Surface cues reduce the latency to name rotated images of objects

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Abstract. Jolicoeur (1985, Memory & Cognition 13 289–303) found a linear increase in the latency to name line drawings of objects rotated (0° to 120°) from the upright (0°) in the initial trial block. This effect was much shallower in later blocks. He proposed that the initial effect may indicate that mental rotation is the default process for recognising rotated objects, and that the decrease in this effect, seen with practice, may reflect the increased use of learned orientation-invariant features. Initially, we were interested in whether object–colour associations that may be learned during the initial block, could account for the reduced latency to name rotated objects, seen in later blocks. In experiment 1 we used full-cue colour images of objects that depicted colour and other surface cues. Surprisingly, given that Jolicoeur’s findings were replicated several times with line drawings, we found that even the initial linear trend in naming latency was shallow. We replicated this result in follow-up experiments. In contrast, when we used less-realistic depictions of the same objects that had fewer visual cues (ie line drawings, coloured drawings, greyscale images), the results were comparable to those of Jolicoeur. Also, the initial linear trends were steeper for these depictions than for full-cue colour images. The results suggest that, when multiple surface cues are available in the image, mental rotation may not be the default recognition process.

1 Introduction
One important function of the human visual system is object constancy, or the ability to recognise objects despite changes in the retinal image caused by object or observer movement. It has been suggested that object constancy may make use of several normalisation processes to map the varied retinal input onto stable, long-term representations of objects. To explore one of these putative normalisation processes, namely mental rotation, the ability to identify images of common objects rotated from the familiar upright orientation has been examined (for a review see Jolicoeur and Humphrey 1998). Although many such experiments have been conducted, virtually all of these have used black-on-white line drawings that depict an object’s shape, but not its surface features, such as colour, texture, and shading. In the real world, of course, surface cues are readily available to the visual system. Moreover, such cues could potentially be used for recognising objects in unfamiliar orientations. We explored this possibility in the present set of experiments.

Jolicoeur (1985) conducted one of the most influential series of experiments examining the recognition of disoriented images of familiar objects. He had participants name line drawings of objects presented at each of six orientations [60° and 120° in the clockwise (CW) and counterclockwise (CCW) directions, along with the familiar upright (ie 0°), and the 180° orientation] across six blocks of trials. In the initial block there was a linear increase in naming latency as drawings were rotated from the upright (0° to 120°), but this linear trend was much shallower by the second block. This finding has been replicated many times (eg Jolicoeur 1985, 1988; Jolicoeur and Milliken 1989; McMullen and Jolicoeur 1990, 1992; McMullen et al 1995; Murray 1995; Murray et al 1993).
To account for these results, Jolicoeur (1985, 1990) proposed that two separate processes may underlie object constancy (also see Humphreys and Riddoch 1984). The first process was mental rotation. Jolicoeur proposed that the initial effect may reflect a process of mentally rotating an input to match a familiar view of the object stored in memory (eg upright view). He argued that mental rotation was the default process for recognising objects in unfamiliar orientations (also see Tarr and Pinker 1989; for alternative explanations see Corballis 1988; Hamm and McMullen 1998; Hummel and Biederman 1992; Perrett et al 1998). In another experiment, Jolicoeur (1985, experiment 3) found that the slope of the linear trend in naming latency, in the initial block, was similar to that for left/right orientation judgments, a task that is assumed to require mental rotation. This similarity in slopes was taken to support the hypothesis that a mental-rotation process mediated recognition, at least in the initial block.

The second process proposed by Jolicoeur (1985, 1990) was related to the decrease that is seen with practice in the linear trend in latency as a function of orientation. Specifically, Jolicoeur proposed that this decrease may indicate that experience with specific objects reduces the reliance on mental rotation for the recognition of these objects on later encounters. Instead, there may be an increased use of learned features that are salient at all orientations (eg size and colour) for recognising the objects (for an alternative account see Tarr and Pinker 1989). Consistent with the idea that it was experience with specific objects that was important, Jolicoeur (1985) found that the decrease in the linear trend in naming latency did not occur if a new set of objects was named in the second block. He suggested that participants might have learned associations between specific objects and their orientation-invariant features in the initial block, and then used these associations to recognise these objects in later blocks.

Surface colour is a feature that often remains salient despite changes in object orientation. Potentially, a learned association between a specific object and its colour could be used for recognising the object on later encounters, independent of its orientation. In fact, Jolicoeur (1985) found that the linear trend in naming latency decreased more rapidly with practice when participants named water-coloured drawings (his experiment 1), rather than line drawings (his experiments 2 and 3). This finding indicated that participants may have learned associations between specific objects and their colours during the initial block, and then used this information to identify rotated objects in later blocks.

Jolicoeur (1985) also noted that even the initial effect was shallower with coloured drawings, suggesting that colour may even improve the recognition of novel exemplars of rotated objects. This improvement could have been due to the facilitation of perceptual processes by colour information, or to participants’ use of prior knowledge about object-colour associations. This latter explanation is plausible given that many of Jolicoeur’s coloured drawings were of natural objects (eg fruits), rather than manufactured objects (eg table). It has been shown consistently that depicting natural objects with colour, rather than achromatically, leads to better performance on recognition tasks (Davidoff and Ostergaard 1988; Humphrey et al 1994; Joseph 1997; Joseph and Proffitt 1996; Ostergaard and Davidoff 1985; Price and Humphreys 1989; Tanaka and Presnell 1999; Wurm et al 1993). This colour advantage is seen less consistently for manufactured objects (Biederman and Ju 1988, experiment 3; Brodie et al 1991, experiment 3; Davidoff and Ostergaard 1988; Price and Humphreys 1989; but also see Biederman and Ju 1988, experiments 1–2, 4–5; Brodie et al 1991, experiment 4; Humphrey et al 1994; Tanaka and Presnell 1999). Also, it has been shown that the colour advantage in recognising natural objects may be due to the use of stored knowledge about object colour (but see Wurm et al 1993). It is unclear, however, how colour improves the recognition of manufactured objects, in those instances in which it does.
The hypothesis that surface colour may improve the recognition of objects in unfamiliar orientations is consistent with a more general proposal concerning the role of colour in object recognition. It has been argued that colour may play a larger role in recognition when an object’s shape alone is insufficient for identification (Biederman and Ju 1988; Price and Humphreys 1989). There is some evidence to support this argument. For example, Wurm et al (1993) found a colour advantage for naming food items that was larger with less familiar depictions of the items’ shapes (e.g. apple slices versus a whole apple). Wurm et al. found, however, that participants’ knowledge about the colour of the food items could not account for this colour advantage, indicating that the advantage may have been related to the facilitation of perceptual processes.

