Effects of stimulus orientation on the identification of common polyoriented objects

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Experimental evidence has shown that the time taken to recognize objects is often dependent on stimulus orientation in the image plane. This effect has been taken as evidence that recognition is mediated by orientation-specific stored representations of object shapes. However, the factors that determine the orientation specificity of these representations remain unclear. This issue is examined using a word-picture verification paradigm in which subjects identified line drawings of common mono- and polyoriented objects at different orientations. A detailed analysis of the results showed that, in contrast to mono-oriented objects, the recognition of polyoriented objects is not dependent on stimulus orientation. This interaction provides a further constraint on hypotheses about the factors that determine the apparent orientation specificity of stored shape representations. In particular, they support previous proposals that objects are encoded in stored representations at familiar stimulus orientations.

It is well documented that the time taken to recognize objects is often dependent on the orientation of the stimulus in the image plane—that is, a plane perpendicular to the line of sight (e.g., Arguin & Leek, 1995; Jolicoeur, 1985; Maki, 1986; McMullen & Farah, 1991; Murray, Jolicoeur, McMullen, & Ingleton, 1993; Rock, 1973; Schwartz, 1981; Tarr & Pinker, 1989). However, the theoretical implications of this effect remain the subject of considerable debate (see, e.g., Biederman & Gerhardstein, 1993; Corballis, 1988; Leek, 1996; Tarr & Pinker, 1990; Wagemans, Van Gool, & Lamote, 1996).

One important issue concerns the functional origin of orientation effects in recognition tasks. For example, it could be that these effects actually result from the operation of mental processes that play no direct role in stimulus identification, such as the preparation and planning of motor actions or the calculation of stimulus orientation for the purposes of reaching and grasping even when such actions are not required by the task (see, e.g., Deutsch, Bourbon, Papanicolaou, & Eisenberg, 1988; Georgopoulos, Lurito, Petrides, Schwartz, & Massey, 1989). However, it is more generally assumed that they result from processes that directly support recognition. One prominent version of this account is that they reflect the use of a spatial normalization process that transforms a

perceptual representation of a stimulus to match a stored orientation-specific representation of object shape held in long-term memory (e.g., Bülthoff & Edelman, 1992; Edelman & Bülthoff, 1992; Jolicoeur, 1985; Rock, 1973; Tarr, 1995; Tarr & Bülthoff, 1995; Tarr & Pinker, 1989; Ullman, 1989). Some evidence in support of this possibility is that orientation effects seem to be influenced by stored object-specific knowledge. Thus, the time taken to recognize mono-oriented objects like cars and buildings, which are almost always seen at the same orientation in the environment, generally increases as a function of the angular distance between the orientation of the stimulus and the object's familiar upright orientation (see, e.g., Jolicoeur, 1985; McMullen & Farah, 1991; Rock, 1973). If orientation effects arise from processes that play no role in stimulus identification, it is not clear why they should be influenced by stored knowledge about the familiar orientation of particular objects. On the other hand, several theoretical issues related to the orientation-specific representations hypothesis remain unresolved. One important question concerns the kinds of information about object orientation that such representations are likely to encode.

One proposal is that they encode shape descriptions at their familiar canonical orientation (e.g., Rock, 1973; Tarr, 1995; Tarr & Bülthoff, 1995; Tarr & Pinker, 1989; Ullman, 1989). Although this is consistent with the finding that mono-oriented objects are aligned to a single familiar orientation, the generality of this hypothesis is challenged by reports showing that stimulus identification is not always fastest at familiar stimulus orientations (Biederman & Gerhardstein, 1993; Murray et al., 1993; Takano, 1989; Tarr & Pinker, 1990; Wiser, 1981). For example, Wiser found that elongated novel shapes were recognized fastest when presented at a vertical orientation, regardless of the orientation at which they had previously been memorized. This suggests that recognition may

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sometimes be mediated by stored representations that encode shape descriptions at a canonical orientation regardless of the familiarity of that orientation (Palmer, 1989; Wiser, 1981).

