this paper we take such an approach, specifically investigating the possibility of orientation-specific priming that may occur with orientation-dependent recognition. *Orientation priming* occurs when the recognition of a given object at an unfamiliar (or less familiar) viewpoint is facilitated by prior information about the object's orientation. This orientation information may be as abstract as an arrow (Cooper & Shepard, 1973) or as specific as a different object presented at the same orientation as the target (Koriat & Norman, 1985, 1988). *Orientation-dependent recognition* generally describes performance that is impaired at unfamiliar viewpoints relative to familiar ones. Orientation priming and orientation-dependent recognition are typically held to be incompatible in that the latter assumes orientation-specific object representations, but evidence for the former suggests that orientation and shape information are encoded separately. Thus, orientation priming is often cited as evidence for orientation-invariant object recognition mechanisms (Murray, Jolicoeur, McMullen, & Ingleton, 1993).

Lending support to the orientation-invariant approach, some studies have found that diminished effects of orientation due to practice with one or more rotated objects can transfer to other objects not seen previously at practiced orientations (Jolicoeur & Milliken, 1989; Murray et al., 1993). One difficulty in interpreting such results is that there are no specific manipulations in these studies to indicate whether the representations mediating orientation priming are orientation invariant or orientation dependent. Rather it is simply *assumed* that orientation-specific image-based representations could not support such performance (e.g., Biederman & Gerhardstein, 1993, 1995; Jolicoeur & Milliken, 1989; Murray et al., 1993). However, recent extensions to the image-based approach may accommodate orientation-specific generalization between shapes (Beymer & Poggio, 1996; Edelman, 1995b; Lando & Edelman, 1995; Librande, 1992; Moses, Ullman, & Edelman, 1996), although behavioral evidence for this type of generalization has not yet been offered. Thus, the explanatory power of the image-based approach would benefit from a demonstration of orientation priming in the context of orientation-dependent recognition.

One possible mechanism for orientation priming involves the rotation of an abstract frame of reference. For instance, given prior information about the orientation of an incoming stimulus, an abstract reference frame may be reoriented to the expected orientation of the input. Shape representations from memory could then be projected into this reference frame and thereby be pre-aligned with the input shape, allowing a comparison independent of the input orientation. In an early investigation of this possibility, Cooper and Shepard (1973) found that subjects were apparently unable to rotate abstract frames. Specifically, there was almost no change in the pattern of viewpoint dependency obtained in a mirror-judgment task when subjects were provided with either a cue for orientation or identity. In contrast, given 2,000 ms of preparation time as well as both orientation *and* identity cues, subjects were able to judge whether a shape was a normal or mirror-reversed version in constant time. Such results led Cooper and Shepard to conclude that the visual representations used in mental rotation were specific to both orientation *and* shape and, as such, the two properties were not dissociable. A second implication of these results is that an abstract or "empty" reference frame may *not* be reoriented in making perceptual judgments.

Subsequent work on the dissociability of orientation and shape has raised questions about the generality of Cooper and Shepard's (1973) results. Orientation priming has been demonstrated in several studies using a mirror-judgment task similar to that used by Cooper and Shepard (Hinton & Parsons, 1981; Koriat & Norman, 1985, 1988; Robertson, Palmer, & Gomez, 1987). For example, Hinton and Parsons (1981) found that if subjects were explicitly told to rotate their egocentric frame of reference and informed about how to do so, they were able to prepare for a mirror judgment of a rotated letter. The caveat on this result was that all of the stimuli needed to share a common spatial relationship in their normal version (e.g., the characters F, R, G and L all "face right"). Given prior orientation information and this consistency across stimuli, subjects apparently can prepare for the front of any of these letters to face in the appropriate direction (e.g., the horizontal bars of the F facing downwards). This interpretation may also help explain why other studies using alphanumeric characters have obtained orientation priming (Koriat & Norman, 1985, 1988; Robertson et al., 1987) – particularly, when priming was between sequentially presented stimuli. A second problem with generalizing from Cooper and Shepard's (1973) and other results obtained with the mirror-judgment task is that this task may not be mediated by the same mechanisms/representations as object recognition tasks (Corballis, 1988; Jolicoeur, 1990; Tarr & Pinker, 1989). However, consistent with recent findings of orientation priming in the mirror-judgment task, Jolicoeur (1990) obtained evidence for orientation priming in the recognition of letters – one of the few orientation priming studies that used a recognition task.

There are several problems with using alphanumeric characters as stimuli (as did most studies using the mirror-judgment task, Cooper & Shepard, 1973; Hinton & Parsons, 1981; Robertson et al., 1987): 1) They constitute an overlearned class of stimuli which may not produce reliable orientation effects, especially in recognition tasks (Tarr & Pinker, 1989); 2) Different orientations have different levels of familiarity; and, 3) It has been proposed that humans may possess a specialized brain mechanism for their perception (Farah, 1990). One study that avoided some of these problems was run by Humphreys and Quinlan (1988). They investigated whether orientation cues could facilitate the recognition of simple nonsense shapes and obtained some evidence for orientation priming. The extreme simplicity of the stimuli, squares and triangles, however, led to relatively small effects of orientation regardless of any orientation cueing – therefore, it is difficult to draw any strong conclusions regarding the conditions under which orientation priming may be obtained.

Recent studies have begun to examine the possibility of orientation priming with more complex stimuli. For instance, McMullen, Hamm, and Jolicoeur (1995) conducted a study with common objects. To maximize the likelihood of orientation priming they used a single presentation for each object so as to reduce the effect of practice (which has been found to lead to an overall reduction of orientation effects; Jolicoeur, 1985). They found no evidence for orientation priming – cueing the top or the top-bottom axis of objects did not reduce the effects of misorientation. However, an important difference between this study and all of the mirror-judgment studies showing orientation priming is that the latter used repeated presentations of the same stimulus items. Given that repetition of stimuli may be crucial, using novel shapes may be preferable in that such stimuli, in contrast to common objects, have been repeatedly found to produce reliable orientation effects even with considerable practice (Tarr & Pinker, 1989, 1990). Consistent with this interpretation, the goal of the present study was to investigate the possibility of orientation priming in a shape recognition task using moderately complex *novel* stimuli. Provided that both orientation-dependent recognition and orientation priming are obtained, we wish to explore the mechanisms that may lead to such orientation priming, specifically comparing: 1) The rotation of abstract frames of reference; with, 2) Generalization between image-based orientation-specific representations (Beymer & Poggio, 1996; Edelman, 1995b; Lando & Edelman, 1995; Librande, 1992; Moses et al., 1996). Evidence for the latter would offer an important extension of the image-based approach in that orientation priming has typically been taken as evidence against image-based representations (Biederman & Gerhardstein, 1995; Jolicoeur & Milliken, 1989; Murray et al., 1993).

Experiment 1

Experiment 1 builds on Cooper and Shepard's (1973) classic finding that prior orientation information, in the absence of shape information, does not reduce the orientation effect for a mirror judgment on letters. Here we investigated whether this holds true for the *recognition* of moderately complex novel shapes.

Method

Subjects. Seventeen Yale undergraduates participated in return for course credit. None of the subjects had seen the stimuli prior to the experiment.

Materials. The stimuli, consisting of four target shapes and three distractor shapes (Figure 1), were adapted from the novel "tv-antenna" shapes used by Tarr and Pinker (1989; 1990). All of the shapes shared similar features in different spatial relations, thereby precluding the use of local diagnostic features for recognition. All of the shapes also shared a clearly marked vertical axis and a "foot" which helped to define a canonical orientation (the orientation shown in Figure 1). The initial identification of these novel shapes in unfamiliar orientations has been found to yield reliable performance costs related to the degree of misorientation (Tarr & Pinker, 1989, 1990).

For the learning phase, the stimuli were printed individually on 4x6" sheets of paper and for the testing phase the stimuli were presented black on white on a 13" color monitor connected to an Apple Macintosh LC475 personal computer. Subjects viewed the objects binocularly from a distance of approximately 60 cm from the screen and used a chin rest to keep this distance constant and prevent head rotations. This resulted in images (which were not presented in stereo) that subtended a region of approximately 9.9° x 9.9° of visual angle.