Other findings indicate that colour may play a larger role in recognition when an object must be differentiated from other objects that are similar in shape (Joseph 1997; Joseph and Proffitt 1996; Price and Humphreys 1989). Price and Humphreys (1989) found that depicting prototypical surface colour, rather than no colour or an inappropriate colour, improved the naming of objects, and more so when the objects were from structurally similar categories than structurally dissimilar categories. Also, Price and Humphreys (their experiment 2) found that depicting prototypical colour improved the classification of objects into one of two structurally similar categories. Finally, Joseph and Proffitt (1996; see also Joseph 1997) found that participants were worse at deciding that two sequentially presented stimuli depicted different objects when the objects were the same prototypical colour, rather than different colours. This was only true, however, when the objects were highly similar in shape. This effect was found even when words or uncoloured pictures were used as stimuli, suggesting that the effect was due to the activation of stored knowledge about object colour, rather than the facilitation of perceptual processes by surface colour. Also, the effects cited above depended on the prototypicality of colour, indicating that these effects may be related to knowledge about object colour.

In summary, when participants name line drawings of objects, there is a linear increase in naming latency with image orientation in the initial trials that is much shallower in later trials. The initial effect has been taken to indicate that mental rotation may be the default process for recognising rotated objects, while the decrease in this effect, seen with practice, may indicate the increased use of learned orientation-invariant features [i.e. reduced reliance on mental rotation; Jolicoeur (1985, 1990)]. Colour is a feature that could potentially be used for recognising specific objects in unfamiliar orientations, and it has been shown that colour improves recognition in other instances, when an object’s shape alone may be insufficient for recognition (e.g. unfamiliar views). Thus, the purpose of experiment 1 was to test whether associations between specific manufactured objects and their colours, which may be learned during the initial block, could account for the improved naming of rotated images, seen in later blocks. Manufactured objects, as opposed to natural objects, were used to make it easier to test the role of object–colour associations learned during testing, rather than prior to testing (i.e. these objects are typically not strongly associated with a unique colour).

2 General method

Certain aspects of the method were common to all experiments. In each experiment, the latency for participants to identify depictions of rotated objects was examined. Participants identified depictions either by naming them (experiments 1–3), or indicating whether a depiction matched an object name previously presented on the monitor screen (experiment 4). In the naming experiments, each depiction was presented at each of three orientations (i.e. $0^\circ$, $60^\circ$, and $120^\circ$ in the CW or CCW direction) across three naming blocks. In experiment 4, each depiction was presented at only one of three orientations (i.e. $0^\circ$, $60^\circ$, or $120^\circ$ in the CW or CCW direction) in a single block.
Across experiments, the way in which objects were depicted was manipulated to examine how colour and other surface cues might affect the linear trend in response latency with orientation.

2.1 Participants
All participants were undergraduate students from the University of Western Ontario, with a mean age of 19.5 years, participating for course credit or monetary reimbursement. All participants were right handed, indicated that they had normal or corrected-to-normal acuity and normal colour vision, and spoke English as their native language. Any one participant was tested in only one experiment reported in this paper.

2.2 Materials
Stimuli were depictions of manufactured objects with a standard upright orientation (eg chair), selected from the Tarrlab Object Databank (http://www.cog.brown.edu/~tarr/projects/databank.html) and Photo-Objects (Hemera Technologies, Quebec, Canada). Depictions were either computer-generated images of objects that depicted various surface cues, including colour, texture, and shading, or colour photographs. The original full-cue colour images were altered in four ways. (i) Image colour was changed, resulting in three different versions of each image, differing in colour, but not in luminance. Objects were depicted in plausible colours, and colour remained constant for parts with only one appropriate colour (eg tires). To confirm that the colour change did not affect luminance, a Minolta CS-100 Chroma Meter was used to measure luminance values at several points on all three versions. (ii) Greyscale images were created by converting colour images to greyscale mode. Again, luminance remained constant and this was confirmed by measuring luminance values across image types. (iii) Black-on-white line drawings (line width = 3 pixels) were created by tracing both the internal and external contours of object parts, but not texture or shadow lines. These drawings differed from those often used in recognition studies (ie Snodgrass and Vanderwart 1980) in that part contours were more sharply defined, but no texture or shadow cues were depicted. (iv) Coloured drawings were created by filling the line drawings with colour. The hue and mean luminance of these drawings were approximately the same as those of corresponding full-cue colour images. Mean luminance was approximated using an Adobe Photoshop averaging filter. Across the stimulus set, luminance values ranged from 1 to 68 cd m\(^{-2}\).

All stimuli were depicted on a white background (68 cd m\(^{-2}\)) and scaled to fit within a circle subtending 16 deg, when viewed from the testing distance of 57 cm. Images were presented on a flat-screen monitor controlled by a Macintosh micro-computer. Participants were tested in a darkened room, with their heads in a chin rest with both forehead and lateral head stops. In the naming experiments (1–3), response latency was recorded directly by the computer, by using a voice-activated microphone, and responses were recorded manually by the experimenter. In experiment 4, both latencies and responses were recorded directly by the computer, with the subject responding by pressing computer keys.

2.3 Data analysis
In all experiments, mean response latency was calculated from correct trials, for each condition, for those participants with an overall accuracy of at least 80% and an accuracy of at least 60% in each condition. This accuracy criterion was to ensure there were sufficient data points per condition to conduct valid statistical comparisons on latencies. For each condition, the grand mean was used to replace mean latencies that fell ±3 standard deviations from this grand mean. Fewer than 1% of participant means were replaced in any one experiment.