This possibility raises an interesting question about how shape descriptions of common polyoriented objects are encoded in long-term memory—that is, objects like hammers, razors, and pencils that are frequently seen at several different orientations in the environment (Gibson & Robinson, 1935; Newell & Findlay, 1992). Most previous studies of orientation effects with common objects have been restricted to the mono-oriented object class. However, a detailed analysis of the effects of stimulus orientation on the identification of common polyoriented objects may also provide important constraints on hypotheses about the kinds of stored representations that mediate recognition. In particular, if long-term memory stores shape representations at a canonical orientation regardless of familiarity, we might expect polyoriented objects to also be aligned to a single orientation during stimulus identification. In contrast, if the orientation specificity of stored representations is determined by familiarity, we would not expect polyoriented objects to be encoded at a canonical orientation since, by hypothesis, they are likely to have several equally familiar orientations. In addition, such an analysis may provide further evidence about the functional origin of orientation effects. If the effects that have previously been observed with mono-oriented objects result solely from the operation of mental processes that play no direct role in stimulus identification, we might expect these processes to be applied to all objects regardless of their orientability. This predicts that similar orientation effects should be observed for both mono- and polyoriented objects.

These two issues were examined in this paper by comparing the effects of stimulus orientation on the recognition of mono- and polyoriented objects using a word–picture verification paradigm. In this task, subjects judged whether written names of objects matched line drawings presented at different orientations in the image plane. This paradigm has been used in several previous recognition studies (e.g., Hamm & McMullen, 1998; Kosslyn et al., 1994) and was chosen for two main reasons. First, in name production tasks such as picture naming, verbal responses across subjects to specific objects may vary considerably among the superordinate-, basic-, and subordinate-level names. This may be important because prior evidence suggests that orientation effects depend on the level of stimulus classification required by the task (e.g., Biederman & Gehardstein, 1993; Hamm & McMullen, 1998). In the word–picture verification paradigm, the level of stimulus classification required can be more carefully controlled.¹ Second, in name production tasks, the selection of picture stimuli and the reliability of between-group comparisons are additionally constrained by lexical variables that are normally assumed to be irrelevant for object recognition (e.g., name frequency, word

length, and word-initial phoneme). These variables are less important in word–picture verification tasks since task performance is not measured in terms of name production latencies.

METHOD

Subjects

Ninety-six native French-speaking subjects from the Université Pierre Mendes France, Grenoble, participated in the word–picture verification experiment for course credit. All subjects had normal or corrected-to-normal eyesight.

Materials

The stimuli were 96 black-and-white line drawings of common objects that each possessed a clearly defined principal axis of elongation. The set included 24 mono-oriented and 24 polyoriented objects selected on the basis of a prior ratings study, described below.

Although the distinction between mono- and polyoriented objects is reasonably clear on an intuitive basis, the ratings study was carried out to obtain a more objective measure of orientability. The study was carried out at Johns Hopkins University, Baltimore, using 2 subjects who were trained to record the number of different orientations at which they saw 70 familiar objects in the natural environment. The observations were recorded in a response booklet containing a picture of each stimulus depicted at eight orientations 45° apart within a reference frame containing an *x*- and a *y*-axis. The subjects were told that the *x*-axis corresponded to the direction of the gravitational vertical, and the *y*-axis to an imaginary axis perpendicular to the gravitational vertical. They were then given extensive practice recording the orientation of the principal shape axes of different objects relative to this reference frame. Data collection was carried out over a 2-week period. The subjects were told that whenever they saw one of the test objects in the natural environment they should record the approximate orientation of its principal shape axis relative to the closest of the eight orientations depicted in the response booklet.²

At the end of the 2-week period, the number of times each object had been seen by either subject at one of the orientations was calculated. Twenty-four objects that had been seen at only one orientation were selected for use as mono-oriented stimuli in the word–picture verification experiment. The 24 objects that had been seen at the highest number of different orientations were chosen as polyoriented stimuli. The mean number of different orientations at which the polyoriented objects had been seen was 6.75/8 ($SD = 1.33$). A list of the orientation ratings for each stimulus is shown in Appendix A.