Design and Procedure. The experiment began with a learning phase in which the subjects learned the names of the four target shapes. This was accomplished by having subjects physically trace each target shape five times and repeat the associated name aloud, then having subjects draw named shapes from memory. Subjects were given feedback about drawing errors and they continued to draw the named shapes until they could accurately draw each shape three times without error. This learning phase lasted approximately 15 to 30 minutes.

Following learning the names of the targets, subjects proceeded to the computer-controlled testing phase. In this phase, each subject was given 40 practice trials (10 trials per target shape) in which one of the four target shapes was randomly displayed in the canonical orientation until the subject responded by pressing one of four keys labeled with the target names. Feedback for incorrect responses was provided in the form of a beep. Following this practice, subjects were informed that they would now have to identify each shape,

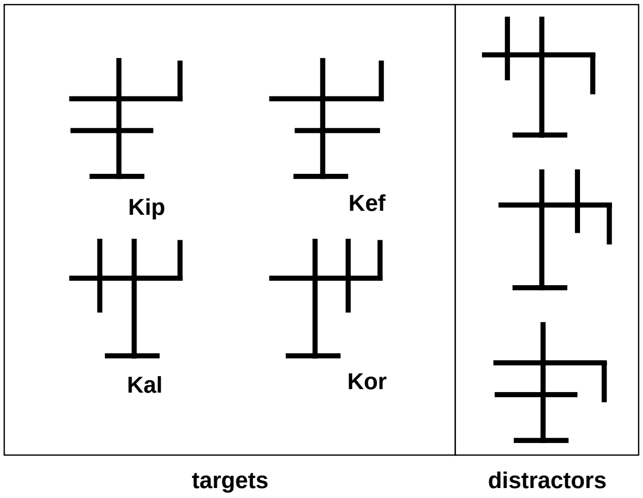

Figure 1. The set of novel objects used in Experiments 1 to 5 in their canonical orientation. Nonsense names were associated with the four target shapes.

disregarding any change in orientation, as quickly and as accurately as possible, as either one of the named target shapes or an unnamed distractor shape (in which case they were to press a key associated with a "none-of-the-above" response). Subjects were also told that on each trial a cue, either a star-like figure or an arrow, would be shown prior to the shape. The star figure was an uninformative cue that provided no information about the orientation of the subsequent shape, while the arrow was an informative cue that provided perfect information about the orientation of the subsequent shape.

Consistent with these instructions, the test trials were of two types: *Orientation-Cued* trials, in which targets were preceded by an arrow indicating their orientation, and *Non-Cued* trials, in which targets were preceded by a star pattern with lines corresponding to all of the orientations of the arrow cues. Each trial began with a fixation cross centered on the screen for 250 ms. This was followed by the cue centered on the screen for 2,000 ms. The long cue duration was chosen to maximize the likelihood that subjects would use the cue. There was then a 250 ms blank, followed by a target or distractor shape that remained centered on the screen until the subject responded. The shapes, both targets and distractors, appeared at any of 12 orientations in the picture plane (30° increments from the canonical orientation: 0°, 30°, 60°, ..., 330°). For both Orientation-Cued and Non-Cued trials, each of the 4 targets was presented 6 times at all 12 orientations and each of the 3 distractors appeared twice at all 12 orientations. This yielded 720 trials (360 for each trial type) that included 80% targets and 20% distractors. Trials were presented in a different random order for each subject and short breaks were given approximately every 60 trials.

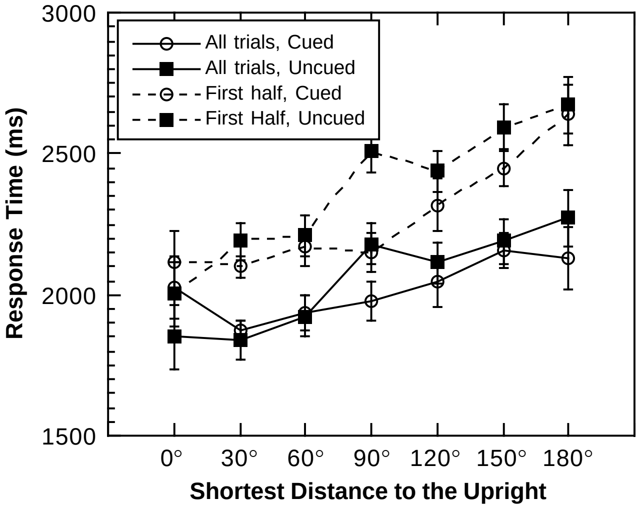

Figure 2. Experiment 1. Mean response times as a function of orientation for correct responses, in the Cued and the Uncued conditions, for the first half of the trials (dashed lines), and for all trials (solid lines). In all graphs, except when specifically stated, error bars represent the normalized within-subject standard error, appropriate for testing repeated measures factors such as differences across orientations.

Results

Only correct target trials with response times between 300 ms and 7,500 ms were included in the analyses. This resulted in approximately 5% of the trials being excluded for each condition. Although less relevant to the issues addressed in this experiment, mean error rates were positively correlated with mean response times (r = .41). Based on the assumption that subjects would rotate the shortest direction to the upright, that is, response times are symmetric around 180° (see Cooper & Shepard, 1973), the data were collapsed across the shortest distance from the canonical orientation, averaging +150° with -150°, +120° with -120°, and so on.

We report an analysis of the first 50% of the trials because orientation priming was more likely to be detectable when the orientation effect was the largest. An analysis of 100% of the trials, however, produced a similar pattern of results and reliability (see Figure 2). For each cueing condition, mean response times were regressed against degree of rotation to determine the slope of the function relating response time to orientation, indicating the putative rate of normalization. For Orientation-Cued trials, the slope was 349°/s with an intercept of 2,020 ms; the r^2 for this regression was .84. For Non-Cued trials, the slope was 276°/s with an intercept of 2,048 ms; r^2 was .93. Even after averaging over 72 repetitions for each shape, the novel shapes still produced orientation effects of a larger magnitude than typically found for familiar objects (McMullen et al., 1995).

An ANOVA was performed on the response times with Orientation (shortest distance to upright, 0-180°) and Condition (Orientation-Cued vs. Non-Cued) as within-subject factors. A linear contrast was also computed for the factor of Orientation. These analyses revealed a main effect of Orientation, $F(6,96) = 12.6$, $p < .001$, no main effect of Condition $F(1,96) = 2.75$, n.s., and no interaction. The linear contrast for Orientation was reliable, $F(1,16) = 47.8$, $p < .001$, with no interaction with Condition. After computing the linear contrast, there was no reliable residual variance associated with orientation.

Discussion

The results of Experiment 1 suggest that prior orientation cueing on a trial-by-trial basis does not reduce the orientation effect associated with the recognition of novel two-dimensional shapes rotated in the picture-plane. This finding is consistent with and extends the findings of Cooper and Shepard (1973) who obtained a similar pattern using a mirror-judgment task with familiar letters, as well as the results from McMullen et al. (1995) with common objects. The similarity of our results with those of Cooper and Shepard (1973) lends some support to the idea that similar representations of shape underlie both mirror and identification judgments (Tarr & Pinker, 1989; Tarr, 1995). Of note is the fact that failures to obtain orientation priming have been interpreted as evidence that shape and orientation information cannot be represented independently (Humphreys & Quinlan, 1988) and that abstract reference frames cannot be rotated (Cooper & Shepard, 1973). This conclusion appears to be inconsistent with the "rotation-for-handedness" hypothesis (so named by Tarr & Pinker, 1989). According to this model (Biederman & Gerhardstein, 1993; Corballis, 1988; Hinton & Parsons, 1981), the *identification* of misoriented shapes is typically accomplished through orientation-free shape representations. When observers must discriminate between normal and mirror-reversed versions of a shape, however, misoriented inputs must be normalized to an egocentric reference frame where left and right are defined. If the rotation-for-handedness hypothesis were correct, one might expect that subjects in Experiment 1, given correct orientation cues, could have used orientation-invariant recognition mechanisms to overcome any secondary effects of orientation (as suggested by Corballis, 1988). Obviously, this was not the case.