The empirical question being investigated was whether colour and other surface cues reduce the reliance on a putative mental-rotation process in the identification of object orientation.
rotated objects. A linear trend in response latency with orientation, comparable to those seen on putative mental-rotation tasks (e.g., left/right orientation decisions), has been taken as evidence that participants may be using mental rotation to identify rotated objects (Jolicoeur 1985, 1990). In all experiments, mean response latencies were submitted to an analysis of variance (ANOVA), with orientation and image type as factors (see experiments for specific details). Also, in the naming experiments, trial block was a factor. A posteriori analyses were conducted with the Newman–Keuls test ($\alpha = 0.05$). Additionally, effects of orientation were explored with a planned contrast set, consisting of a linear contrast, with 1, 0, and $-1$ as weights (i.e., for $0^\circ$, $60^\circ$, $120^\circ$, respectively), and a quadratic contrast, with $-1$, $2$, and $-1$ as weights.

Error rates, expressed as a percentage of total trials per condition, were analysed with an ANOVA, similar in nature to that used in the corresponding response-latency analysis. This was only to ensure that any differences in response latencies were not due to speed/accuracy trade-offs. For naming experiments, errors included incorrect names, failures to trigger the microphone (e.g., hesitations), and premature triggering of the microphone with a vocal utterance (e.g., “ah”). A posteriori analyses were conducted with the Newman–Keuls test ($\alpha = 0.05$).

3 Experiment 1

Jolicoeur (1985) found that when participants named line drawings of objects, there was a linear increase in naming latency as drawings were rotated ($0^\circ$ to $120^\circ$) from the familiar upright in the initial block of trials. This effect was much shallower by the second block. He suggested that participants may have learned associations between specific objects and their orientation-invariant features in the initial block, and then used these associations to recognise rotated drawings in later blocks. In the present experiment, we examined whether associations between specific objects and their colours that may be encoded during the initial block could account for the improved naming of rotated images, seen in later blocks. This was done by having participants name full-cue colour images of manufactured objects rotated $0^\circ$, $60^\circ$, and $120^\circ$ from the upright ($0^\circ$), across three blocks. The colour of half the images was constant across blocks, while the colour of the others varied. If participants use object–colour associations that may be encoded during the initial block to recognise rotated images in later blocks, then the decrease in the linear trend in naming latency should be greater when colour is constant, rather than varied.

3.1 Method

3.1.1 Participants. Thirty-six participants were tested (eighteen males, eighteen females).

3.1.2 Stimuli. Stimuli were full-cue colour images of forty-eight common objects (appendix A1). There were three versions of each image, differing in colour.

3.1.3 Design and procedure. Each participant named each of the forty-eight images three times, once in each of three blocks of trials. Each image was named at each of three orientations ($0^\circ$, $60^\circ$, and $120^\circ$ in the CW or CCW direction) from the familiar upright ($0^\circ$). Images were rotated in the CW direction for half the participants, and the CCW direction for the others. Images were randomly divided into two sets of twenty-four images each—set A and set B. In the first block, participants named eight images from set A at $0^\circ$, eight images from set A at $60^\circ$, and eight images from set A at $120^\circ$. The same was true for set B. Within each naming block the forty-eight images were presented in a random, interleaved manner. The second block was similar to the first, except that each image was presented in a different orientation than in the first block. Also, for half the participants the images in set A were presented in the same colour as in the first block, while the images in set B were presented in a new colour.
The opposite was true for the other participants. In the third block, each image was presented at a different orientation than in the first two blocks. Images that were the same colour in the first two blocks were the same colour in the third block, while images that differed in colour across the first two blocks were a new colour in the third block. Images were ordered randomly within the constraints listed above. The order of block presentation was counterbalanced across participants by using a Latin square, with each image occurring six times (ie three versions × two rotation directions) per condition (ie orientation × naming block × colour constancy).

Participants were instructed to respond as quickly and accurately as possible with the first name that came to mind. Images were on the screen until a response was made or 4 s elapsed. The intertrial interval was 3 s. Prior to testing, participants named three practice images, not included in the test set, at each orientation. This procedure was used in all naming experiments.

3.2 Results
Separate repeated-measures ANOVAs were done on mean naming latencies and error rates, with image orientation (0°, 60°, 120°), naming block (1st, 2nd, 3rd), and image type (colour-constant, colour-varied) as within-participants factors. Comparable analyses were used in subsequent naming experiments.

3.2.1 Naming latency. Figure 1 shows the mean naming-latency results. As expected on the basis of Jolicoeur’s findings, the ANOVA showed significant effects of block and orientation ($F$s > 11.11, $p$s < 0.0001). These effects reflected a decrease in naming latencies across blocks and a linear increase in naming latencies with orientation ($F_{1,35} = 15.64, p < 0.001$), respectively. Contrary to expectation, however, there was no significant orientation-by-block interaction ($F_{4,140} = 0.80, ns$). The linear trend in naming latencies was not significantly steeper in the first block compared with the last two ($F_{1,35} < 0.87, ns$). The mean slopes of the linear trend in naming latency with orientation (in ms deg$^{-1}$) were 0.38, 0.15, and 0.41 for blocks one, two, and three, respectively.

![Figure 1. Mean naming-latency/image-orientation functions obtained in experiment 1, when participants named colour-constant images (filled circles) and colour-varied images (open circles) across three naming blocks (B1, B2, B3).](image)

3.2.2 Error rate. Error rates ranged from 3.1% to 10.1% (see appendix B1). The ANOVA showed a significant effect of block ($F_{1,70} = 7.24, p < 0.01$) that interacted with orientation ($F_{4,140} = 3.64, p < 0.01$). Error rates decreased across blocks, most markedly between the first and third blocks at 120°.