For the word–picture verification experiment, a line drawing of each stimulus was digitized using a scanner and recopied in a 12 × 12 cm frame at the following eight orientations in the image plane: 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. The 0° orientation of the mono-oriented objects always corresponded to their normal upright orientation with respect to the gravitational vertical. Thus, this orientation was vertical for some objects (e.g., skyscraper, lamp) and horizontal for others (car, motorcycle). The 0° orientation of the polyoriented objects was always such that the principal axis of elongation was parallel to the vertical axis of the monitor.

Apparatus

The experiment was run on a Macintosh IIfx computer, using Psychlab Version 0.91 software (Gum, 1995).

Design

There were 14 practice trials followed by 96 experimental trials. On each trial the written basic-level French name of an object (e.g., *arbre*—tree, *voiture*—car) was presented briefly on the screen and then replaced by a picture. There were two types of trials. On *yes* response trials, the name was appropriate for the picture that followed it. On *no* response trials, the name denoted another object type that was visually, and where possible, semantically similar to the picture (e.g., *banjo* → *guitar*). This

was done to ensure that the subjects could not make accurate responses solely by considering either the global shape outlines of the objects or specific individual shape features. The mono- and polyoriented objects chosen from the orientability ratings study were shown only in the *yes* response trials. The stimuli for the *no* response trials were randomly selected pictures of elongated common objects. In total, there were 48 *yes* (24 mono-oriented and 24 polyoriented) and 48 *no* response trials. Since orientation effects in recognition tasks are known to attenuate with practice (see, e.g., Jolicoeur, 1985; Murray et al., 1993), the subjects saw each stimulus only once. In total, each object was seen at each stimulus orientation by 12 different subjects. The trials were randomized prior to the beginning of the experiment.

Procedure

The subjects were seated approximately 36 cm from the monitor. A chinrest was used to prevent inclinations of the head. Each trial began with a prompt that remained in the center of the screen until the subject pressed the space bar. After a blank interval of 500 msec, the written name of an object was displayed for 750 msec in the same location as the prompt followed by another blank interval of 250 msec. After this, a line drawing of an object was presented in the center of the screen at one of eight orientations in the image plane. The line drawing remained on the screen until the subject made a response. The task was to respond "yes" if the written name was appropriate for the picture and "no" if it was not. There was a response deadline of 2,500 msec. If the subjects did not respond before the deadline, they heard an error tone. Responses were made by pressing one of two keys on a standard keyboard labeled "oui" (yes) and "non" (no). The *yes* responses were always made with the dominant hand. The experiment lasted about 20 min.

RESULTS AND DISCUSSION

Analysis of Reaction Times

Preliminary analyses were performed by subjects and items on the mean median reaction times (RTs) for correct responses in the *yes* trials only. Figure 1 shows the mean median RTs across stimulus orientations for the mono- and polyoriented objects.

A two-way analysis of variance (ANOVA) by subjects with stimulus orientation and object type (mono- vs.

polyoriented) as factors showed a significant main effect of stimulus orientation [$F(7,665) = 3.39, p < .001$] and object type [$F(1,95) = 70.46, p < .001$], as well as a significant interaction [$F(7,665) = 2.39, p < .01$]. An analysis of simple effects showed that there was a significant effect of stimulus orientation for the mono-oriented objects [$F(7,665) = 4.33, p < .001$], but not the polyoriented objects [$F(7,665) = 1.5$]. A two-way ANOVA by items showed a significant main effect of stimulus orientation [$F(7,161) = 2.70, p < .01$] and a significant interaction [$F(7,161) = 3.75, p < .001$], but the main effect of object type just failed to reach significance [$F(1,23) = 3.45, p < .07$]. An analysis of simple effects confirmed that there was a significant effect of stimulus orientation for the mono-oriented objects [$F(7,161) = 6.59, p < .001$], but not for the polyoriented objects [$F(7,161) = 0.67$].

Additional analyses using the *t* test for related groups showed that there were no significant differences between the RTs for mono-oriented objects presented at their upright canonical orientation and the RTs for the polyoriented objects presented at any of the eight stimulus orientations. This suggests that the absence of an orientation effect for the polyoriented objects cannot be solely accounted for in terms of a ceiling or floor effect.

