Effects of plane rotation, task, and complexity on recognition of familiar and chimeric objects

TOBY J. LLOYD-JONES

University of Kent, Canterbury, England

and

LINDA LUCKHURST

University of Buckingham, Buckingham, England

We examined the effects of plane rotation, task, and visual complexity on the recognition of familiar and chimeric objects. The effects of rotation, with response times increasing linearly and monotonically with rotation from the upright, were equivalent for tasks requiring different degrees of visual differentiation of the target from contrasting stimuli—namely, (1) deciding whether the stimulus was living or nonliving (semantic classification), (2) deciding whether the stimulus was an object or a nonobject (object decision), and (3) naming. The effects of complexity, with shorter response times to more complex stimuli, were most apparent in semantic classification and object decision and were additive with the effects of rotation. We discuss the implications of these results for theories of the relationship between the process of normalization and the determining of object identity.

We are able to recognize an object even when its shape does not exactly match that encountered previously. This generalization over variations in shape is evident when objects seen from different viewpoints are recognized. However, there can be costs associated with this ability. In particular, there is a monotonic increase in naming time with an increase in the angular deviation of pictures from the standard upright (Joliceur, 1985). Two accounts of this phenomenon are predominant (see Joliceur, 1990, and Lawson, 1999, for reviews). Transformation accounts propose that a process of normalization reduces the difference between the input representation and the view-specific stored image. The argument of multiple-view accounts is that there are several stored representations of each familiar object and that a given view is matched to the nearest view-specific representation. However, in certain cases—particularly, if small distinctive sets of objects are presented repeatedly—no costs of change in viewpoint are observed. An additional possibility, therefore, is that the recognition of invariant features may allow objects to be recognized irrespective of view. These three accounts are not mutually exclusive (e.g., Humphreys & Riddoch, 1984; Joliceur, 1990; Tarr & Pinker, 1989, 1990).

Effects of Rotation on Object Identification Across Different Tasks

The primary focus of the present article is the relationship between the process of normalization and the deter-

mining of object identity. Several accounts of the effects of within-plane rotation (henceforth, *rotation*) have assumed that costs associated with rotation occur because objects have to be normalized *before* visual identification takes place (e.g., Joliceur, 1990; Murray, 1997; Tarr & Pinker, 1989). It has also been argued, albeit less frequently, that normalization takes place *after* visual identification (e.g., Corballis, 1988; De Caro, 1998).

However, Hamm and McMullen (1998) found rotation effects in a word-picture verification paradigm for subordinate-level identification (e.g., of a dog as a *Scottish terrier*), but not for basic-level (as a *dog*) or superordinate-level (as an *animal*) identification. They argued that the previously observed effects of rotation on naming were due to subordinate-level visual identification and that basic-level visual identification is invariant with respect to rotation. Superordinate-level identification is assumed to be based on basic-level visual identification and on subsequent associated activation within semantics, which allows one to access superordinate identity (cf. Joliceur, Gluck, & Kosslyn, 1984).

Hamm and McMullen (1998) proposed that rotated object images are normalized *after* basic-level orientation-invariant representations have been contacted, when additional visual processing determines relatively precise spatial relations between object parts. Thus, knowledge of the basic-level category guides normalization, in order to determine subordinate-level identity. They argued that this is the case when it is necessary to visually differentiate between highly visually similar objects that share many parts and may only be distinguishable in terms of the spatial location of these parts (e.g., as when discriminating between *Scottish terriers*, *Irish setters*, and *cocker spaniels*). One problem with this account, however, is that they used relatively few objects in a verification paradigm. Lawson (1999)

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argued that, typically, rotation effects are weaker in verification than in naming, because visual differentiation is usually easier. This ease of differentiation, together with the use of relatively few objects, makes it likely that orientation-invariant features were extracted to enable basic-level identification (Lawson, 1999, pp. 231–232).

In the present research, we examined the claim that normalization is invoked only for subordinate-level identification. Given the potential importance of visual differentiation for normalization, we did so by using tasks that required different degrees of differentiation of the target from contrasting stimuli. Importantly, visual identification at the basic level would seem to have been required, at most, for a subset of these tasks.

The rationale for task selection was as follows. Access to stored visual knowledge about objects may vary as a function of the visual similarity between the target and members of the same category or members of contrasting categories and of how these relationships map onto different responses (e.g., Humphreys, Lamote, & Lloyd-Jones, 1995; Jolicoeur et al., 1984; Lloyd-Jones & Humphreys, 1997a, 1997b; Snodgrass & McCullough, 1986). We focused primarily on the visual similarity of a target to members of a contrasting category, in forced two-choice decisions, and examined the effects of rotation on (1) decisions as to whether the stimulus was a living or a nonliving object (semantic classification), (2) decisions as to whether the stimulus was an object that may be encountered in real life (object decision), and (3) responses with the first correct name that came to mind (*free* naming). Naming was used as a comparison task, for which effects of rotation had been observed previously (e.g., Jolicoeur, 1985; McMullen & Jolicoeur, 1992).