3.3 Discussion
Surprisingly, the results of the present experiment showed that, when participants named full-cue colour images of objects, there was only a small linear increase in naming latency as images were rotated from the upright, even in the initial block (0.38 ms deg$^{-1}$). This result made it difficult to assess the hypothesis that participants...
used object–colour associations that may be learned during the initial block, to recognise rotated images in later blocks. Moreover, the present results differed from those Jolicoeur (1985) obtained with line drawings. Jolicoeur reported a steep linear increase in naming latency with orientation in the initial block (0.85 to 2.33 ms deg⁻¹) that was much shallower by the second block. One possible explanation for this discrepancy is that the availability of colour improves the naming of rotated exemplars of objects, even when these exemplars are novel. Obviously, this improvement would not require object–colour associations that may be learned during task performance. Consistent with this explanation, Jolicoeur observed that the initial increase in naming latency with orientation was shallower with coloured drawings (0.85 ms deg⁻¹, his experiment 1) than with line drawings (2.33 ms deg⁻¹, his experiment 2). Even with coloured drawings, however, the initial effect was quite steep and the effect was much shallower by the second block.

Another possibility is that the discrepancy between the present results and those of Jolicoeur might be due to a procedural difference (eg in our experiment 1 the stimuli were rotated in one direction, whereas Jolicoeur rotated stimuli in both directions). Also, the results of the present experiment may be specific to the set of objects selected (eg some of the objects, such as the rollerblade, did not possess a unique upright orientation). In experiment 2 we examined whether the surface colour, available in full-cue colour images, improves the naming of rotated objects, even in the initial block of trials.

4 Experiment 2
In the present experiment we examined whether the minimal effect of orientation on the latency to name novel full-cue colour images of rotated objects, seen in experiment 1, was related to the presence of colour in these images. This was done by comparing the latency for participants to name line drawings, greyscale images, and full-cue colour images of the objects named in experiment 1. If the effects observed in experiment 1 were due to the presence of colour, then the initial linear trend in naming latency should be steeper for line drawings and greyscale images (ie colour is absent) than for full-cue colour images. Also, this linear trend should be much shallower by the second block with line drawings, as reported by Jolicoeur (1985), and with greyscale images.

4.1 Method
4.1.1 Participants. Thirty-six participants were tested (eighteen males, eighteen females).

4.1.2 Stimuli. Stimuli were full-cue colour images, greyscale images, and line drawings of fifty-four objects, including the forty-eight used in experiment 1 (see appendix A1).

4.1.3 Design and procedure. The design was similar to that of experiment 1. Across three blocks, each participant named each of the fifty-four objects three times, once at each of three orientations (0°, 60°, and 120° in the CW or CCW direction) from the upright. The fifty-four objects were randomly divided into three sets of eighteen objects each—set A, set B, and set C. One set was depicted as line drawings, one set as greyscale images, and one set as full-cue colour images. The way the three sets were depicted was counterbalanced across participants using all six possible combinations. In the first block, participants named six images from set A at 0°, six images at 60°, and six images at 120°. The same was true for sets B and C. In the last two blocks, each object was renamed at the remaining two orientations, but the manner in which each object was depicted did not change. Within a block the fifty-four images were presented in a randomly interleaved manner. The order of block presentation was counterbalanced across participants using a Latin square, with each image occurring four times (ie twice per direction of rotation) in each experimental condition (ie orientation × block × image type).
4.2 Results

4.2.1 Naming latency. Figure 2 shows the mean naming-latency data. As in experiment 1, the ANOVA showed significant effects of block and orientation ($F_{4,39} = 141.29$, $p < 0.0001$). Naming latencies decreased with practice and increased in a linear manner with orientation ($F_{13,5} = 1.41$, $p < 0.0001$). In contrast to experiment 1, there was a significant interaction between orientation and block ($F_{4,140} = 3.47$, $p < 0.01$), as expected on the basis of Jolicoeur’s findings. The linear trend in naming latencies was steeper in the first block than in the last two blocks ($F_{13,5} = 4.67$, $p < 0.02$). This effect, however, was dependent on image type. The ANOVA showed a significant effect of image type ($F_{27,0} = 5.35$, $p < 0.01$), qualified by orientation ($F_{4,140} = 2.50$, $p < 0.05$), and qualified further by an orientation-by-block interaction ($F_{8,280} = 2.66$, $p < 0.01$).

The mean slope of the latency/orientation functions (in ms deg$^{-1}$) in naming blocks one, two, and three, respectively, was 1.51, 0.77, and 0.30 for line drawings, 1.46, 0.41, and 0.70 for greyscale images, and 0.32, 0.56, and 0.06 for full-cue colour images. For line drawings and greyscale images, there was a significant orientation-by-block interaction ($F_{13,5} > 2.84$, $p < 0.03$), reflecting that the linear trend in naming latencies was steeper in the first block than in the last two blocks ($F_{13,5} < 4.13$, $p < 0.05$). In contrast, for full-cue colour images there was no significant orientation-by-block interaction ($F = 2.31$, ns). The linear trend was not statistically reliable in the first block ($F_{13,5} = 1.36$, ns; other image types $F$s > 22.63, $p < 0.0001$) and there was no statistically reliable change across blocks ($F$s < 0.73, ns). There was, however, a significant change in the direction of the quadratic trend across the first two blocks ($F = 4.54$, $p < 0.05$) for naming full-cue colour images, but the trend was not significant in either block ($F$s < 2.69, ns).

Further, the magnitude of the initial linear trend in naming latencies differed across image types. In the first block, there was a significant orientation-by-image-type interaction ($F_{4,140} = 3.08$, $p < 0.02$; others $F$s < 2.19, ns). The linear trend was steeper for line drawings and greyscale images than for full-cue colour images ($F_{13,5} > 6.73$, $p < 0.02$), although the latency to name upright images ($0^\circ$) did not differ significantly across image types (1001, 951, and 991 ms for line drawings, greyscale images, and full-cue colour images, respectively).
4.2.2 Error rate. Error rates ranged from 3.2% to 13.4% (see appendix B2). There were significant effects of block ($F_{2,70} = 18.10, p < 0.0001$), orientation ($F_{2,70} = 3.30, p < 0.05$), and image type ($F_{2,70} = 7.17, p < 0.01$). Error rates decreased with practice. A posteriori tests showed no significant differences across orientations. Error rates were higher for line drawings than for greyscale images and full-cue colour images, which did not differ significantly from each other. These effects were independent of orientation. Thus, the effect of image type on the linear trend in naming latencies could not be due to speed/accuracy trade-offs.