An analysis was also performed to examine whether the pattern of RTs for the mono-oriented objects increased as a function of the angular distance of the stimuli from their familiar canonical orientation, as shown in several previous reports (e.g., Jolicoeur, 1985). In order to examine this possibility, the median RTs at each stimulus orientation, excluding 180°, were regressed against their angular distance from the 0° orientation.³ The results showed that within this range of orientations, distance from the canonical orientation accounted for a significant amount of variance in the RTs for the mono-oriented objects

Figure 1. Mean median reaction times (RTs) for the mono- and polyoriented objects as a function of stimulus orientation. Bars indicate standard error. RTs at the 0° orientation are repeated for ease of comparison.

$[r^2 = .84; F(1,6) = 27.16, p < .003]$, but not the poly-oriented objects $[r^2 = .06; F(1,6) = 0.31]$. Although this analysis is relatively weak, since it is based on RTs across only seven orientations, it does distinguish between the different patterns observed for the mono- and polyoriented objects.

Analysis of Error Rates

An analysis of error rates showed that the subjects made 394/4,604 (8.55%) errors on *no* response trials and 191/4,604 (4.14%) errors on *yes* response trials. A Wilcoxon test showed that this difference was significant [$Z_{\text{corr}} = -6.51, p < .001$]. For the *yes* responses, the subjects made 73/2,302 (3.17%) errors on mono-oriented object trials and 118/2,302 (5.12%) errors on polyoriented object trials, although this difference was not significant. The percentage error rates in the *yes* response trials as a function of stimulus orientation for both object types is shown in Figure 2.

A two-way ANOVA on error rates for the *yes* response trials with stimulus orientation and object type as factors showed that there were no main effects of either factor and no significant interaction. This suggests that the pattern of RTs for the mono- and polyoriented objects cannot be solely accounted for in terms of a speed–accuracy tradeoff.

Additional Planned Analyses of Polyoriented Object RTs

The results presented so far are consistent with previous reports that the time taken to identify mono-oriented objects is dependent on the angular distance of the stimulus from the canonical orientation. In contrast, the time taken to identify polyoriented objects does not appear to

be dependent on stimulus orientation. However, this finding shows only that polyoriented objects are not aligned to a single arbitrarily determined image plane orientation at which the principal axis of elongation is parallel with the visual vertical. The preliminary analyses do not address the possibility that polyoriented objects are aligned to some other single orientation.

One possibility is that these objects are aligned to a single orientation that is consistent across subjects but different across objects. If this were the case, we would expect the pattern of RTs for *individual* polyoriented objects to show an alignment of the stimulus to a single orientation—as observed for the mono-oriented objects. Since the canonical orientation may vary across objects, these alignment effects may have been obscured in the preliminary analyses by averaging RTs across objects. This possibility was examined by considering the pattern of RTs for the polyoriented objects on an item-by-item basis. For each object, the stimulus orientation with the fastest RT was assumed to be the canonical orientation. This orientation was recoded as the 0° orientation and adjacent cells were recoded as a function of their angular distance from the canonical orientation. For example, if the fastest RT for the pencil was at 90°, this orientation would be recoded as the 0° orientation and the RT at 135° recoded as the 45° orientation, and so on. Once the data for each object had been recoded in this way, the pattern of mean median RTs across stimulus orientations was recalculated. A one-way ANOVA on the realigned data showed that there was a significant effect of stimulus orientation for the polyoriented objects [$F(7,322) = 10.4, p < .001$]. However, this effect is not surprising given that the 0° orientation now contained only the fastest RTs and had an artificially low mean. The crucial question is

Figure 2. Percentage errors for the mono- and polyoriented objects as a function of stimulus orientation in the *yes* response trials.

whether the pattern of RTs across stimulus orientations increases as a function of the angular distance between the orientation of the stimulus and the putative canonical orientation, as was previously observed for the mono-oriented objects. A simple regression analysis showed that this was not the case: The angular distance of the stimulus from the 0° orientation was not a significant predictor of RTs [$r^2 = .28$, $F(1,6) = 1.95$, $p < .22$].