Semantic classification may involve more abstract or more specific visual representations, depending on the stimulus set: Pictures of fruits take longer to classify as fruits, when contrasted with vegetables rather than with animals (Job, Rumiati, & Lotto, 1992; Snodgrass & McCullough, 1986). In contrast, there is a tendency for pictures of fruits to be classified as fruits in less time than corresponding basic-level names when they are contrasted with animals, but not when they are contrasted with vegetables (Job et al., 1992). This pattern of results is consistent with a fast picture classification process in the visually dissimilar comparison condition (i.e., fruits contrasted with animals), based either on early visual processing, which produces a coarse shape representation using information common to category members, or on a basic-level visual representation (Job et al., 1992; Snodgrass & McCullough, 1986). For the visually similar comparison condition (i.e., fruits compared with vegetables), Job et al. suggested that there is a slower process based on access to semantic information. We propose, therefore, that a visually dissimilar comparison of living objects contrasted with nonliving objects will involve a fast picture classification process, which does not require visual processing equivalent to identification at the subordinate level.

Similarly, object decisions may require different levels of visual abstraction, depending on how nonobjects are con-

structed. We used two variants of the task. We made the task of visually differentiating objects from nonobjects either relatively easy, by constructing chimeric nonobjects through the use of parts exchanged across living and nonliving things (*across-category object decision*; e.g., *duck–boot*), or relatively difficult, by constructing nonobjects through the use of parts exchanged within living and nonliving things (*within-category object decision*; e.g., *chicken–rabbit*). Basic-level visual identification is likely necessary, but additional visual processing equivalent to subordinate-level identification is not required. Examples of both kinds of nonobjects are given in Figure 1.

In contrast, for *free* naming, the participants were required to name the object quickly and efficiently. In this case, the stimulus had to be matched to a unique label, and hence, finer visual differentiation would likely be necessary than in semantic classification and object decision, for which the stimulus need only be matched with a more general object label (living/nonliving or object/nonobject).

We predicted the shortest response times (RTs) to semantic classification and the longest RTs to naming. RTs for object decision should be between these two extremes, with the difficult version producing longer RTs than the easy version. Consistent with this, Lloyd-Jones and Humphreys (1997a) found shorter RTs for semantic classification than for naming (in their case, the semantic decisions were fruits/vegetable and clothing/furniture, which likely involved greater visual differentiation than did the living/nonliving classification used here). In addition, Lloyd-Jones and colleagues (Lloyd-Jones & Humphreys, 1997b; Lloyd-Jones & Luckhurst, 2002) found substantially shorter RTs for object decision than for naming.

Predictions concerning the effects of rotation across tasks were as follows. If normalization procedures are invoked only *after* basic-level orientation-invariant representations have been contacted and only when the spatial relations of an object must be determined to make fine visual discriminations between a target and competitors, we would predict *no* effects of rotation for semantic classification as living/nonliving and for object decision. We could plausibly argue that these decisions do not require visual representations as precise as those for naming. Furthermore, these decisions do not necessitate determining the spatial relations between object parts to the degree necessary, for instance, to differentiate the target from other objects sharing many parts. Rather, at most, identification at the basic-level would seem to be likely. In contrast, if naming requires additional visual processing equivalent to subordinate-level identification (as was suggested by Hamm & McMullen, 1998, p. 423), we would predict effects of rotation for this task alone.

Alternatively, if normalization procedures can operate on less precise visual representations than those necessary for subordinate-level identification, we would predict effects of rotation for all tasks. In this case, if normalization occurs prior to identification, we must assume an early, primitive shape representation, sufficient for determining the general pose of an object, but insufficient for classifying the object. One possibility is an orientation-dependent

Across-Category Object Decision: Low-Decomposable Nonobjects

Across-Category Object Decision: High-Decomposable Nonobjects

Within-Category Object Decision: Low-Decomposable Nonobjects

Within-Category Object Decision: High-Decomposable Nonobjects

Figure 1. Examples of high- and low-decomposable nonobjects.

axis-finding mechanism, which may guide the normalization process (Tarr & Pinker, 1991). Note that in object decision, participants have to classify both objects and nonobjects. Nonobjects were constructed to have a clear top and bottom and a main axis around which the object was rotated. Therefore, if some early orientation-dependent axis-finding mechanism influences and guides the normalization process, we would predict effects of rotation for nonobjects that are equivalent to those for objects. A second possibility is that normalization may occur after identification and may be used to *double-check* identity information derived from coarse *orientation-free descriptions* on some subset of trials (i.e., representations of shapes that are independent of any coordinate system—essentially, orientation-invariant shape attributes). On this account, ro-

tated objects are likely to give rise only to coarse levels of activation in memory, and so normalization is used in order to verify identity (Corballis, 1988). In this case too, we would predict effects of rotation for all tasks.

Effects of Visual Complexity

As a subsidiary issue, we examined the effects of visual complexity on identification and normalization in the different tasks. Effects of complexity on object identification have been little studied, and the few relevant studies have found little or no effect of variations in complexity (for a review, see Johnson, Paivio, & Clark, 1996). Biederman (1987) reported a small trend toward shorter RTs for the naming of more complex objects (where *complexity* is defined in terms of number of *geons*, orientation-invariant

components that encode three-dimensional information about an object). He proposed that the lack of a disadvantage for more complex objects is consistent with parallel activation of representations derived from the stimulus, rather than with a serial trace of the contours of the object to establish whether two elements are joined by a common curve (e.g., Jolicoeur, Ullman, & Mackay, 1991; Ullman, 1984). Biederman (1987, p. 131) further speculated that the trend toward an advantage for more complex objects results from an increased number of potentially diagnostic matches of component parts to object representations stored in memory. We note, however, that this has not been modeled in recent connectionist implementations of this account (e.g., Hummel & Biederman, 1992), and in fact, more complex objects will have a greater number of spatial relations, which may detrimentally influence the process of matching *geon feature assemblies* to stored object representations (see Hummel & Holyoak, 1997, for a discussion of the detrimental effects of complexity in a similar connectionist architecture).