4.3 Discussion

When participants named full-cue colour images of objects rotated from the upright, the results were comparable to those obtained in experiment 1. In fact, the latency to name these images did not change significantly as the images were rotated from the upright. In contrast, when participants named line drawings and greyscale images, the effects were comparable to those reported by Jolicoeur (1985), indicating that the discrepancy between the results obtained in experiment 1 and those reported by Jolicoeur could not be entirely due to methodological issues. More specifically, there was a linear increase in naming latency as images were rotated from the upright in the initial block that was reliably reduced by the second block. Also, compared with full-cue colour images, the initial effect was steeper for naming line drawings or greyscale images, although upright images were named equally fast across image types.

The present results show that using full-cue colour images that depict surface colour adds no benefit to the naming of objects, depicted in a canonical upright orientation, relative to achromatic images (see also Biederman and Ju 1988; Brodie et al 1991; Humphrey et al 1994; Tanaka and Presnell 1999). The results, however, do indicate that using full-cue colour images does improve the naming of the same objects when they are rotated from the canonical upright, even on the initial stimulus presentation. The present results suggest that when surface colour is available in the visual input, a mental-rotation process may not be needed for recognising objects in unfamiliar orientations.

The difference in the linear trend in naming latency between greyscale images and full-cue colour images is especially important. Although greyscale images do not depict colour, they do depict all the other surface cues available in full-cue colour images, such as texture and shading gradients and luminance discontinuities. Thus, it is unclear whether the improved naming of rotated colour images is due to the presence of colour alone or the combination of colour with other surface cues. Jolicoeur (1985, his experiment 1) obtained a steep linear trend in naming latency in the initial block and a large reduction in this trend in later blocks, when he used coloured drawings of objects. These drawings depict colour, but they do not depict other surface cues, such as realistic texture and shading. Jolicoeur’s results, in combination with the results of the present experiment, suggest that it is the combination of surface cues that is important. This question was explored in experiment 3.

5 Experiment 3

In the present experiment we examined whether the reduced linear trend in naming latency with orientation for novel full-cue colour images was related to the combination of colour and other surface cues, rather than the presence of colour alone. This was done by having participants name full-cue colour images and less-realistic coloured drawings (ie surface colour alone) of the objects used in experiments 1 and 2. If the reduction in the linear trend for full-cue colour images was due to the combination of colour and other surface cues, then the initial linear trend should be shallower for full-cue colour images than coloured drawings. Also, it was expected that orientation might have an effect on the latency to name coloured drawings in the first block, as in
Jolicoeur’s experiment (1985, his experiment I), but in was unknown how large this effect would be. Thus, participants also named line drawings, to re-examine the idea that object–colour associations that may be encoded during the initial block could account for the improved naming of rotated objects, seen in later blocks.

5.1 Method
The methods were identical to those of experiment 2, with the exception that, in addition to line drawings and full-cue colour images, participants named coloured drawings of the fifty-four objects (see appendix A1), rather than greyscale images.

5.2 Results
5.2.1 Naming latency. Figure 3 shows the mean naming-latency data. The ANOVA showed significant effects of block and orientation ($F_{2,70} > 17.89, ps < 0.0001$) and a significant interaction between these factors ($F_{4,140} = 5.24, p < 0.001$). The linear trend in naming latency was steeper in the first block than in later blocks ($F_{1,35} > 14.25, ps < 0.001$). As in experiment 2, this effect varied with image type. The ANOVA showed a significant effect of image type ($F_{2,70} = 8.98, p < 0.001$), qualified by orientation and block ($F_{4,140} > 2.54, ps < 0.05$) and qualified further by an orientation-by-block interaction ($F_{8,280} = 1.98, p < 0.05$).

The mean slopes of the linear trend in naming latency (in ms deg$^{-1}$) in blocks one, two, and three, respectively, were 1.39, 0.54, and 0.06 for line drawings, 1.30, –0.23, and 0.15 for coloured drawings, and 0.40, 0.34, and 0.44 for full-cue colour images. For line drawings and coloured drawings, there was a significant orientation-by-block interaction ($F_{4,140} > 2.61, ps < 0.04$). The linear trend in naming latencies was steeper in the first block than in later blocks ($F_{1,35} > 3.18, ps < 0.09$). In contrast, for full-cue colour images there was no significant orientation-by-block interaction ($F = 0.11$, ns). The linear trend was not statistically reliable in the first block ($F_{1,35} = 2.71$, ns; other $Fs > 10.98, ps < 0.01$) and it did not change significantly across blocks ($Fs < 0.03$, ns).

Further, the magnitude of the initial linear trend in naming latencies varied with image type. In the first block, there was a trend for an orientation-by-image-type interaction ($F_{4,140} = 1.99, p < 0.10$). The linear trend was steeper for line drawings
and coloured drawings ($F = 3.15$, $p < 0.05$, one-tail) than full-cue colour images, but the latency to name upright images did not differ significantly across image types (1070, 986, and 1034 ms for line drawings, coloured drawings, and full-cue colour images, respectively).

Also, there was a significant orientation-by-image-type interaction in the second block ($F = 2.60$, $p < 0.04$). The linear trend was significantly larger for coloured drawings than both line drawings and full-cue colour images ($F_{s} > 4.16$, $ps < 0.05$), although the linear trend was only significant for line drawings ($F = 6.66$, $p < 0.02$; other $Fs < 2.47$, ns). Also, the quadratic trend differed across line drawings and full-cue colour images ($F = 6.26$, $p < 0.02$), although the trend was not statistically reliable for either image type ($Fs < 3.51$, ns).