Despite the present results, however, we should be relatively cautious in generalizing from our findings. In particular, a large body of research has explored the conditions under which orientation cueing could potentially diminish the costs for processing rotated shapes. For example, the use of a stimulus set in which all characters point only "rightward" or "leftward" is one such manipulation. That is, provided that subjects are instructed on how to use orientation cues for a given stimulus set, orientation priming can be obtained (Hinton & Parsons, 1981). Another example is provided by Robertson et al. (1987) who found evidence that normalization of a misoriented shape configuration could reduce the need to normalize a subsequent shape configuration, but only as long as the second shape configuration appeared in the same orientation and reflection as the first configuration. Although both studies used mirror judgments, it is possible that such conditions generalize to recognition judgments.

Experiment 2

One conjecture regarding Experiment 1 is that the high degree of similarity between the shapes may have reduced any advantage for Orientation-Cued trials as compared to Non-Cued trials. In particular, it may be that for Orientation-Cued trials the orientation specified by the *preceding highly similar rotated shape* (which was named) provided a stronger orientation prime than the relatively abstract arrow cue (on which no judgment was made). Because there was an equal probability of any of the twelve orientations preceding a given trial, on average, orientation cueing from a previous trial would result in no diminution of orientation effects. Experiment 2 was designed to test this possibility by examining whether orientation cueing produces greater facilitation if given in the form of a similarly-shaped target in the same orientation, in particular, when both the cue shape and the target shape have to be identified. Such facilitation would offer evidence that orientation priming may occur automatically, without subjects being instructed explicitly to use orientation information. As in Experiment 1 we used a design in which subjects identified shapes presented in a random order. This procedure has often been used to measure orientation effects in shape recognition (Jolicoeur, 1985; Tarr & Pinker, 1989). However, the results of such studies are typically compiled by averaging response times across all trials of a given orientation, that is, without any regard for the preceding or subsequent trials. In the present experiment, we consider sequential trial effects, dividing the trials according to the characteristics of the preceding trial (see Koriat & Norman, 1988, for similar procedure in a mirror-judgment experiment). More specifically, in Experiment 2 a target can be preceded by the same object in the same view (the "SoSv" condition), a different object in the same view (the "DoSv" condition), the same object in a different view (the "SoDv" condition) or a different object in a different view (the "DoDv" condition). Logically, the strongest orientation priming effect is predicted for the SoSv condition. Of particular interest, however, is whether orientation priming is obtained for the DoSv condition. A dimunition of orientation effects in this condition would indicate that orientation cues may be effective even when the two named shapes are only similar, not identical, but do share the same orientation.

Method

Subjects. Twenty Yale undergraduates participated in the experiment in return for course credit. None of the subjects had seen the stimuli prior to the experiment.

Materials. The stimuli and presentation methods were identical to those used in Experiment 1.

Design and Procedure. The learning phase and 40 practice trials were identical to those used in Experiment 1. Although the task in the testing phase was also identical to Experiment 1, the orientations used and the number of trials differed. Here the 4 target shapes appeared 6 times at each of the following 7 orientations, 0°, 30°, 90°, 150°, 180°, 240°, and 300°; the 3 distractor shapes appeared once at each of twelve orientations, 0° to 330° (82% targets and 18% distractors). Of these trials, 58 were paired systematically in order to increase the frequency of trials preceded by a different object in the same orientation (the DoSv condition). These pairs were randomized with the remaining trials to produce 204 trials in a different pseudo-random order for each subject. On average, the proportions of trials in the different conditions were: SoSv, 1.50%; SoDv, 14.0%; DoDv, 62.5%; and DoSv, 22.0%. The timing for each trial was identical to that used in Experiment 1 with the exception that no orientation cue was shown.

Results

The data for one subject was excluded on the basis of extremely poor accuracy (45%). For the remaining 19 subjects, only correct target trials with response times between 300 ms and 7,500 ms were included in the analyses. This resulted in approximately 5% of the trials being excluded. As in Experiment 1, mean error rates were positively correlated with mean response times (r = .85). Results were again analyzed in terms of the shortest distance to the canonical orientation (although here there was no need to average orientations across 180° in that the 7 orientations were distributed so as to sample a given distance from the canonical orientation only once).

Since subjects performed fewer trials in Experiment 2 as compared to Experiment 1 (204 vs. 720), response times for all 204 trials were analyzed. Mean response times, collapsed across all trial types, were regressed against the degree of rotation. The slope of this function was 286°/s with an intercept of 1,728 ms; r^2 was .78. Similar regressions were also performed for each trial type (see Figure 3). For DoDv trials, the slope was 233°/s with an intercept of 1,891 ms; r^2 was .82. For DoSv trials, the slope was 180°/s with an intercept of 1,725 ms; r^2 was .78. For SoDv trials, the slope was 256°/s with an intercept of 1,830 ms; r^2 was .65. Finally, for SoSv trials, there was essentially no orientation effect. The slope was 4,717°/s with an intercept of 1,245 ms; moreover, there was an extremely poor linear fit for the data, r^2 being only .003.

An ANOVA was performed on response times with Orientation (shortest distance to upright, 0–180°) and Condition (SoDv, SoSv, DoSv, DoDv) as within-subject factors. There was a main effect of Orientation, $F(6,108) = 2.92$, $p < .01$, and a marginally reliable interaction of Condition with Orientation, $F(18, 240) = 1.55$, $p = .07$, reflected in the fact that SoSv trials yielded a relatively flat function as compared to the other three conditions. A linear contrast was also computed for DoSv trials in that the DoSv condition is the most diagnostic in terms of testing for orientation priming. The linear contrast for DoSv trials was reliable $F(1,18) = 4.58$, $p < .05$, but left reliable residual variance associated with Orientation $F(5,18) = 2.32$, $p = .05$. As can be seen in Figure 3, there was little difference between the linearity obtained for the DoSv condition and the DoDv and SoDv conditions.

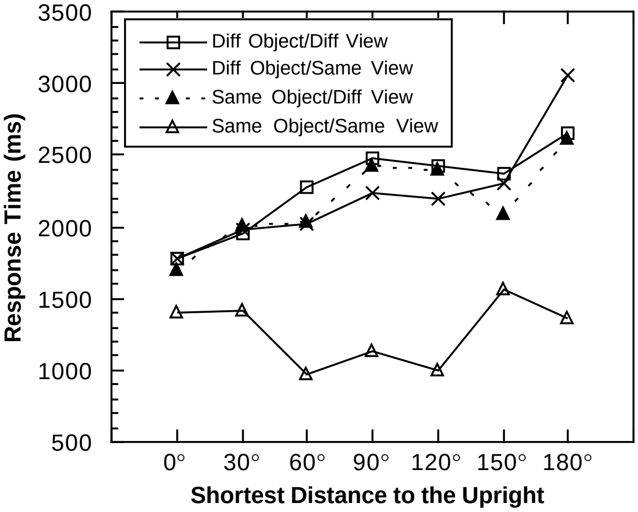

Figure 3. Experiment 2. Mean response times as a function of orientation for correct responses by type of trial: Different object-Different View; Different Object-Same View; Same Object-Difference View; Same Object-Same View. Error bars are not shown for clarity.

Discussion

Experiment 2 provides further evidence that prior orientation information of an abstract nature does not reduce the costs associated with recognizing misoriented two-dimensional shapes. In particular, the results do not support the hypothesis that orientation dependence may be reduced by the prior presentation of a visually similar shape in the same orientation as the target shape. On the other hand, the trials preceded by the same shape in the same orientation did show a dramatic shift to orientation-invariant performance. Importantly, this diminished cost for orientation cannot be accounted for by simple response priming in that the effect of orientation was not reliably reduced for trials preceded by the same target in a *different* orientation (SoDv trials). Thus, orientation priming does seem possible in terms of a specific shape at a specific orientation. Even given this result, the results of Experiment 2 seem to indicate that salient and predictive orientation cues independent of a given shape do not prompt diminished effects of orientation on recognition. This conclusion comes with a caveat however – cueing in this experiment was random in that subjects were never informed that the preceding shape would sometimes provide helpful information, and, indeed, the majority of preceding shapes *did not* provide any useful cues. Therefore, all we can conclude based on Experiment 2 is that potential cues to orientation are insufficient when there is no overall contingency between the orientation information and the orientation of the next stimulus.