Studies have also reported effects of visual complexity on mental image rotation, with more complex stimuli requiring longer to rotate mentally (for reviews, see Dror, Ivey, & Rogus, 1997; Kosslyn, 1994). Kosslyn suggested that, under certain circumstances, local details may be scanned to augment the global image during the rotation process. However, although it has been widely assumed that mental rotation is used to recognize plane rotated pictures (e.g., Jolicoeur, 1990; Tarr & Pinker, 1989), recent studies have suggested that normalization may involve transformation processes other than mental rotation (Jolicoeur, Corballis, & Lawson, 1998; Lawson & Jolicoeur, 1999). Candidate processes include *image alignment* (Ullman, 1989) and *view interpolation* (Bülthoff & Edelman, 1993; Ullman & Basri, 1991).

The findings outlined above suggest that effects of complexity may be evident in object (and nonobject) identification, with shorter RTs for more complex stimuli. In addition, if normalization involves mental rotation, more complex objects may take longer to rotate.

METHOD

Participants

There were three groups of participants: Twenty-four participants performed semantic classification, 48 performed object decision, and 24 named objects. All were University of Kent undergraduate students, participating in partial fulfillment of a course requirement or for payment. All were native English speakers, with normal or corrected-to-normal vision. The participants were naive as to the purpose of the experiment and had not previously participated in a rotated picture experiment.

Materials and Apparatus

Object complexity was operationalized in terms of visual *decomposability*. There were 72 line drawings of objects, 36 *high decomposable* and 36 *low decomposable* (full lists are given in Table 1). Drawings of objects were selected from the standardized set of Snodgrass and Vanderwart (1980). Object decomposability ratings were obtained for all of the Snodgrass and Vanderwart set from 34 raters (who did not take part in the experiment). The raters were asked to decide into how many parts each picture may be decomposed, em-

phasizing that parts need not be nameable but must be visible in the drawing. The objects were then divided into high- and low-decomposable sets, where high = 10.85 parts and low = 5.45 parts, on average [$t(70) = 10.214, p < .0001$]. These sets were matched for contour overlap (Humphreys, Riddoch, & Quinlan, 1988), image agreement, imageability (ratings from 30 raters, using instructions from Snodgrass & Vanderwart, 1980), age of acquisition (ratings from Snodgrass & Yuditsky, 1996), familiarity, name agreement, word frequency (Francis & Kučera, 1962), number of syllables, and number of letters (all pairwise comparison $ps > .05$). The objects were also carefully selected to be mono-oriented (usually seen from a single viewpoint) and not radially symmetric (where objects appear highly similar in different orientations).

For the object decision tasks, nonobjects were constructed in two ways. For the across-category object decision task, nonobjects were constructed by exchanging parts *across* living/nonliving categories, within a particular high- or low-decomposable set of objects. For the within-category object decision task, nonobjects were constructed by exchanging parts *within* living/nonliving category and within a particular high- or low-decomposable set of objects. For both tasks, this process involved a two-way exchange of parts (e.g., a *duck-boot* nonobject was complemented by a *boot-duck* nonobject constructed using the remaining parts of the first nonobject). Nonobjects were constructed so as to have a clear top and bottom and central axis and to be radially non-symmetric. Rotations of the nonobjects 60° and 120° from upright were obtained using the main object axis (see Figure 1 for examples). The main axis of an object may be determined by elongation and/or other cues, such as axes of symmetry and identification of component parts of the object (e.g., the head of an animal); we therefore used the main axis agreed upon by at least four fifths of the independent judges. The nonobjects were created so as to have all the Gestalt properties of pictures of objects. Thus, the participants were not able to respond on the basis of gross figural differences between the objects and the nonobjects.

The stimuli were presented on a PowerMac 8200/120 computer using SuperLab software (Version 1.5.7). For semantic classification and object decision tasks, keypresses activated computer-controlled collection of RTs (measured in milliseconds), and the timing cycle began with the onset of the target and terminated with the participant's response. For naming tasks, latencies in vocalizing were obtained by interfacing the computer with a crystal clock and voice-activated relay so that the timing cycle began with the onset of the target and terminated with the participant's response.