5.2.2 Error rate. Error rates ranged from 2.3% to 10.6% (see appendix B3). The ANOVA showed significant effects of block ($F_{27} = 7.26$, $p < 0.01$) and image type ($F_{27} = 4.23$, $p < 0.02$). Error rates decreased with practice. Error rates were higher for line drawings than coloured drawings and full-cue colour images, which did not differ significantly. These differences were independent of orientation. Thus, the effect of image type on the linear trend in naming latencies could not be due to speed/accuracy trade-offs.

5.3 Discussion
Consistent with the results of experiments 1 and 2, when participants named full-cue colour images of objects rotated from the upright there was no significant effect of orientation on naming latency, even in the initial block. Also, as expected, when participants named line drawings of the same objects, there was a linear increase in naming latency in the initial block as images were rotated from the upright that was significantly shallower by the second block. Moreover, this latter effect was also observed when participants named coloured drawings of the objects. Further, compared with full-cue colour images, the initial effect was significantly steeper for naming line drawings or coloured drawings, although upright images were named equally fast across image types. The present results show that it is the combination of colour and other surface cues, such as texture and shading, that improves the naming of full-cue colour images of objects in unfamiliar orientations, rather than surface colour alone.

In addition, in the second block, the linear trend in naming latency with orientation was shallower when participants named coloured drawings than when they named line drawings (ie the linear trend appeared to decrease more rapidly with practice). This result may indicate that participants were using object–colour associations, learned during the initial block, to recognise rotated coloured drawings in later blocks. In the second block, however, the linear trend was also significantly shallower when participants named coloured drawings compared with full-cue colour images, making the difference between line drawings and coloured drawings difficult to interpret.\(^{(1)}\)

There was little evidence, in the present set of experiments, that participants used object–colour associations that may have been learned during the initial block to recognise drawings in later blocks. Consistent with this, Cave et al (1996) found no effect of manipulating the colour of drawings of objects (mostly manufactured), presented in a canonical orientation, across naming blocks. There are several possible reasons for the result. First, it is possible that there was not enough variation in colour across images within a block for participants to form associations between specific images and unique colours. Second, it may have been that the variation in object colour across blocks was not large enough for participants to classify the new colour as different

\(^{(1)}\) In an additional experiment comparing the latency to name line drawings, coloured drawings, greyscale images, and full-cue colour images of objects rotated to six different orientations (ie 0°, 180°, 60°, and 120° in both the CW and CCW directions) showed no difference in the decrease in the linear trend between line drawings and coloured drawings (Nicholson, unpublished PhD dissertation).
from the original (ie our experiment 1). Thus, despite the change in hue, participants may still have used colour information learned during the initial block to identify images. Third, it may have been that naming the images interfered with participants’ ability to learn object–colour associations. Anecdotally, however, some participants remarked that the colour of some objects varied across blocks (ie our experiment 1), suggesting that object–colour associations were formed. Also, Cave et al (1996) found that participants were above chance at reporting changes in the colour of previously named drawings, again indicating that colour information can be encoded during naming tasks. Fourth, it may simply be that object–colour associations were learned, but participants did not use these associations, because they knew from past experience that manufactured objects are not strongly associated with a single colour. In fact, the mere act of changing the colour of some images across blocks may have indicated to participants that object–colour associations were not reliable cues for identification (ie our experiment 1).

So far it has been shown that when participants name full-cue colour images of objects rotated from the familiar upright there is, at best, a minimal linear trend in naming latency with orientation, even in the initial block. It is possible, however, that the effect of orientation on the latency to identify full-cue colour images of objects would be steeper if participants were asked to identify the objects at the subordinate level. Rosch et al (1976) referred to three levels of object categorisation; the superordinate (eg animal), basic (eg dog), and subordinate (eg poodle) levels. It has been argued that basic-level categorisation precedes subordinate and superordinate categorisation (Jolicoeur et al 1984; Rosch et al 1976). Moreover, Hamm and McMullen (1998) have shown that there is a steep linear trend in response latency with orientation when participants identify line drawings of objects at the subordinate level, but not when they identify the same drawings at the basic level. They argued that objects may first be identified at the basic level using a process that is independent of orientation, and then identified at the subordinate level using an orientation-normalisation process (perhaps mental rotation).

In object-naming studies it is difficult to control the level at which participants identify objects (ie participants are asked to use the first name that comes to mind). Hamm and McMullen (1998) have argued that linear effects are obtained in naming studies (eg Jolicoeur 1985) because participants tend to give subordinate names. Often, however, in these naming studies the objects are selected from a few basic categories (eg six in Jolicoeur 1985; experiment 1), whereas in the present stimulus set the objects were chosen from a wide range of categories (ie greater than thirty; see appendix A1). This may have inclined participants to give fewer subordinate names. It may be that if participants were asked to identify full-cue colour images of objects at the subordinate level, a steep linear trend in response latency would be obtained (ie a trend steep enough to be consistent with mental rotation). This possibility was explored in experiment 4.

6 Experiment 4

In the present experiment we examined whether having participants identify full-cue colour images of objects at the subordinate level would result in a linear trend in latency with orientation which would be steep enough to be consistent with mental rotation [ie as defined by slopes obtained on putative mental-rotation tasks, such as left/right orientation judgments; see for argument Jolicoeur (1985, 1990)]. Hamm and McMullen (1998) hypothesised that an orientation-normalisation process (perhaps mental rotation) is necessary for subordinate-level, but not basic-level identification. To test their hypothesis, they had participants decide whether line drawings of objects rotated from the familiar upright matched a preceding subordinate object-name (eg sail boat). Consistent with the hypothesis, results showed a linear increase in latencies
with orientation (0° to 120°) for match trials that was comparable to those obtained in naming studies with line drawings (ie subordinate identification is needed to decide that a picture of a sail boat matches the name sail boat). Further, on mismatch trials, some participants were presented with stimuli from the same basic category (eg sail boat followed by tug boat), while others were presented with stimuli from different categories (eg sail boat followed by wheelchair). Again, consistent with Hamm and McMullen’s hypothesis, there was a linear increase in latencies with orientation for trials in which the stimuli were from the same category (ie subordinate identification is needed to decide that a tug boat is not a sail boat). In contrast, there was no significant effect of orientation for trials in which the stimuli were from different categories (ie only basic identification is needed to decide that a wheelchair is not a sail boat).