For comparison, the same recoding procedure was applied to the RT data for the mono-oriented objects. A one-way ANOVA on the recoded data showed that there was a significant effect of stimulus orientation [$F(7,322) = 13.6$, $p < .001$]. A simple regression analysis also confirmed that the angular distance of the stimulus from the canonical orientation remained a significant predictor of RTs [$r^2 = .80$; $F(1,6) = 24.57$, $p < .01$]. Thus, the results of these analyses are inconsistent with the possibility that polyoriented objects are aligned to a single orientation that is the same across subjects but different across objects.

Another possibility that was not examined in the preliminary analyses is that polyoriented objects might be aligned to a single orientation that varies across both subjects and objects (Cutzu & Edelman, 1994). One way to examine this possibility would be to consider the patterns of RTs across stimulus orientations for each subject and item separately. However, since each subject saw each item only once, this analysis was not possible. Instead, an alternative analysis was performed on the basis of the following prediction: If the canonical orientation of polyoriented objects varies both across subjects and objects, we would expect the variance in RTs for each object at each stimulus orientation (i.e., within each cell) to be larger for the polyoriented objects than for the mono-oriented objects. This is because for any given stimulus orientation, the angular distance to the canonical orientation should vary across subjects for the polyoriented objects but be the same across subjects for the mono-oriented objects.⁴ This prediction was tested by calculating the standard deviation in RTs at each stimulus orientation for each item separately—that is, in all 384 cells (48 objects $\times$ 8 orientations). The mean standard deviation per cell for the mono-oriented objects was 292 msec ($SD = 141$ msec) and for the polyoriented objects it was 281 msec ($SD = 167$ msec). A t test for related groups showed that this difference was not significant [$t(1,191) = .69$]. The results of this analysis are inconsistent with the possibility that polyoriented objects are aligned to a single orientation that varies across both subjects and objects.

Further Issues

It has been assumed that the crucial distinction between the two object types contrasted in this experiment is orientability—that is, the number of different orientations at which the objects are normally seen in the environment. However, one might argue that the mono- and polyoriented stimuli also differ systematically in other respects. First, the mono-oriented objects generally tend

to be physically larger than the polyoriented objects. Previous studies on mental imagery suggest that different stimulus properties may influence mental rotation performance (e.g., Kosslyn, 1973; Kosslyn & Alper, 1977). Thus, one might argue that the observed patterns of RTs actually reflect an interaction of object size and rotation rate. Second, the line drawings of the mono- and polyoriented stimuli might also differ systematically in terms of their compactness—that is, the ratio of contour perimeter and area. On some hypotheses, this factor has been assumed to influence recognition performance (e.g., Zusne, 1970). For example, it may be that pictorial compactness affects how quickly the orientation of the principal shape axis of the stimulus could be computed. Thus, the observed interaction in RTs may actually depend on pictorial compactness rather than orientability. The following post hoc analyses were carried out to address these possibilities.⁵

Effects of Physical Size

The effect of physical size was examined in the following manner: First, 10 additional subjects were presented with a randomized list containing the names of the 24 mono- and 24 polyoriented objects used in the word–picture verification experiment. They were asked to rate the relative volumetric size of each object using a scale in which the largest object (skyscraper) was preassigned a value of 10,000, and the smallest object (screw) a value of 1. A physical size index was calculated by taking the mean ratings across subjects for each object. Second, an RT index for each stimulus was calculated using the data from the word–picture verification experiment. This was done by subtracting the median RTs for each item at the 0° orientation from the average RT across stimulus orientations between 45° and 315°. The physical size and RT indices for each stimulus are shown in Appendix A.

The effect of physical size was examined using a multiple regression analysis on data from the 23 mono- and 23 polyoriented objects for which physical size ratings were obtained. In the analysis, two predictor variables—the physical size index for each object and a dummy code for orientability—were regressed against the RT index. The results showed that the two predictor variables accounted for a significant amount of variance in the RT index [$r^2_{\text{multiple}} = .261$; $F(2,43) = 7.62$, $p < .001$]. Analyses using partial correlation showed that the amount of variance accounted for solely by orientability with physical size partialled out was significant [$\text{Corr}_{\text{partial}} = -.48$; $t(43) = -3.62$, $p < .001$], but physical size alone was not a significant factor [$\text{Corr}_{\text{partial}} = -.06$, $t(43) = -.40$].