Design and Procedure

Different groups of participants performed each task. The two main factors examined in all the tasks were rotation (0° vs. 60° vs. 120° from upright) and decomposability (high vs. low). A standard counterbalancing design was used, so that the 72 objects were ordered into three sets of 12 high- and 12 low-decomposable objects for each of the three rotation conditions (0°, 60°, and 120° from upright),

Table 1
Experimental Stimuli

High-Decomposable Objects
ant, bicycle, bus, chair, church, couch, cow, desk, dog, elephant, fox, giraffe, goat, gorilla, grasshopper, helicopter, house, kangaroo, leopard, lion, motorcycle, mouse, piano, pig, rabbit, raccoon, rhino, rocking chair, roller skate, rooster, stove, telephone, tiger, train, turtle, zebra
Low-Decomposable Objects
airplane, alligator, basket, bear, boot, cap, cup, dress, duck, eagle, frog, harp, hat, hi-fi, iron, kettle, monkey, nose, ostrich, peacock, penguin, pitcher, pot, refrigerator, sailboat, shoe, skunk, sled, suitcase, swan, television, toaster, toe, truck, wagon, whistle

matched as far as possible on the variables outlined above. The stimuli were counterbalanced across participants and rotation conditions, so that each object appeared once for each subject and, across the task, appeared equally often in each rotation condition.

For semantic classification, the decision was living versus nonliving. A total of six high- and low-decomposable filler items were used to equate the number of living and nonliving items in each of the three high- and low-decomposability sets and to ensure that each set had equal numbers. Data from filler items were not included in the analyses.

For object decision, two additional factors were (1) whether the stimulus was an object or a nonobject and (2) whether the participants performed an across-category object decision task, in which the nonobjects were constructed by using parts from both living and nonliving objects, or a within-category object decision task, in which the nonobjects were constructed by using parts only from living or nonliving objects. The same counterbalancing design was used for nonobjects for each object decision task.

For naming, we will detail the criteria adopted for classification as a correct or incorrect response in the Results section for that task.

There were 10 practice trials, using items not otherwise encountered (items were equal numbers of high- and low-decomposable objects). The stimuli were presented centered at fixation until the participant responded with a keypress (for semantic classification and object decision) or a naming response. For keypress responses, the participant responded by pressing either the "z" or the "m" on the keyboard, identifying the stimulus as either living or nonliving in the semantic classification task or as an object or a nonobject in the object decision task. The mapping of key onto response was counterbalanced and controlled for hand dominance.

Mean correct RTs and errors were collated. The mean correct RTs, standard errors, and percentages of errors for each task and for each condition are given in Figures 2–5. A trial was scored as an error if (1) the participant gave an incorrect response, (2) the response latency was outside the criterion used for data trimming, or (3) a machine error occurred. In the error analysis, only trials falling into Categories 1 and 2 were used. Data were trimmed by using the nonrecursive moving criterion cutoff procedure of Van Selst and Jolicoeur (1994) in order to take sample size into account. This criterion resulted in the removal of 1.3% of the data. Subscripts 1 and 2 attached to the F statistic refer to the by-participant and by-item analyses, respectively. There was no evidence of a speed–accuracy tradeoff qualifying the interpretation of the RT data for any task.

We used analyses of variance (ANOVAs) to examine the effects of rotation (0° vs. 60° vs. 120°) and decomposability (high vs. low decomposability). For object decision, additional factors were object type (object vs. nonobject) and difficulty (across-category object decision vs. within-category object decision). Significant and marginally significant ($p < .07$) results are reported. To establish a linear component for the effects of rotation, we carried out tests for linear trend and deviation from linear trend (i.e., a test on the residual variance after the variance for the linear trend was removed; when there are three points, as here, this is equivalent to a test for a quadratic trend; see, e.g., Ferguson & Takane, 1989, pp. 328–332). For other planned comparisons, we used the cells means tests procedure advocated by Toothaker (1993, pp. 74–78). Alpha was set at $p < .05$. We will summarize the main findings after presentation of the results for each task.

For clarity, we will present across-task statistical comparisons first, to see whether the effects of rotation on objects were equivalent for the different tasks. We will then present the results for each task individually.

RESULTS

Across-Task Comparison

ANOVAs were carried out on RTs and errors to objects in semantic classification, across- and within-category

object decision, and naming. We label this factor *task*. The other factors are the same in subsequent analyses—namely, rotation and decomposability.

Response times. There was a main effect of rotation [$F_1(2,184) = 37.78$, $MS_e = 9,355$, $p < .001$; $F_2(2,140) = 30.12$, $MS_e = 17,372$, $p < .001$], with a large linear component to the effect [$F_1(1,92) = 77.82$, $p < .001$; $F_2(1,70) = 70.42$, $p < .001$] and no significant deviation from linearity [$F_1(1,92) = 1.09$; $F_2 < 1$]. There was a main effect of task [$F_1(3,92) = 36.91$, $MS_e = 134,142$, $p < .001$; $F_2(3,210) = 328.10$, $MS_e = 25,470$, $p < .001$]. Planned comparisons revealed the following pattern of RTs: semantic classification (650 msec) < across-category object decision (787 msec) < within-category object decision (942 msec) < naming (1,079 msec). Finally, there was a main effect of decomposability, with longer RTs to low-decomposable objects by participants only [$F_1(1,92) = 9.86$, $MS_e = 7,012$, $p < .005$; $F_2(1,70) = 1.99$, $MS_e = 92,525$].

Importantly, there was no task $\times$ rotation interaction [$F_1(6,184) = 1.48$, $MS_e = 9,355$; $F_2(6,420) = 1.69$, $MS_e = 12,637$] and no interaction between task and the linear component of rotation [$F_1(3,92) = 1.64$; $F_2(1,70) = 0.73$].