In the present experiment we examined whether having participants identify full-cue colour images of objects at the subordinate level would result in a steep linear trend in decision latency with orientation, by using a task that was similar to that used by Hamm and McMullen. Also, other participants identified line drawings of the same objects, to ensure that the results of Hamm and McMullen could be replicated with the stimuli and procedure of the present experiment. Also, it was of interest to examine whether the effects obtained in experiments 2 and 3, with a naming task, could be replicated in this different task.

6.1 Method

6.1.1 Participants. Ninety-six participants were tested (forty-eight males, forty-eight females).

6.1.2 Stimuli. Stimuli were line drawings and full-cue colour images of forty-eight manufactured objects that could readily be identified at the basic and subordinate levels (see appendix A2). There were twelve exemplars from each of four categories, including footwear, headwear, cars, and chairs.

6.1.3 Design and procedure. Participants were randomly divided into four groups of twenty-four participants each. Two groups named line drawings and two groups named full-cue colour images. Participants decided whether each of the forty-eight images matched a preceding subordinate object-name. There were twenty-four match trials and twenty-four mismatch trials, six of each from each of the four categories. In the present experiment there was only one block of trials. Participants were presented with eight images at 0°, eight at 60°, and eight at 120°, for both match and mismatch trials. For half the participants images were rotated in the CW direction and for the others images were rotated in the CCW direction. For mismatch trials, the nature of the relationship between the name and the image differed across groups. For two groups (ie one line drawing, one full-cue colour image) the mismatch name depicted an object from the same basic category as the object depicted in the subsequent image (eg beret followed sombrero, both are headwear). For the other two groups, the mismatch name differed from the subsequent image at both the basic and superordinate levels (eg station wagon followed sombrero, a car and headwear or a vehicle and clothing). All mismatch names were subordinate names of objects belonging to the four categories tested, but none were names of objects used as stimuli. Counterbalancing was done with a Latin square, with each object occurring four times (two × CW; two × CCW) in each experimental condition (ie orientation × decision type × participant group).

Trials began with the name in black, lower-case letters (1500 ms), then a blank screen (500 ms), and then finally the image. Participants were asked to indicate, as quickly and accurately as possible, whether or not the image matched the name, by pressing keys. Trials ended after a response or after 4000 ms had elapsed from stimulus onset. The intertrial interval was 1000 ms.
6.2 Results

Mean response latencies and error rates were submitted to separate ANOVAs, with orientation and trial type as within-participants factors and participant group as a between-participants factor. The four groups were line drawings/same category (LS), colour images/same category (CS), line drawings/different category (LD), and colour images/different category (CD).

6.2.1 Response latency. Figure 4 shows the mean response latency data. The ANOVA showed significant effects of orientation ($F_{2,184} = 25.16, \ p < 0.001$) and group ($F_{3,92} = 6.38, \ p < 0.001$), and a significant interaction between these two factors ($F_{6,184} = 2.56, \ p < 0.03$). The mean slopes of the latency–orientation functions (in ms deg$^{-1}$) were 1.04, 0.52, 0.32, and 0.29 for the LS, CS, LD, and CD groups, respectively. Within each group, the linear trend in response latencies with orientation was significant ($F_{1,92} > 6.78, \ ps < 0.05$), but this trend was steeper in the LS group than the other groups ($F_{1,92} > 5.32, \ ps < 0.03$; other comparisons $Fs < 0.99$, ns). For upright images, latencies were slower for the LS (763 ms) and CS groups (730 ms) than for the CD group (609 ms; LD—660 ms).

The ANOVA also revealed a significant interaction between group and trial type ($F_{3,92} = 3.25, \ p < 0.03$). An analysis of simple interactions showed a significant effect of trial type, but only within the CD group ($F_{1,92} = 6.28, \ p < 0.02$; other groups, $Fs < 2.92$, ns). Match trials were slower than mismatch trials.

![Figure 4. Mean decision-latency/image-orientation functions obtained in experiment 4 on match decisions and mismatch decisions for line–same, colour–same, line–different, and colour–different groups.](image)

6.2.2 Error rate. Error rates ranged from 1.0% to 13.0% (see appendix B4). The ANOVA showed significant effects of group ($F_{3,92} = 5.20, \ p < 0.01$) and orientation ($F_{2,184} = 5.43, \ p < 0.01$), and a significant interaction between these two factors ($F_{4,184} = 2.27, \ p < 0.04$). There was a significant effect of orientation, but only within the two same-category groups ($F_{2,184} > 4.71, \ ps < 0.01$). Importantly, there was no indication that the differences in the linear trend in decision latencies across groups could be due to speed/accuracy trade-offs. The ANOVA also showed a significant effect of trial type ($F_{1,92} = 32.90, \ p < 0.001$). Error rates were higher for match trials than mismatch trials.
6.3 Discussion
There were three results of interest in the present experiment. First, the linear trend in response latency with orientation was steeper for the LS group (ie hypothesised to require subordinate identification) than the LD group (ie hypothesised to require basic identification). This showed that the effects reported by Hamm and McMullen (1998) could be replicated with the stimuli and procedure used in the present experiment.(2) Second, the linear trend was steeper for the LS group than the CS group, although there was no significant difference across the two different-category groups. The linear trends were comparable to those obtained with a naming task (our experiments 1 and 2). This finding showed that the effects obtained in experiments 2 and 3 could be replicated using a different task. Also, the finding indicated that the surface cues, available in full-cue colour images, are more beneficial when participants must identify objects at the subordinate level [ie discriminate between similarly shaped objects; see also (Joseph 1997; Joseph and Proffitt 1996; Price and Humphreys 1989)]. Third, the linear effect of orientation on decision latency did not differ significantly across the two colour groups. For both groups, the linear trend was comparable to those obtained when participants named full-cue colour images (experiments 1 – 3). This showed that, even when subordinate-level identification was putatively required, the linear effect of orientation on identification latency was minimal when objects were depicted with full-cue colour images. The result suggests that, when multiple surface cues are available in the visual input, mental rotation may not be the default process for recognising rotated objects, even at the subordinate level.