Effects of Pictorial Compactness

The effect of pictorial compactness was examined by first calculating the compactness value for each mono- and polyoriented stimulus using the formula compactness = (P^2/A) , where P is the length of the perimeter contour of the image and A is the area (Zusne, 1970). The compact-

ness value for each object together with dummy codes for orientability were then regressed against the RT index. As previously, the results showed that the two predictor variables accounted for a significant amount of variance in the RT index [$r^2_{\text{multiple}} = .30$; $F(2,45) = 9.64$, $p < .001$]. Partial correlations showed that the amount of variance accounted for solely by orientability with compactness partialled out was significant [$\text{Corr}_{\text{partial}} = -.49$; $t(45) = -3.78$, $p < .001$], but compactness alone was not a significant factor [$\text{Corr}_{\text{partial}} = -.15$; $t(43) = -.30$].

These post hoc analyses show that differences in the pictorial compactness and physical size between the mono- and polyoriented objects do not contribute to the interaction of RTs across stimulus orientations observed in the word–picture verification experiment.

GENERAL DISCUSSION

These results, consistent with several previous reports, show that the time taken to identify line drawings of common mono-oriented objects increases as a function of the angular distance between the orientation of the stimulus and its familiar canonical orientation. In contrast, the time taken to identify common polyoriented objects seems to be independent of their image plane orientation. Further analyses support the view that this interaction derives from differences in the orientability of mono- and polyoriented objects rather than other stimulus properties that might be expected to influence the time taken to identify misoriented objects such as pictorial compactness or physical size.

In the first place, it is necessary to consider one potential challenge to the importance of these results on the grounds that the word–picture verification task used in this experiment has little relevance for hypotheses about the mental processes and shape representations that mediate everyday object recognition. In response to this challenge, it is important to note that a similar orientation effect was observed for the mono-oriented objects in this experiment, as has previously been observed in several other studies using, arguably, more direct recognition tasks such as picture naming (e.g., Jolicoeur, 1985). The similarity of these effects from different experimental paradigms provides some motivation for assuming that the word–picture verification task taps functional processes that are ordinarily recruited during object recognition. Consequently, it is suggested that these results provide new evidence both about the functional origin of orientation effects and about the kinds of stored representations that mediate object recognition.

First, the results are inconsistent with the hypothesis that orientation effects in recognition tasks result from mental processes that are applied to all objects but that play no direct role in stimulus identification. If this were the case, we would expect polyoriented objects to show similar orientation effects to mono-oriented objects.

Second, the results are inconsistent with the possibility that recognition is mediated by stored representations that encode shape descriptions at a canonical orientation regardless of its familiarity. If this were so, we would expect polyoriented objects to be aligned to a single orientation during stimulus identification. However, the results showed that this was not the case.⁶

How, then, can these results be accounted for? One recent proposal that can account for these results is the “multiple-views” hypothesis (see, e.g., Tarr, 1995; Tarr & Bülthoff, 1995; Tarr & Pinker, 1989). On this hypothesis, it is assumed that long-term memory encodes orientation-specific shape descriptions. The orientation specificity of the representations is determined by the orientation at which objects are encountered—that is, by familiarity. Since mono-oriented objects are, by hypothesis, usually seen only at a single orientation, they are likely to be encoded in long-term memory at their familiar canonical orientation. However, polyoriented objects, which are often seen at several orientations, may be encoded in multiple orientation-specific representations at different familiar orientations. On some versions of this hypothesis, the recogni-

tion of misoriented objects is assumed to involve a continuous spatial transformation or alignment of the stimulus to match the orientation of the corresponding stored representation (see, e.g., Tarr, 1995; Tarr & Pinker, 1989; Ullman, 1989). Thus, the time taken to identify a misoriented mono-oriented object may be assumed to increase as a function of the angular distance between the orientation of the stimulus and its canonical orientation. In contrast, assuming that there is a sufficiently large number of different orientation-specific representations, the time taken to identify polyoriented objects may be relatively constant because the angular distance to the nearest stored representation is likely to be roughly equal regardless of stimulus orientation.