Errors. There was a main effect of rotation [$F_1(2,184) = 11.89$, $p < .001$; $F_2(2,140) = 9.35$, $p < .001$], with a large linear component to the effect [$F_1(1,92) = 22.95$, $p < .001$; $F_2(1,70) = 13.16$, $p < .001$] and no significant deviation from linearity ($F_s < 1$). There was a main effect of task [$F_1(3,92) = 22.3$, $p < .001$; $F_2(3,210) = 8.73$, $p < .001$]. Planned comparisons of the main effect of task revealed more errors to naming and within-category object decision (with no difference between the two), as compared with across-category object decision and semantic classification (with no difference between the two). Finally, there was a main effect of decomposability by participants only, with more errors to low-decomposable objects [$F_1(1,92) = 34.3$, $p < .001$; $F_2(1,70) = 2.38$].

There was no task $\times$ rotation interaction [$F_1(6,184) = 0.81$, $MS_e = 1.03$; $F_2(6,420) = 1.11$, $MS_e = 0.65$] and no interaction between task and the linear component of rotation [$F_1(3,92) = 1.20$; $F_2(1,70) = 0.73$].

Semantic Classification

Response times. A visual summary is given in Figure 2. There was a main effect of rotation [$F_1(2,46) = 10.50$, $MS_e = 3,655$, $p < .001$; $F_2(2,140) = 11.74$, $MS_e = 6,154$, $p < .001$], with a large linear component to the effect [$F_1(1,23) = 30.47$, $p < .001$; $F_2(1,70) = 29.83$, $p < .001$] and no significant deviation from linearity ($F_s < 1$). There was also a main effect of decomposability, with longer response times for low-decomposable objects [$F_1(1,23) = 31.68$, $MS_e = 1,901$, $p < .001$; $F_2(1,70) = 11.29$, $MS_e = 12,595$, $p < .005$]. There was no decomposability $\times$ rotation interaction ($F_s < 1.25$).¹

Errors. There was a main effect of decomposability, with more errors for low-decomposable objects by participants only [$F_1(1,23) = 14.98$, $MS_e = 0.50$, $p < .001$; $F_2(1,70) = 2.09$, $MS_e = 2.41$].

Figure 2. Mean reaction times (RTs, in milliseconds), standard errors, and percentages of errors (PEs) for semantic classification for high- and low-decomposable objects at 0°, 60°, and 120° of rotation from upright. Note that this graph has a different range and scale from those of Figures 3–5.

Object Decision

Response times. Visual summaries are given in Figure 3 (across-category object decision) and Figure 4 (within-category object decision). There was a main effect of rotation [$F_1(2,92) = 32.22$, $MS_e = 15,032$, $p < .001$], with a large linear component to the effect [$F_1(1,46) = 73.79$, $p < .001$] and no significant deviation from linearity [$F_1(1,46) = 1.71$]. There was a main effect of decomposability, with longer RTs for low-decomposable stimuli [$F_1(1,46) = 15.79$, $MS_e = 27,513$, $p < .001$]. There was a main effect of object type, with longer RTs for nonobjects [$F_1(1,46) = 58.25$, $MS_e = 40,960$, $p < .001$]. There was a main effect of difficulty, with longer RTs for within-category object decision [$F_1(1,46) = 11.23$, $MS_e = 403,822$, $p < .005$]. Finally, there was a decomposability $\times$ object type interaction [$F_1(1,46) = 12.83$, $MS_e = 19,164$, $p < .001$]. Planned comparisons revealed longer RTs for low- than for high-decomposable object types only for nonobjects.

Since different nonobjects were constructed for across- and within-category object decision tasks, we conducted separate item analyses on each task. The pattern of results was the same. For across-category object decision, there was a main effect of rotation [$F_2(2,280) = 18.21$, $MS_e = 18,332$, $p < .001$], with a large linear component to the effect [$F_2(1,140) = 40.67$, $p < .001$], although there was also a significant deviation from linearity [$F_2(1,140) =$

6.67, $p < .01$]. There was a main effect of decomposability, with longer RTs for low-decomposable stimuli [$F_2(1,140) = 19.48$, $MS_e = 38,102$, $p < .001$]. There was also a main effect of object type, with longer RTs for nonobjects [$F_2(1,140) = 37.36$, $MS_e = 38,102$, $p < .001$]. Finally, there was a decomposability $\times$ object type interaction [$F_2(1,140) = 6.42$, $MS_e = 38,102$, $p < .05$]. For within-category object decision, there was a main effect of rotation [$F_2(2,280) = 18.32$, $MS_e = 32,698$, $p < .001$], with a large linear component to the effect [$F_2(1,140) = 39.01$, $p < .001$] and no significant deviation from linearity ($F_2 < 1$). There was a main effect of decomposability, with longer RTs for low-decomposable stimuli [$F_2(1,140) = 6.24$, $MS_e = 41,974$, $p < .05$]. There was also a main effect of object type [$F_2(1,140) = 84.05$, $MS_e = 41,974$, $p < .001$]. Finally, there was a decomposability $\times$ object type interaction [$F_2(1,140) = 4.95$, $MS_e = 41,974$, $p < .05$].