Experiment 3

The results of Experiments 1 and 2 suggest that 1) Abstract orientation cues (i.e., cues that are not visually similar to the targets) are insufficient for producing orientation priming; 2) Visually similar orientation cues, other than exact identity cues, are also insufficient for producing orientation priming. This latter conclusion, however, is based on a cueing condition in which the orientations of the rotated targets were more often than not inconsistent with the potential cue. Experiment 3 was designed to test the possibility that orientation information in the form of a visually similar target *can* diminish the costs associated with orientation. Specifically, we consider a context in which the orientation cues are explicitly and maximally predictive of the subsequent stimulus orientation.

This manipulation was accomplished by using an identification task in which a series of adjacent trials were blocked to contain a single orientation. If, as Cooper and Shepard (1973) suggest, orientation information without specific shape information cannot be used to prepare for an incoming stimulus, then blocking by orientation should not diminish any effect of orientation. However, if the blocking manipulation turns out to be one condition that produces orientation priming, the relationship between shape and orientation information in shape recognition may need to be reconsidered.

Method

Subjects. Thirty Yale undergraduates participated in return for course credit. None of the subjects had seen the stimuli prior to the experiment.

Materials. The stimuli and presentation methods were identical to those used in Experiment 1.

Design and Procedure. The learning phase and 40 practice trials were identical to those used in Experiment 1. Although the task in the testing phase was also identical to Experiment 1, the instructions and the trial distribution differed. First, in addition to the general instructions regarding the recognition task, subjects were also informed that sequences of trials would be blocked by orientation, that is, that they would see several trials in a series at the same orientation but that the identity of the shape would vary from trial to trial. The order in which the blocks appeared was random and each block was preceded by a short break. The testing phase included a total of 180 trials organized in 12 blocks of 15 trials, each block including only one of 12 orientations in the picture plane (0°, 30°, 60°, ..., 330°). Each block included the 4 targets appearing 3 times each and the 3 distractors appearing once each, all in random order (80% targets and 20% distractors). The timing for each trial was identical to that used in Experiment 2.

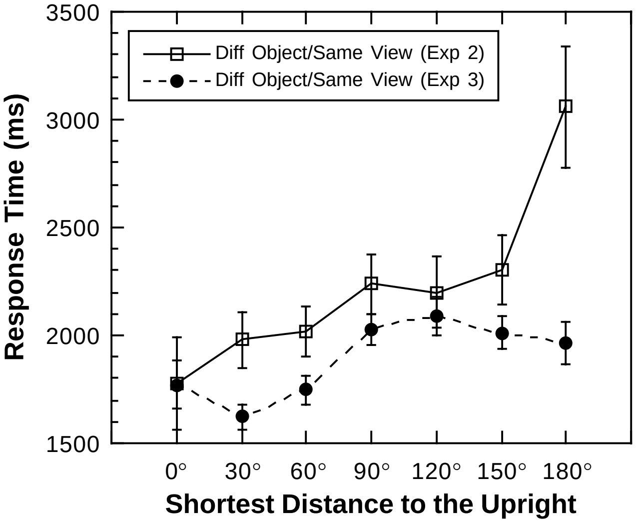

Figure 4. Mean response times as a function of orientation for correct responses for DoSv trials in Experiment 3, compared with similar trials in Experiment 2.

Results

Only correct target trials with response times between 300 ms and 7,500 ms were included in the analyses. This resulted in 6.7% of the trials being excluded. Mean error rates were positively correlated with mean response times ($r = .82$). Only the DoSv trials are of interest here – all other trials are SoSv trials, for which response priming is expected based on the results of Experiment 2. However, as in Experiment 2, the SoSv trials yielded almost no orientation effect: the slope was 1,256°/s, with an intercept of 1,126 ms; r^2 was .38. The effect of orientation (collapsed across 180°) for DoSv trials is presented in Figure 4 and compared to DoSv trials from Experiment 2. Note the apparent difference in the effect of orientation on identification times. These effects were tested by regressing response times for DoSv trials against orientation (shortest distance to upright). The slope of this function was 492°/s with an intercept of 1,708 ms; r^2 was .56. By comparison, the slope for DoSv trials in Experiment 2 was a much slower 180°/s. A linear contrast computed for DoSv trials in Experiment 3 was reliable, $F(1,29) = 5.36$, $p < .05$, and left no reliable residual variance.

Inspection of Figure 4 reveals that the orientation effects for DoSv trials in Experiments 2 and 3 differ primarily at larger misorientations, i.e., at 150° and 180°. Thus, any orientation priming in the DoSv condition in a blocked design appears to occur at those orientations for which identification

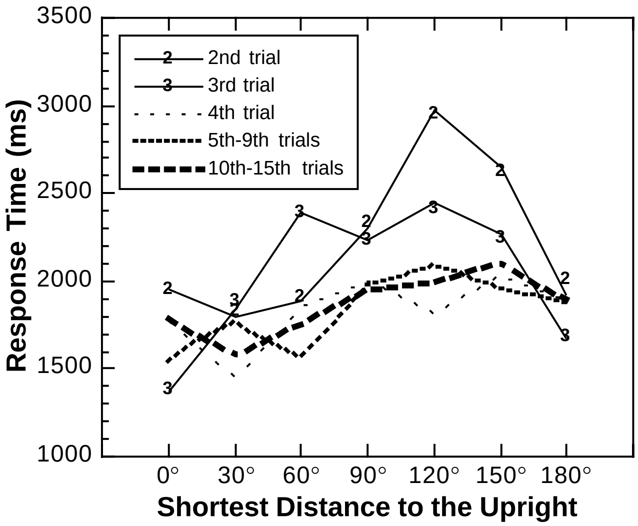

Figure 5. Experiment 3. Mean response times as a function of orientation for correct responses in DoSv trials, on the 2nd, 3rd, 4th, 5th to 9th and 10th to 15th trials.

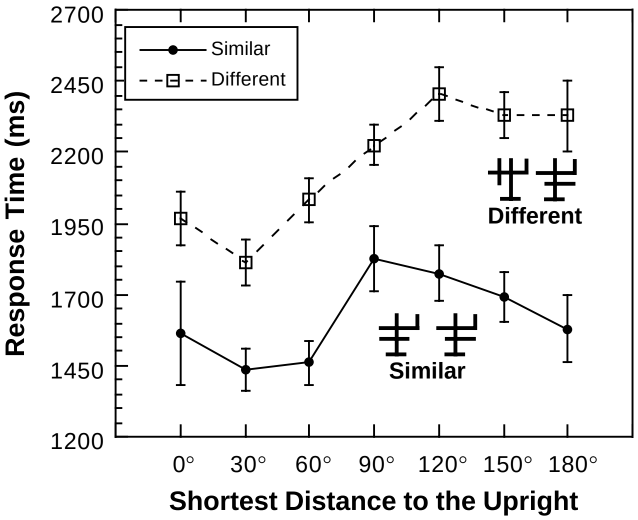

Figure 6. Experiment 3. Mean response time as a function of orientation for correct responses in DoSv trials for the targets preceded by another similar target as opposed to a more different one.

was the most dependent upon orientation in the random design (i.e., where response times were slowest). An ANOVA on response times with Orientation (shortest distance to upright, 0 to 180°) as a within-subjects factor and Experiment (2 or 3) as a between-subjects factor yielded a reliable Orientation x Experiment interaction, $F(6{,}282) = 5.40$, $p < .001$. Importantly, it is unlikely that the diminished effect of orientation at these larger misorientations could be explained by the subjects physically rotating their heads based on the expectation of a series of trials at a single orientation: 150° and 180° are rather extreme head rotations, especially using a chin rest!