Another possibility that is consistent with the multiple-views hypothesis is that polyoriented objects are stored at only two or three different orientations. Unfortunately, the present experiment does not allow us to examine this possibility since only a relatively small number of different stimulus orientations were probed. One might also speculate about the kinds of stored representations that encode natural kinds versus artifacts. Most of the objects used in this experiment were artifacts, but certain natural kinds of objects, like cats, squirrels, and birds, are normally assumed to have a canonical orientation, although, arguably, they are not strongly mono-oriented (e.g., Palmer, Rosch, & Chase, 1981; Rosch, 1978).⁷ Thus, although these results support the view that familiarity is an important determinant of the canonical image plane orientation of mono-oriented objects, this does not preclude the possibility that other factors also play a role (see, e.g., Cutzu & Edelman, 1994; Palmer et al., 1981).

Finally, some alternative accounts of the interaction between mono- and polyoriented objects must also be considered. One possibility is that polyoriented objects are encoded in orientation-invariant representations such as the object-centered structural descriptions proposed by Marr and Nishihara (1978). Another possibility is that the recognition of polyoriented objects is mediated by some kind of orientation-invariant feature identification process (see, e.g., Corballis, 1988; Humphreys & Riddoch, 1984; Jolicoeur, 1985, 1990; Murray et al., 1993; Sutherland, 1968; Takano, 1989; Tarr, 1995; Ullman, 1989). However, although some evidence suggests that orientation-invariant recognition for image plane rotations may be achieved under certain conditions (Murray et al., 1993; Takano, 1989; Tarr & Pinker, 1990), it is not obvious why only polyoriented objects could be encoded in object-centered representations or identified using an orientation-invariant feature-matching process. First, in terms of the hypothesis proposed by Marr and Nishihara, the polyoriented objects used in this experiment each possessed a clearly defined principal axis of elongation that should be sufficient for the computation of an axis-based, object-centered representation. Second, given the rich feature structure of most common mono- and polyoriented objects, it is not obvious why a feature-based orientation-invariant process could be applied to only one object class. Thus, as presently articulated, these alternative hypotheses do not seem to provide an entirely satisfactory account of the interaction between mono- and polyoriented objects observed in this experiment.

In summary, the results reported in this paper show that, unlike common mono-oriented objects, polyoriented objects are not aligned to a single orientation during recognition. This finding provides some new evidence about the functional origin of orientation effects in recognition tasks and about the kinds of stored orientation-specific representations that mediate recognition. It is argued that these results are consistent with previous hypotheses that the recognition of polyoriented objects is mediated by multiple orientation-specific stored representations that encode information about the familiar orientations at which objects have previously been encountered.

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NOTES

1. Of course, it is not possible to ensure that each subject accesses the same kinds of information during task performance. However, the word-picture verification paradigm does allow us to at least control the level of shape classification *necessary* for accurate performance (e.g., superordinate, basic, or subordinate).
2. It should be stressed that the purpose of these ratings was merely to provide a very approximate measure of stimulus orientability as a basis for selecting stimuli for use in the word-picture verification experiment. They were not intended to provide a definitive set of orientability ratings.
3. RTs for stimuli presented at 180° were excluded from this analysis since previous reports have shown that they generally decrease at this orientation (i.e., when mono-oriented objects are presented upside down). A similar pattern also seems to have been present in this experiment (Figure 1). The reason why there is an M-shaped rather than an inverted U-shaped RT function remains unclear (see Biederman & Gerhardstein, 1993; Jolicoeur, 1985; Tarr & Pinker, 1989).
4. Another possibility would be that larger variance in the RTs for the polyoriented objects could reflect greater heterogeneity among these items in terms of others factors, such as object familiarity or visual complexity. However, since the variance was not larger for the polyoriented objects, these factors were not taken into account in the present analysis.
5. The author thanks James Cutting for raising these possibilities and suggesting the analyses.
6. It is also interesting to note that the observation of a strong orientation effect for the mono-oriented objects in this experiment seems to be inconsistent with the finding recently reported by Hamm and McMullen (1998) that such effects appear only when the task requires subordinate-level classification (see also Biederman & Gerhardstein, 1993). In the present experiment, word-picture pairings were at a basic level. This suggests that basic-level classification, at least under certain conditions, is sufficient for producing orientation effects. However, the exact reason for these different results is not clear.
7. For example, it would be interesting to exploit image plane orientation effects as a means of examining the kinds of stored representations that mediate the recognition of these types of natural objects—that is, whether, like artifactual mono-oriented objects, natural objects are also aligned to a single image plane orientation during recognition.