Errors. There was a main effect of rotation [$F_1(2,92) = 15.81$, $MS_e = 2.32$, $p < .001$], with a large linear component to the effect [$F_1(1,46) = 73.5$, $p < .001$] and no significant deviation from linearity ($F_1 < 1$). There was a main effect of decomposability, with more errors to low-decomposable stimuli [$F_1(1,46) = 6.06$, $MS_e = 1.48$, $p < .05$]. There was a main effect of object type, with more errors to nonobjects [$F_1(1,46) = 46.30$, $MS_e = 4.38$, $p < .001$]. There was a main effect of difficulty, with more errors for within-category object decision [$F_1(1,46) =$

Figure 3. Mean reaction times (RTs, in milliseconds), standard errors, and percentages of errors (PEs) for across-category object decision for high- and low-decomposable objects and nonobjects at 0°, 60°, and 120° of rotation from upright.

78.84, $MS_e = 4.34$, $p < .001$]. Finally, there was an object type $\times$ difficulty interaction [$F_1(1,46) = 31.48$, $MS_e = 4.38$, $p < .001$]. Planned comparisons revealed more errors for nonobjects than for objects only for within-category object decision.

Since different nonobjects were constructed for across- and within-category object decision tasks, we conducted separate item analyses on each task. For across-category object decision, there was a main effect of rotation [$F_2(2,280) = 10.54$, $MS_e = 0.74$, $p < .001$], with a large linear component to the effect [$F_2(1,140) = 15.93$, $p < .001$] and no significant deviation from linearity ($F_2 < 1$). There was also a marginally significant main effect of decomposability, with more errors to low-decomposable stimuli [$F_2(1,140) = 3.73$, $MS_e = 1.98$, $p = .05$]. For within-category object decision, there was a main effect of rotation [$F_2(2,280) = 13.15$, $MS_e = 1.20$, $p < .001$], with a large linear component to the effect [$F_2(1,140) = 23.54$, $p < .001$] and no significant deviation from linearity ($F_2 < 1$). There was a main effect of object type [$F_2(1,140) = 32.59$, $MS_e = 6.91$, $p < .001$]. There was also a rotation $\times$ object type interaction [$F_2(2,280) = 5.22$, $MS_e = 1.20$, $p < .01$]. Note that this interaction, which is not evident for the participants analysis or for the across-category object decision item analysis,

most likely arises owing to a rogue value's elevating the error rate for objects in the 60° condition.

Naming

Responses were classified as correct or as errors in the following way. Responses were considered correct if they corresponded to the dominant name given in the Snodgrass and Vanderwart (1980) norms or if 10% of the participants tested by Snodgrass and Vanderwart consistently used an alternative name (e.g., most participants referred to *rooster* by the name *chicken*, and more than 10% considered *hen* appropriate. These were therefore considered correct names). We also accepted alternative names as correct if they were given by a minimum of 25% of our participants. Following this procedure, six alternative names were accepted as correct (*hen* and *chicken* for *rooster*, *crocodile* for *alligator*, *sofa* for *couch*, *cart* for *wagon*, and *record player* for *hi-fi*). The remaining responses were considered as errors (although superordinate terms, for instance, are not strictly an error). To examine the nature of errors defined in this way, three independent judges were asked to classify naming errors into seven categories on the basis of the correct name as determined by Snodgrass and Vanderwart. These seven categories accounted for all errors.

Figure 4. Mean reaction times (RTs, in milliseconds), standard errors, and percentages of errors (PEs) for within-category object decision for high- and low-decomposable objects and nonobjects at 0°, 60°, and 120° of rotation from upright.

The total proportion of errors was 10.3% (179/1,728 items). Of the 179 errors, the proportion of each error type was as follows: (1) doesn't know name, 3.3%; (2) lower level identification response (e.g., for *bear* responds *polar bear*), 2.8%; (3) within-level identification response (e.g., for *cap* responds *shoe*), 73.7%; (4) across-level identification response (e.g., for *toe* responds *ship*), 2.8%; (5) higher level identification response (for *goat* responds *animal*), 10.6%; (6) within-level identification + phonologically similar response (e.g., for *toe* responds *thumb*), 5.7%; and (7) across-level identification and phonologically similar response (e.g., for *record player*, deemed an acceptable alternative for *hi-fi*, responds *recorder*), 1.1%. The majority of errors, therefore, are within-level identifications according to the names given by Snodgrass and Vanderwart (1980), and the vast majority of these errors were at the basic level. Thus, the 73.7% comprised of 117 basic-level errors and 15 subordinate-level errors. Furthermore, only a small proportion of these errors were to objects that, if named correctly according to Snodgrass and Vanderwart, would be named at the subordinate level—that is, birds (rooster, duck, eagle, ostrich, peacock, penguin, and swan), insects (ant, grasshopper), rocking chair, and sail-

boat. There were, therefore, an insufficient number of errors to independently analyze either subordinate-level or superordinate-level error responses.

Response times. A visual summary is given in Figure 5. There was a main effect of rotation [$F_1(2,46) = 6.53$, $MS_e = 15,826$, $p < .005$; $F_2(2,140) = 6.33$, $MS_e = 19,078$, $p < .005$], with a large linear component to the effect [$F_1(1,23) = 10.52$, $p < .001$; $F_2(1,70) = 12.91$, $p < .001$] and no significant deviation from linearity [$F_1(1,23) = 1.81$; $F_2 < 1$]. There was no main effect of decomposability and no decomposability $\times$ rotation interaction (for the latter, $F_s < 2.40$).