To investigate whether blocking *per se* or the repetition of targets at the same orientation was responsible for the observed orientation priming, response time data was divided into bins based on sequential order within a block. Figure 5 shows the functions obtained for the 2nd, 3rd, 4th, 5th-9th, and 10th-15th trials of each block. Inspection of the graph reveals that the effect of orientation is reduced dramatically from the 2nd to the 3rd trials, and again from the 3rd to the 4th trials, but does not diminish further during the remainder of the block. Interestingly, on the 2nd and 3rd trials, the 150° and 180° orientations are already nearly as fast as smaller misorientations, but that the peak at 120° only diminishes with further repetition. That is, orientation priming appears to be already occurring in the 2nd and 3rd trials of the 150° and 180° blocks, but only in the 4th trial of the 120° block. To examine these inferences t-tests were run on all pairwise comparisons between the data points shown in Figure 5, looking at individual orientations, we found that the only reliable differences were the following: at 60°, subjects were faster in the 5th-9th trials (as well as subsequent trials) as compared to the 3rd trial, $t(28) = 3.14$, $p < .005$, and at 120°, subjects were faster in the 4th trial (as well as subsequent trials) as compared to the 2nd trial $t(40) = 2.50$, $p < .05$. This peak at 120° was not predicted – one post-hoc explanation is that subjects may make best use of orientation information in those cases that require the greatest normalization. That is, the larger the potential cost of normalizing the stimulus shape, the more rapidly subjects will adopt an alternative strategy based on orientation priming.

Finally, several subjects indicated at the end of the learning phase that it became easier to remember the individual target shapes once they realized that they could group them in two pairs of similar shapes. All subjects who mentioned this strategy grouped KIP with KEF and KAL with KOR (see Figure 1). Thus, it is possible that visual similarity (as described by subjects in this experiment) might influence the efficacy of a given shape as an orientation cue for the recognition of a subsequent shape. To investigate this issue, we plotted the DoSv trials in which the cue shape was visually similar to the target and the DoSv trials in which the cue shape was visually dissimilar. The results of this analysis are shown in Figure 6. Note that there is a clear overall response time advantage for the DoSv-similar trials. There also appears to be a clear reduction of orientation effects at larger misorientations, 90° to 180°, for DoSv-similar trials as compared to DoSv-different trials. An ANOVA with a linear contrast for Orientation and Similarity (similar/different) as factors revealed a reliable linear main effect, $F(1{,}29) = 11.1$, $p < .005$, a reliable effect of Similarity, $F(1{,}29) = 61.6$, $p < .001$, and, crucially, a marginally reliable Linear x Similarity interaction, $F(1{,}29) = 3.37$, $p = .07$. More specifically, paired t-tests (all reliable at $p < .05$) for all pairwise comparisons for each of the two functions represented in Figure 6 indicated that when the objects were different, the response times for small misorientations (0°-60°) were not reliably different from one another, the response times for large misorientations (90°-180°) were also not reliably different from one another, but that the response times for small misorientations were reliably faster than the response times for large misorientations. In contrast, when the objects were similar, all response times, from both small and large misorientations, were not reliably different from one another. Crucially, the larger misorientation (180°) was not found to be reliably different from the other misorientations. This suggests that orientation priming was greatest for similar objects at the largest possible misorientations. Although this is an admittedly post hoc comparison, such a pattern is predicted if: 1) Subjects rely most heavily on orientation cues in those blocks requiring the largest normalizations; and, 2) Subjects are more readily able to employ such orientation cues when they come in the form of a shape that is visually similar to the target (the most extreme example being a SoSv trial).

Discussion

The results of Experiment 3 point to at least one condition under which orientation information without diagnostic shape information can be used by subjects in order to prepare for an incoming stimulus – the recognition of visually similar target shapes repeated at the same orientation. Interestingly, since we know from previous studies and Experiments 1 and 2 that abstract cues are inefficient, it appears as if shape and orientation are neither completely dissociated nor completely associated. Subjects are able to use members of a homogeneous class as orientation cues even though they are in the process of distinguishing between these shapes – a task that would seem to highlight the differences among the shapes. Moreover, it is unlikely that this orientation priming can be explained simply by subjects being explicitly aware of the orientation repetition. First, several studies using a mirror-judgment included explicit instructions prepare for an incoming stimulus based on orientation information (which is more than we told subjects here) and still found little evidence for orientation priming (Cooper & Shepard, 1973; Hinton & Parsons, 1981). Second, orientation repetition was not completely effective until the fourth trial (which is the third trial that could have shown orientation priming, since the orientation was unpredictable for the first trial of each block). Thus, despite the fact that subjects were most likely aware of the consistency of orientation following the first block of trials, it took some time for them to decide whether it was worth using a "prepared" reference frame – although they ultimately do appear to adopt this strategy within some blocks. In contrast, many of the studies of orientation priming in mirror judgments found that subjects could not prepare an empty reference frame (Cooper & Shepard, 1973; Robertson et al., 1987; Humphreys & Quinlan, 1988). Likewise, Jordan and Huntsman (1990) used an orientation blocking manipulation that failed to produce orientation priming in word identification and lexical decision. However, Jolicoeur (1990) found that letter identification in three-letter displays containing letters that were all in the same or similar orientations was facilitated relative to displays in which the orientations of the three letters were disparate. This effect, which may be akin to the facilitation obtained here, was interpreted as evidence for the ability to rotate an abstract frame of reference.

One intriguing alternative to the "rotation of an abstract frame" interpretation is that the repetition of similar shapes at a consistent orientation led to the sustained activation of orientation-specific shape representations for *the class of all visually similar* shapes (for example, see Edelman, 1995a, 1995b). Such class-general activation would allow subsequent identification judgments *at the same orientation* to be performed without the use of normalization. Within this framework, one possible reason for why orientation priming was not obtained for rotations of 30° to 120° is that shapes appearing at these orientations would be close enough to the upright to activate a canonical shape representation at the orientation used during initial learning – an "attractor" of sorts. Notably, given the significant body of results suggesting that abstract frames of reference cannot be rotated, this "image-based generalization" account has the advantage of not appealing to dissociable orientation and shape representations. Moreover, this account is consistent with multiple-views theories of object recognition that have been based, in part, on evidence garnered using stimuli similar to those used here (Tarr & Pinker, 1989, 1990; Tarr, 1995). Because the multiple-views approach assumes that object representations are image-based (Bülthoff et al., 1995; Tarr & Bülthoff, 1995), the theory also predicts that the greatest priming (disregarding SoSv trials) should occur for those trials preceded by the most similar targets (given a common orientation) because the shape representations of the prime and the target would share the greatest number of features.[1]

Experiment 4

An image-based generalization account of orientation priming, such as that outlined above, predicts that no explicit knowledge of orientation blocking is required in order to obtain facilitation – activation of visually similar shape representations being a natural consequence of recognition within image-based distributed representation models (Weinshall, Edelman, & Bülthoff, 1990; Edelman & Weinshall, 1991; Edelman, 1995b, 1995a). Experiment 4 tests this by specifically asking whether orientation priming occurs in a context where subjects are unlikely to be aware of orientation blocking. A second prediction of an image-based generalization account is that the degree of facilitation should be related to

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[1] One possible explanation for why orientation blocking did not produce orientation priming in a word identification experiment (Jordan & Huntsman, 1990) is that word identification is mediated by many non-visual processes. For example, two orthographically similar patterns can have widely different semantic interpretations (e.g., "block" and "flock").

the number of preceding same-orientation similar-shape trials. This is because activation is posited to "accumulate" across orientation-specific shape representations with each subsequent trial (Perrett, Oram, & Wachsmuth, 1996). In Experiment 3 this prediction was difficult to test because the explicit blocking manipulation may have resulted in strategic factors interacting with automatic factors. To address this concern in our tests of these predictions we adopted a design in which short runs of same-orientation trials are embedded within random-orientation trials. This manipulation provides a measure of orientation priming in a context where it is less likely that subjects will become aware of the repetition of orientations and, given no strategic priming, a more effective means for assessing the impact of the number of repetitions on the magnitude of orientation priming.