APPENDIX A

A List of the Mono- and Polyoriented Objects Used in the Yes Response Trials Together With Their Reaction Times (RTs) and Compactness and Physical Size Values

Stimulus	Index		
	RT	Compactness	Physical Size
Mono-oriented			
1 chair	60.5	44.7	20
2 lamp	38.0	31.6	15
3 computer	331.0	14.4	41
4 truck	117.5	22.9	300
5 television	63.5	18.7	42
6 motorcycle	66.0	25.8	50
7 stool	-36.5	49.1	50
8 tree	123.0	14.9	140
9 car	164.5	18.9	200
10 table	88.0	104.5	50
11 fridge	218.5	18.0	70
12 bench	184.0	13.0	50
13 sailboat	89.0	14.6	500
14 washing machine	2.5	16.5	50
15 desk	41.5	20.8	50
16 wardrobe	48.0	16.4	70
17 dresser	140.5	19.1	50
18 clock	72.0	29.1	65
19 crane	43.5	172.6	500
20 church	127.5	17.5	800
21 bed	123.5	24.1	80
22 house	-50.0	16.2	500
23 skyscraper	247.5	30.1	10,000
24 signpost	98.5	98.6	43
Mean	100.0	35.55	162.4*
Polyoriented			
25 pencil	43.0	76.6	5
26 lighter	81.5	19.0	7
27 razor	-173.5	77.3	5
28 clothespeg	37.5	71.4	5
29 scissors	-73.0	146.1	8
30 banana	-102.5	15.9	12
31 tennis	141.5	31.7	25
32 comb	-77.0	194.6	8
33 carrot	-11.5	62.5	9
34 pen	-92.0	25.3	5
35 match	4.0	73.5	2
36 nail	16.0	51.9	2
37 hammer	143.0	48.9	15
38 knife	-25.5	53.0	8
39 axe	204.0	47.9	20
40 toothbrush	-80.5	56.5	8
41 key	68.5	33.5	5
42 screwdriver	-66.0	82.8	9
43 pear	-127.5	20.3	10
44 flashlight	33.5	39.7	9
45 lipstick	-33.5	24.6	4
46 paintbrush	-70.0	68.3	9
47 cigarette	-30.5	60.4	4
48 screw	-278.5	26.3	1
Mean	-19.5	58.7	8.4*

*The mean physical size excludes the preassigned values of 10,000 and 1 for skyscraper and screw, respectively.

APPENDIX B
A List of Stimuli Used in the *No Response Trials*

Written Name	Picture Stimulus
1 bagpipe	accordion
2 lizard	alligator
3 harpoon	anchor
4 onion	apple
5 leek	asparagus
6 wolf	bear
7 thermos	bottle
8 dragonfly	butterfly
9 giraffe	camel
10 dagger	candlestick
11 flute	wineglass
12 squirrel	cat
13 cucumber	celery
14 pheasant	chicken
15 clog	shoe
16 bison	cow
17 hamster	mouse
18 horse	deer
19 pigeon	duck
20 mitten	glove
21 flamingo	swan
22 banjo	guitar
23 bonnet	hat
24 stocking	boot
25 cigar	pipe
26 hair-dryer	iron
27 egg-cup	vase
28 deckchair	ironing-board
29 fairy-light	lightbulb
30 tricycle	bicycle
31 hydroplane	helicopter
32 radish	mushroom
33 hairclip	padlock
34 briefcase	suitcase
35 bucket	watering-can
36 telescope	binoculars
37 mop	broom
38 metal-file	wrench
39 rifle	pistol
40 glider	airplane
41 hairbrush	brush
42 glass	cup
43 avocado	pepper
44 coconut	pineapple
45 coffee-pot	pitcher
46 tweezers	pliers
47 chainsaw	saw
48 frying-pan	saucepan

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