A number of objects may be considered to have been named at the subordinate level, rather than at the basic level (cf. Hamm & McMullen, 1998, p. 423): birds, insects, rocking chair, and sailboat (11 in all). We therefore repeated the analyses by dropping these items; the results were unaltered.²

Errors. Analysis of overall error scores showed a main effect of rotation [$F_1(2,46) = 12.95$, $p < .001$; $F_2(2,140) = 6.05$, $p < .005$], with a large linear component to the effect [$F_1(1,23) = 26.70$, $p < .001$; $F_2(1,70) = 9.63$, $p < .001$] and no significant deviation from linearity [$F_1(1,23) =$

Figure 5. Mean reaction times (RTs, in milliseconds), standard errors, and percentages of errors (PEs) for naming high- and low-decomposable objects at 0°, 60°, and 120° of rotation from upright.

2.44; $F_2(1,70) = 2.30$]. There was also a main effect of decomposability, with more errors for low-decomposable objects by participants only [$F_1(1,23) = 25.12, p < .001$; $F_2(1,70) = 1.16$].

Summary of Overall Results

The results are clear cut: (1) There were differences in RTs to objects for the three tasks, with RTs to semantic classification < across-category object decision < within-category object decision < naming; (2) there were equivalent effects of rotation for the three tasks and for both objects and nonobjects in object decision, with a linear and monotonic increase in RT with angular deviation of pictures from the standard upright (with RTs to 0° < 60° < 120° of rotation from upright); (3) there were shorter responses to high- than to low-decomposable objects in semantic classification and to high- than to low-decomposable nonobjects in across-category and within-category object decision. There was also some evidence for complexity effects, in the same direction, on object accuracy for objects in object decision and naming.

DISCUSSION

Effects of Rotation on Object Identification Across Different Tasks

The task differences are consistent with different levels of the visual differentiation, between a target and com-

petitor objects, that is necessary for identification. Shortest RTs were observed for semantic classification. This is consistent with a fast picture classification process in which either the visual information common to a number of category members is computed (e.g., coarse global shape properties) in order to make a decision or a basic-level representation is activated. Responses were shorter to across-category than to within-category object decisions. In the former case, the target object had to be differentiated from nonobjects composed of parts of both living and nonliving things. In the latter case, the target had to be differentiated from nonobjects that were more visually similar to objects, since they were composed of parts of objects from the same living or nonliving category. Finally, for naming, the stimulus had to be matched to a unique label, and hence, finer visual differentiation was likely necessary than in the semantic classification and object decision tasks, in which the target had only to be matched with a more general object label.

The effects of rotation were equivalent across tasks for both objects and nonobjects. This evidence argues strongly against Hamm and McMullen's (1998) claim that rotation effects are evident only when identification requires subordinate-level visual processing that includes normalization of the stimulus. It is unlikely that additional visual processing beyond that required to establish basic-level identity was involved, and involved equally, in all three tasks used here: RTs ranged from 650 to 1,194 msec for objects

and nonobjects, and responses could be mapped onto basic-level or more primitive representations. Rather, we propose that additive effects of task and rotation are consistent with accounts proposing (1) normalization prior to identification, perhaps through an orientation-dependent axis-finding mechanism that guides the normalization process (Tarr & Pinker, 1991), or (2) normalization after some form of identification has occurred, perhaps after coarse object-centered shape representations have been established that are sufficient for locating the internal axes of rotated objects and guiding normalization (Corballis, 1988).

We can reconcile the present results with those of Hamm and McMullen (1998) in the following way. Hamm and McMullen used relatively few, distinct objects in a verification paradigm. This ease of discriminability makes it likely that orientation-invariant features were extracted to enable basic-level identification (Lawson, 1999). Hence, they observed effects of rotation for subordinate-level, but not basic-level, word-picture matching. More recently, however, in a picture-naming paradigm, Dickerson and Humphreys (1999) found larger rotation effects for subordinate-level naming than for basic-level naming and minimal effects for superordinate-level naming. There are two points to note here. First, their subordinate-level naming task was very difficult, with average RTs and error rates of 1,643 msec and 19%, respectively. This suggests that visual discriminations were likely much more difficult than those required here. This difficulty may have encouraged participants to invoke additional processes that influence normalization—for instance, scanning local details to augment the global shape during the rotation process. Second, their failure to find an effect of rotation on RTs in superordinate-level naming may be due to lack of power or, as they suggest, to the use of orientation-invariant features. There was a trend toward an effect of rotation in the accuracy data for this task, and a number of their selected items were not strongly mono-oriented and, therefore, not expected to show strong effects of rotation (e.g., trout, shark, catfish, angel fish, rifle, revolver, machine gun, and pistol).

Effects of Complexity

Effects of complexity, with shorter responses to more complex objects, were apparent for objects in semantic classification and for nonobjects in across- and within-category object decision. There was also a trend to similar effects of complexity for objects in object decision and naming.