Subjects. Twenty-four Yale undergraduates participated in return for course credit. None of the subjects had seen the stimuli prior to the experiment.

Materials. The stimuli and presentation methods were identical to those used in Experiment 1.

Design and Procedure. The learning phase and 40 practice trials were identical to those used in Experiment 1. Although the task in the testing phase was also identical to Experiment 1, the trial distribution differed. The testing phase included a total of 240 trials organized into a Block condition consisting of 12 blocks of 6 trials, each block including only target shapes in one of 6 orientations in the picture plane (0°, 60°, 120°, 180°, 240°, and 300°) and a Random condition consisting of 72 distractor trials and 96 target trials, to which the 6 orientations were evenly assigned. The Blocked trials and Random trials were intermixed randomly for each subject. The same shape never occurred twice in a row within a same-orientation block and each block was preceded by a distractor shape at a different orientation. Blocks were organized so that the 3rd and 6th trials were preceded by the most visually similar target shapes, while the 2nd, 4th, and 5th trials were preceded by more visually dissimilar target shapes (i.e., the pattern A-B-B'-A'-B-B' was used for each block, although the actual shapes corresponding to A and B varied). The order of the blocks and of the filler trials was randomized for each subject. The timing for each trial was identical to that used in Experiment 2.

Results

Only correct target trials with response times between 300 ms and 7,500 ms were included in the analyses. This resulted in the rejection of 13% of the trials. Mean error rates were more strongly correlated with mean response times in the Blocked DoSv (r = .95) than in the Random condition (r = .17). However, no subject reported noticing the blocking manipulation when queried at the end of the experiment. Figure 7 shows response times as a function of orientation (collapsed across 180°) for the Blocked DoSv and the Random trials (which includes the first trial of each block). An ANOVA on response times with Orientation (shortest distance to upright, 0°, 60°, 120°, 180°) and Condition (Random, Blocked) as within-subject factors yielded reliable main effects for Orientation, $F(3,69) = 33.9$, $p < .001$, and Condition, $F(1,69) = 44.3$, $p < .001$. Most importantly, there was a reliable Orientation x Condition interaction, $F(3,69) = 3.90$, $p < .01$.

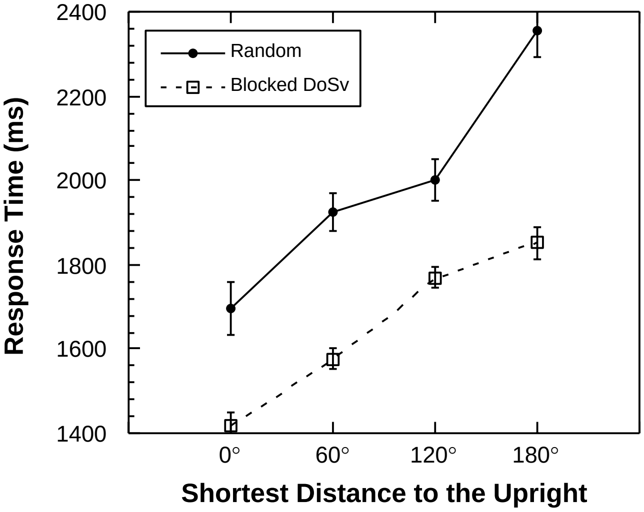

Figure 7. Experiment 4. Mean response times as a function of orientation (collapsed across 180°) for Blocked DoSv trials and the Random orientation trials.

To understand the impact of orientation repetition on orientation priming, Figure 8 shows response times (collapsed across 180°) for the first trial of each block (which was really another random-orientation trial) and the DoSv trials in the 2nd, 4th, and 5th position of each block. Note that the 3rd and 6th trials were excluded on the basis of the trial order described above in which the 3rd and the 6th trials of a block were always preceded by the most visually similar target shape (known to provide the greatest priming – see Figure 6). In contrast, the 2nd, 4th, and 5th trials were always preceded by a more dissimilar target shape, therefore, these trials allow the strongest test of orientation priming across repetition.

In Experiment 3 we observed that the orientation priming produced by blocking occurred only at larger misorientations. Therefore, given that the same shapes and task was used in Experiment 4, Figure 8 shows only response times only for 120° and 180°. In order to test the prediction that the degree of orientation priming effect is related to the number of same-orientation different-shape repetitions, we performed an ANOVA on response times using only large Orientations (120° and 180°) and Serial Position (1st, 2nd, 4th, and 5th) as within-subject factors. This analysis revealed reliable main effects of Orientation, $F(1,92) = 5.69$, $p < .05$, and Serial Position, $F(3,69)=18.1$, $p < .001$, as well as a reliable Orientation x Position interaction, $F(3,23)=7.46$, $p < .001$. A

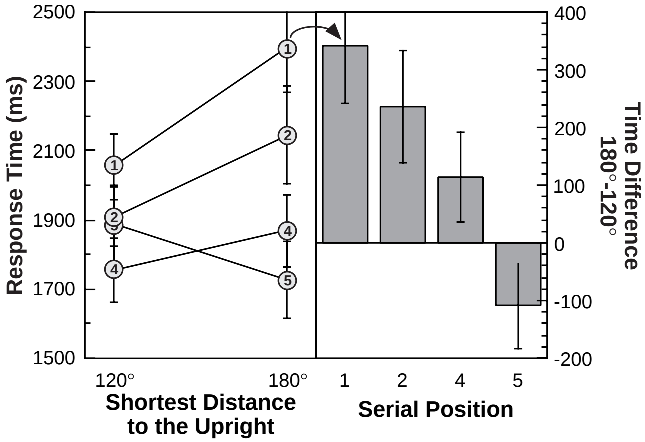

Figure 8. Experiment 4. Mean response times in the Block condition as a function of orientation for correct responses by serial position of trial. Trial 1 is always preceded by a distractor shape in a different orientation, while Trials 2, 4, and 5 are always preceded by a relatively dissimilar target shape in the same orientation.

linear x linear contrast was also computed on the same data points to test the hypothesis that the effect of orientation diminished with increasing serial position. This "fan effect" contrast was reliable, $F(1,23) = 19.2$, $p < .001$, and the residual was not reliable.

Discussion

Results of Experiment 4 provide further support for the idea that at larger misorientations orientation priming can be obtained by blocking trials by orientation (as found in Experiment 3). Moreover, here orientation priming through blocking was obtained using short runs of trials intermixed with random trials, thereby reducing the likelihood that subjects were aware of the blocking manipulation. This finding suggests that orientation priming may sometimes occur automatically and, in particular, as a by-product of normal shape processing during recognition.

A second result, that orientation priming increased roughly linearly with repetition of visually similar shapes, provides further support for the claim that priming results from the accumulation of activation within shape representations. Indeed, an account of orientation priming in terms of the rotation of a reference frame would have to posit faster normalization with each repetition (for arguments against this type of model see Tarr & Pinker, 1991). In contrast, image-based models naturally predict that as evidence accumulates within orientation-specific shape representations (due to the repetition of homogeneous target shapes), there will be an increase in orientation priming for the recognition of visually similar shapes at the same orientation (Weinshall et al., 1990; Edelman, 1995a).

Consistent with this interpretation, based on the results of our experiments in which orientation priming was not obtained (Experiments 1 and 2) and those in which it was obtained (Experiments 3 and 4), it appears that a recurring factor in the occurrence of orientation priming is that the prime is visually similar to the target. This is consistent with many of the earlier studies of orientation priming (Robertson et al., 1987; Koriat & Norman, 1988; Humphreys & Quinlan, 1988; Jolicoeur, 1990). As illustrated in Figure 9, we propose a network of units each representing the appearance of an object in a given orientation and broadly tuned to visual properties present within the image (Edelman & Weinshall, 1991; Logothetis & Pauls, 1995). Of course, while, for convenience, we refer to these as "units," a network of distributed representations preferentially tuned for specific shapes would apply just as well. Regardless of the specificity of tuning, the essential point is that these units contribute to the recognition of an input shape in a manner proportional to the strength of their response to that input, i.e., based on their visual similarity.

A unit could be activated by different exemplars of a homogeneous class seen from the preferred viewpoint of the unit or the same exemplar from several viewpoints close to the preferred viewpoint, albeit, less strongly in either case than the resultant activation from the preferred exemplar in the preferred viewpoint (Figure 9a; for neurophysiological evidence consistent with this account see Perrett, Oram, and Wachsmuth, 1996).[2] This early stage of activity within the network might be sufficient for classification; for instance, recognizing all of the stimuli used up to this point as instances of the "tv-antenna" class. In order to discriminate one shape from its visually similar cohorts (i.e., subordinate-level recognition), however, the pattern of activity within the network must become narrower so as to increase the signal for the correct exemplar relative to the incorrect exemplars (Figure 9b). Such a process is presumed to mediate each identification in the experiments we have reported to this point. Notice that although subordinate-level recognition requires the representational unit(s) encoding the current target to reach a higher level of activation relative to its cohorts, we do not assume that the cohort units have zero activation at the moment when recognition is achieved. Indeed, it is this residual activation for visually similar members of a class (at an orientation common to that of the target) that we propose may give rise to orientation priming.

Experiment 5

Given our results to this point there is at least one alternative to the account we have offered: Visual similarity between the prime and the target may be unnecessary and any shape recognized at a common orientation in the preceding

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[2] Certainly, such an approach owes a debt to the so-called "stochastic" models in experimental psychology. In particular, such models accumulate noisy information over time and show longer response times to poorer matches. Thus, they require more evidence to reach a given threshold when the signal is small relative to the noise (see for instance, Green & Swets, 1966; Luce, 1986).

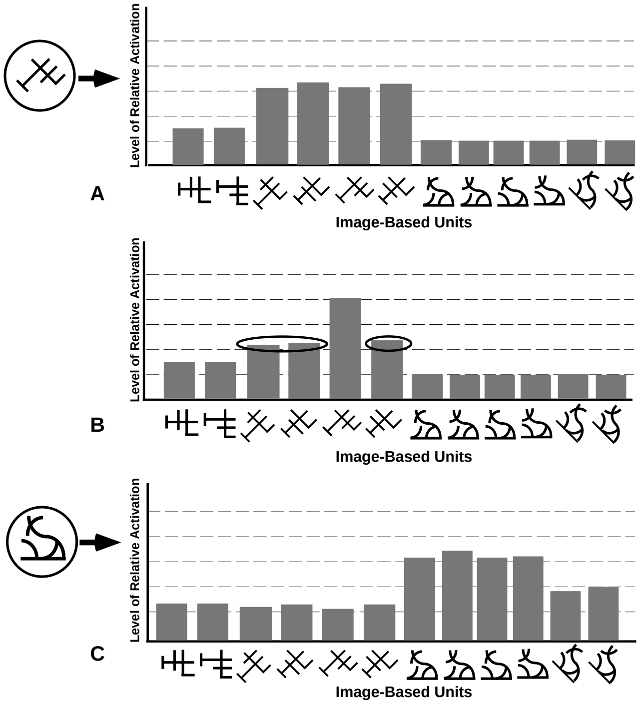

Figure 9. Hypothetical activity in a network of image-based units. a) Early response to a rotated object of a first homogeneous class. b) Late response leading to subordinate recognition. The elliptical areas indicate the residual activation from the early stage of processing which could lead to orientation priming. c) Early response to an object of a second homogeneous class.

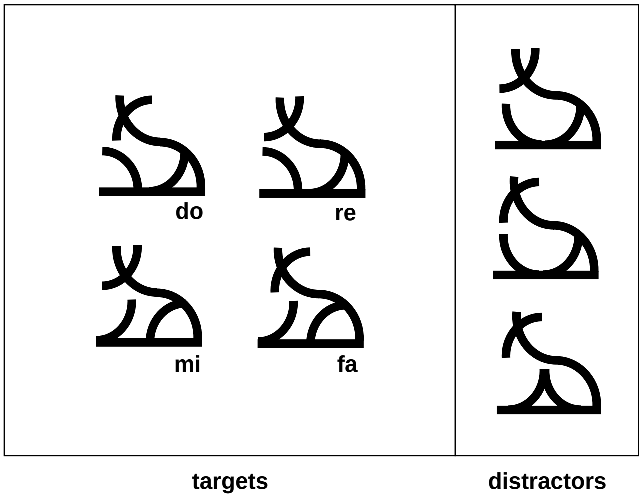

Figure 10. Second set of novel shapes, used in Experiment 5, in their canonical orientation.

trial might be sufficient to produce orientation priming. In other words, it is possible that what is primed is the process of normalization for a given orientation. This is more or less equivalent to an explanation based on the normalization of an "abstract" reference frame in that it assumes no effect of the particular shape of the prime or target. Rather, what the two trials have in common is the initial orientation of the shape and the normalization operation required in both cases. In contrast, when the cue remains the same throughout an experiment, as with the arrow used in Cooper and Shepard's original study and Experiment 1 in the present study, no normalization is necessary for its recognition, hence no priming occurs. While some of the results of Experiment 3 (see Figure 6) appear to indicate that visual similarity plays an important role in orientation priming, this conclusion was based on an admittedly post hoc analysis. Therefore, as a more direct test, in Experiment 5 we used a design in which target shapes from two shape-defined categories were alternated so that the prime was guaranteed to be from a different category than the target. Within the network-activation framework a shape prime from a different perceptual category should lead to the activation of a different population of image-based units, in some sense "erasing" the residual activation from the preceding target (see Figure 9c). Thus, we predict no orientation priming for same-orientation different-category trials. In contrast, if it is the normalization of an abstract reference frame that is primed, we should obtain orientation priming for same-orientation different-category trials.

Method

Subjects. Thirteen Yale undergraduates participated in return for course credit. None of the subjects had seen the stimuli prior to the experiment.

Materials. The stimuli and presentation methods were identical to those used in Experiment 1. In addition, a second class of homogeneous stimuli was created. In contrast to the shapes used in Experiments 1-4, these shapes were composed primarily of curves to maximize the visual *dissimilarity* between this class and the original class. Importantly, the shapes still contained a common "foot" grounding the default orientation for all members of the class. The four targets and the three distractors of this new class are shown in Figure 10.

Design and Procedure. The learning phase, identical to that used in Experiment 1, was used to teach subjects both classes of shapes. Following training on both classes, 24 practice trials were run in which targets from both classes were randomly intermixed. Because of the introduction of a second class of shapes, there were nine possible response keys corresponding to the four targets from each class and the "none-of-the-above" distractor response. The timing for each trial was identical to that used in Experiment 2. The testing phase was somewhat different from that used previously in that subjects were informed that sometimes a series of 15 trials at a single orientation would occur and that they would be prompted about this fact prior to the block. Each such series included 12 targets (6 from each class) and 3 distractors (80% targets and 20% distractors). The testing phase included 24 such blocks at one of 12 orientations (0°-330°, every 30°; for a total of 306 blocked trials). These blocks were randomly intermixed with 360 trials in which orientation varied in a pseudo-random fashion – a shape could be followed by a shape at any orientation except for the identical orientation. The explicit prompts and the large number of trials per block were used in order to maximize the possibility of orientation priming. In both the Blocked and the Random conditions targets of the two classes were constrained to alternate (A-B-A-B...) such that a target was *never* preceded by another shape from the same class.

Results

Only correct target trials with response times between 300 ms and 7,500 ms were included in the analyses. This resulted in 10.1% of the trials being excluded. Mean error rates were positively correlated with mean response times in both conditions (Blocked: r = .93; Random: r = .89).