The effects of complexity cannot be attributed to pre-existing differences between the stimulus sets other than object decomposability (e.g., familiarity, name frequency, or age of acquisition). Furthermore, our results are not consistent with either (1) a serial curve-tracing account of complexity or (2) a normalization process involving mental image rotation. These accounts predict longer RTs, and longer rotation times, respectively, for more complex stimuli. Rather, with respect to normalization, our data are consistent with Joliceur et al. (1998) and Lawson and

Joliceur (1999), who suggest that it may not be the same as mental rotation.³

We can explain the effects of complexity on identification by reference to componential object representations (e.g., Biederman, 1987). For basic-level object identification, component representations are matched, in parallel, with unlimited capacity to stored object representations, which are also componentially structured. The additional components in more complex objects afford a redundancy gain from the greater number of possible diagnostic matches to their representations in memory. However, it is not clear on this account why these effects should be most apparent in semantic classification and in object decisions to nonobjects. One possibility, given the trend toward an effect of complexity in naming and the fact that observed power is much greater for semantic classification and object decision than for naming, is that null effects are due to lack of power (the observed power values for a main effect of complexity, where $\alpha = .05$, were .97, 1.00, and .17 for semantic classification, object decision, and naming, respectively). Naming likely involves processes additional to those for semantic classification and object decision, which may have washed out the effects of a variable located at an early stage of processing (Lloyd-Jones & Humphreys, 1997b; Lloyd-Jones & Luckhurst, 2002). However, this cannot explain the larger effects of complexity on nonobjects, as compared with objects, in object decision. For nonobjects, therefore, the effects of complexity may have been exaggerated by an additional serial search process that was used to determine the location of incongruous parts. Consistent with such a strategy, RTs for rejecting nonobjects were longer than those for accepting objects (994 vs. 864 msec, respectively).

Biederman's (1987; see also Hummel & Biederman, 1992) recognition-by-components theory also has the potential to explain the effects of rotation observed here. Biederman's (1987) account does not posit an image transformation process but proposes that, for rotated stimuli, "an effect arises . . . from the perturbation of the 'top-of' relations among the components" (Biederman, 1987, p. 140). These relations and others, such as *side-connected* and *larger-than*, are specified for joined pairs of orientation-invariant geons, so that the same geons in different relations may represent different objects at the basic level (e.g., a cup and a pail). If we assume that semantic classification, object decision, and naming involve basic-level identification, a disruption of *top-of* spatial relations among components can account for the effects of rotation observed here. In a similar vein, Hummel and Biederman (1992, p. 506) have suggested that the detrimental effects of rotation on performance may result from disruption to the original coarse orientations of component geons and their spatial relations, as well as from the creation of spurious *beside* spatial relations among components as objects are rotated.

Conclusions

The data presented in this article contradict Hamm and McMullen's (1998) transformation account of object recog-

nitition, whereby effects of rotation reflect subordinate-level visual processing, which includes normalization of the stimulus. We provide evidence that normalization may operate on less precise visual representations than those necessary for subordinate-level identification. An alternative possibility is that the effects of rotation reflect the disruption of componential object representations necessary for basic-level identification. The effects of complexity on task performance provide converging evidence for the importance of such object representations.

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NOTES

1. One concern here is that living things may be identified more easily as members of their superordinate category (Riddoch & Humphreys, 1987). There are more living things in the high-decomposability set (58%) than in the low-decomposability set (30%); therefore, to control for this potential confound, we carried out an analysis of covariance with living/nonliving as the covariate (living objects were assigned a value of 0, and nonliving objects were assigned a value of 1 in the analysis). The covariate was not significant [$F_2(1,69) = 2.9$, $MS_e = 12,257$], and the main effects remained [rotation, $F_2(2,138) = 6.19$, $MS_e = 6,192$, $p < .005$; and decomposability, $F_2(1,69) = 7.35$, $MS_e = 12,257$, $p < .01$; least squares means for high- and low-decomposable objects were 634 and 677 msec, respectively].

2. For RTs, a main effect of rotation remains [$F_1(2,46) = 5.88$, $MS_e = 16,450$, $p < .005$; $F_2(2,118) = 7.93$, $MS_e = 14,914$, $p < .001$], with a large linear component to the effect [$F_1(1,23) = 13.09$, $p < .001$; $F_2(1,59) = 18.90$, $p < .001$] and no significant deviation from linearity ($F_s < 1$). If we analyze only the dropped items, there are no significant effects ($F_s < 1$).

Similarly, for errors, the main effect of rotation remains, although it is marginally significant [$F_1(2,46) = 2.48$, $MS_e = 66.16$, $p = .09$; $F_2(2,118) = 2.86$, $MS_e = 0.66$, $p = .06$]. There is also a main effect of decomposability, with more errors for low-decomposable objects by participants only [$F_1(1,23) = 38.72$, $MS_e = 68.69$, $p < .001$; $F_2(1,59) = 1.59$]. If we analyze only the dropped items, there are no significant effects ($F_s < 1$).

3. Converging evidence for this conclusion comes from measuring the rate at which rotated images are normalized. We calculated the slope of

the RT–angle-of-rotation function for each object and nonobject, averaged over tasks. The mean slope was 1,272 deg/sec. This rate is faster than the arbitrary upper limit on rotation speed of approximately 1000 deg/sec for *mental rotation*, as suggested by Cohen and Kubovy (1993). Nevertheless, it is within the rates cited for rotated natural object naming (Hamm & McMullen, 1998; Jolicœur, 1985; McMullen & Jolicœur, 1992). It is possible, however, that rotation speed reflects normalization and some other procedure for making judgments—for instance, the use of orientation-invariant features (cf. Dickerson & Humphreys, 1999).

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