An ANOVA on response times with Shape Class and Orientation as within-subject factors revealed no reliable difference between the two classes and no interaction with Orientation function, therefore results were collapsed across the two classes in all subsequent analyses. Mean response time as a function of orientation for the Blocked and Random conditions are presented in Figure 11. A regression of response time against orientation was performed for each condition. In the Random condition the slope was 508°/s with an intercept of 1,903 ms; r^2 was .91. In the Blocked condition the slope was 318°/s with an intercept of 1,778 ms; r^2 was .89. An ANOVA was performed on response times with Orientation and Condition as within-subject factors revealed only a reliable effect main effect of Orientation, $F(6,12) = 14.8$, $p < .001$. A linear contrast for this factor was reliable, $F(1,12) = 33.0, p < .001$, with no interaction with Condition. The residual was not reliable.

Discussion

The results from Experiment 5 are consistent with the predictions of the network-activation framework and image-based generalization. This approach appears compatible with the orientation priming obtained in Experiments 3 and 4 and the failure to obtain orientation priming in the present experiment. In contrast, the alternative, priming of an abstract frame of reference, would not predict the obtained pattern of results. It appears that orientation can most easily be primed by a shape from the same homogeneous class as the target shape. Supporting this hypothesis, Experiment 5 failed to reveal any evidence for orientation priming for a blocking manipulation when the prime and target shapes were from visually dissimilar classes. This failure to obtain orientation priming occurred despite the fact that subjects were explicitly informed about the blocking manipulation and the use of long runs of 15 trials per block. By way of comparison, orientation priming was obtained in Experiment 4 despite the fact that subjects were unaware of the orientation blocking manipulation and the blocks were only 6 trials long. Overall, these results provide further evidence that orientation priming may be an automatic consequence of orientation-dependent shape recognition mechanisms.

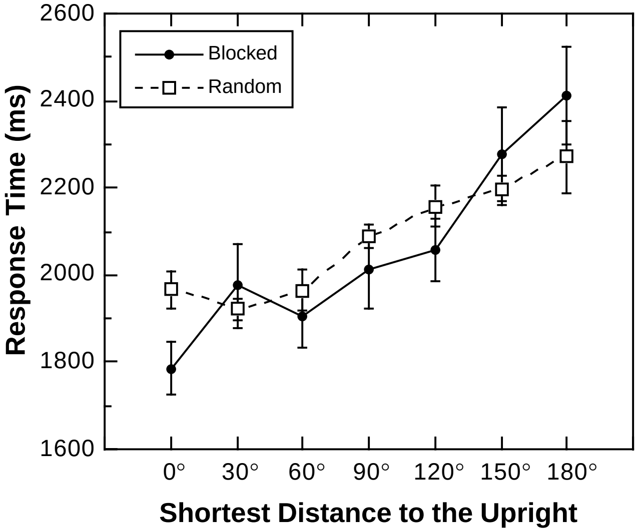

Figure 11. Experiment 5. Mean response times as a function of orientation for correct responses by condition. Error bars show the standard error of the mean, appropriate for comparing the two conditions.

General Discussion

Failure to obtain orientation priming in the absence of shape cues has often been taken as evidence that shape and orientation are not represented independently (Cooper & Shepard, 1973; Shepard & Cooper, 1982; Kosslyn, Pinker, Smith, & Shwartz, 1981). In other words, the fact that subjects cannot use an orientation cue in order to prepare in advance to identify a misoriented stimulus has been cited as evidence that objects are visually represented in a viewpoint-specific fashion, thereby supporting image-based theories of object recognition (Bülthoff & Edelman, 1992; Edelman & Weinshall, 1991; Poggio & Edelman, 1990; Tarr, 1995). In contrast, evidence for orientation priming has been cited as evidence that objects are visually represented in a viewpoint-invariant fashion (Humphreys & Quinlan, 1988; Koriat & Norman, 1988; Jolicoeur, 1990), thereby supporting structural-description theories (Biederman, 1987; Biederman & Gerhardstein, 1993). In this paper, however, we propose that image-based theories are compatible with orientation priming, as long as this priming is *shape* dependent. Thus, much as the magnitude of priming between two images of the same object may depend on the similarity of viewpoints, the magnitude of priming between two images of different objects may depend on the similarity of shapes.

Our results lend support to this interpretation, demonstrating that orientation priming is possible when the primes are shapes from the same visually homogeneous class as the targets. Given the high degree of recognition accuracy of our subjects in Experiments 3 and 4, it is clear that the priming occurred even though subjects identified the prime and the target as two different objects. When the cue was visually dissimilar, as in Experiment 5, no facilitation was produced by the prior orientation information. As reviewed earlier, this pattern of results supports an image-based approach to object recognition, and, in particular, models that represent objects as broadly tuned viewpoint-sensitive representations encoding both shape and orientation (Weinshall et al., 1990; Edelman & Weinshall, 1991; Edelman, 1995a; Perrett et al., 1996).

Our ability to identify an object and distinguish it from visually similar cohorts despite the variation inherent in viewing conditions is often considered to be one of the most impressive achievements of the human visual system (Marr, 1982). In this regard, it may seem puzzling that the image-based approach predicts costs for orientation normalizations for a given shape and yet generalization between similar views of different shapes. However, given that image-based similarity at least in part determines the connections between different representational units within the visual system (Edelman, 1995b), it is not unreasonable to propose that the representation of Object A at 120° is strongly connected to the representation of Object B at 120° when A and B are visually similar. Indeed, in a system in which objects are represented in a viewpoint-dependent manner, the same view of two different objects of the same class may very well be more similar than two different views of the same object (Bülthoff et al., 1995).

It could, of course, be argued that such a recognition system does not provide sufficient generalization between different depth-rotated views of the same object. However, generalization between views may indeed be difficult in that it often happens that abrupt changes in surface geometry can lead to two nearby viewpoints being very different in terms of visible image structure. Thus, researchers have recently postulated view-based representations in which each geometrically-defined characteristic views form distinct units within the overall representation (Freeman & Chakravarty, 1980; Koenderink, 1987). Such models attempt to address the fact that image-based similarity alone is unlikely to lead to a structured representation across rotations in depth, even though we clearly show shape constancy across such transformations. One possibility is that mechanisms different from those that compute image-based similarity are used to create associations between different views of the same object. Indeed, recent single-cell recording work by Miyashita et al. (Miyashita, 1988; Miyashita, Date, & Okuno, 1993; Miyashita & Chang, 1988) on the inferotemporal (IT) cortex of monkeys points to such a mechanism. Testing monkeys in a match-to-sample task with a large number of novel patterns, Miyashita first found that individual cells become tuned to a small number of visually similar objects. Within the image-based generalization framework, these cells can be viewed as responding to the presentation of similar objects because of common image information. However, Miyashita also found that after sequentially pairing arbitrary pairs of patterns for a large number of trials, some cells would also become tuned to pairs of *dissimilar* visual patterns. Thus, there appears to be a second associative mechanism that creates connections between visually dissimilar input that co-occur in time. Psychophysical evidence for such a mechanism may be found in a recent study by Lawson, Humphreys, and Watson (1994) who reported that structured sequences of views objects lead to better recognition performance relative to randomly ordered sequences of the same objects. Moreover, lesions of entorhinal and perirhinal cortex seem to disrupt temporal associations but leave shape associations intact (Gasic, 1995). In terms of the regularities of the world, sensitivity to the temporal contiguity of images is a reasonable strategy – images that follow each other in time are more than likely to be different views of the same physical object.

In summary, our present findings offer some evidence for orientation priming in terms of shape similarity. In particular, we suggest that a single object representation system may mediate the orientation priming obtained here as well as many previous findings of orientation dependence in recognition (Bülthoff & Edelman, 1992; Edelman & Bülthoff, 1992; Humphrey & Khan, 1992; Tarr, Hayward, Gauthier, & Williams, 1994) and the reduction of orientation effects with practice (Jolicoeur, 1985; Tarr & Pinker, 1989; Tarr, 1995). Moreover, given recent neuroscientific (Logothetis & Pauls, 1995; Perrett et al., 1996) and computational (Edelman & Weinshall, 1991; Edelman, 1995b; Lando & Edelman, 1995; Moses et al., 1996) advances, there are reasons to believe that an image-based network-activation approach provides great promise for understanding human visual recognition performance.

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