7 General discussion
Jolicoeur (1985) found that, when participants name line drawings of objects, there is a linear increase in naming latency as drawings are rotated from the familiar upright in the initial block that is much shallower by the second block. Jolicoeur (1985, 1990) proposed that two processes may mediate object recognition. First, he proposed that the initial effect may reflect that mental rotation is the default process for recognising objects in unfamiliar orientations. Second, he proposed that the decrease in this effect, seen with practice, may reflect the increased use of orientation-invariant features (and the reduced use of mental rotation) for the recognition of specific objects on later encounters. Such features could become associated with specific objects through experience.

Initially, the research reported here was motivated by Jolicoeur’s (1985, 1990) hypothesis that participants learned associations between specific objects and their features during the initial block, and then used these associations to recognise rotated versions of the objects in later blocks. More specifically, experiment 1 was designed to examine whether associations between specific objects and their colours, that may be formed during the initial block, could account for the improved naming of rotated objects.

(2) Hamm and McMullen (1998) hypothesised that, on match trials, orientation should influence latency equally in the two conditions, because subordinate identification should be required to match a subordinate name to an object. Consistent with their hypothesis, they found that, on match trials, the linear trend in response latency did not differ significantly between the LS group (0.81 ms deg⁻¹) and the LD group (0.63 ms deg⁻¹). In contrast, in the present experiment, on match trials, there was a large linear trend in the LS group (1.13 ms deg⁻¹), but not in the LD group (0.32 ms deg⁻¹). It is likely that, in the present experiment, participants in the LD group realised that on all mismatch trials the name and object were from different categories (eg race car is a car and sombrero is a hat), enabling them to use basic-level information to make correct match responses. Another possibility is that participants in the LD group were more likely to realise that on all mismatch trials the name and the object did not share the same semantic features (eg a race car has wheels, but a sombrero does not), enabling them to use semantic cues to make correct match responses.
objects, seen in later blocks. To do this, we had participants name full-cue colour images of objects rotated from the upright across three naming blocks, with the colour of half the images varied across blocks. These full-cue colour images were quite realistic, depicting surface colour, as well as other surface cues such as texture and shading gradients. Surprisingly, we found that, when participants named the full-cue colour images, there was only a shallow linear increase in naming latency with image orientation in the initial block. Further, this initial trend was not significantly steeper than those obtained in later blocks. Given these results, it was difficult to assess whether participants used object–colour associations, that may have been learned during the initial block, to recognise rotated versions of objects in later blocks. Moreover, the results of this initial experiment were markedly different than those reported by Jolicoeur (1985) and several others using line drawings (Jolicoeur 1988; Jolicoeur and Milliken 1989; McMullen et al 1995; McMullen and Jolicoeur 1990, 1992; Murray 1995; Murray et al 1993). This discrepancy raised the possibility that the surface colour, which is available in full-cue colour images, may reduce the linear increase in the latency to name rotated images, even on the initial stimulus presentation. Obviously, this improvement in naming did not depend on object–colour associations learned during task performance.

The hypothesis that the availability of surface colour reduced the latency to name rotated objects, even on the initial stimulus presentation, was supported by the results of experiments 2 and 3. In fact, in these experiments, when participants named full-cue colour images of objects, there was no significant change in latencies as images were rotated from the upright in the initial block. In contrast, the results were comparable to those reported by Jolicoeur, when participants named line drawings and greyscale images (ie surface colour is absent) of the same objects (experiment 2). That is, there was a linear increase in naming latency with orientation in the initial block that was significantly shallower by the second block. Further, the initial effect of orientation on naming latency was steeper for naming line drawings and greyscale images, compared with full-cue colour images, although the latency to name upright images (ie 0°) did not differ significantly across image types. These results show that using full-cue colour images that depict surface colour adds little or no benefit to the naming of manufactured objects, depicted in a canonical upright orientation, relative to achromatic images. This finding is consistent with those reported by others (Biederman and Ju 1988; Brodie et al 1991; Humphrey et al 1994; Tanaka and Presnell 1999). The results, however, do indicate that using full-cue colour images does improve the naming of the same objects when they are rotated from the upright, even on the initial stimulus presentation. In addition, effects similar to those obtained with line drawings (experiments 2 and 3) and greyscale images (experiment 2) were obtained in experiment 3 with coloured drawings (ie colour is the only surface cue available). This result shows that the combination of colour and other surface cues, which is available in full-cue colour images, is important for improving the naming of objects rotated from the upright, rather than surface colour alone. Thus, the results of the first three experiments suggested that mental rotation may not be the default process for recognising objects in unfamiliar orientations, when multiple surface cues are available in the visual input.

In experiment 4 we examined whether we could obtain a linear increase in the latency to identify full-cue colour images of rotated objects, which was of a magnitude consistent with a mental-rotation process [ie comparable to those obtained for other putative mental-rotation tasks; see, for argument Jolicoeur (1985, 1990)]. Hamm and McMullen (1998) have argued that an orientation-normalisation process (perhaps mental rotation) may be used for subordinate-level identification, but not for basic-level identification. Using line drawings of objects, Hamm and McMullen found a steep linear increase in response latency with orientation on a recognition task hypothesised to require subordinate identification, but no significant change in latency with
orientation on a similar task hypothesised to require basic identification. In experiment 4, with tasks similar to those used by Hamm and McMullen, we found that, when participants were presented with full-cue colour images of rotated objects, the effect of orientation on response latency was not influenced by the putative level of object identification. The linear increase in latency as images were rotated from the upright was shallow on both tasks. The magnitudes of these linear trends were comparable to those obtained in experiments 1 through 3 with a naming task. Thus, the results of the four present experiments suggest that when multiple surface cues are available in the visual input, which is usually the case in the real world, mental rotation may not be needed for recognising objects in unfamiliar orientations, even at the subordinate level.

7.1 Surface cues and the recognition of objects in unfamiliar orientations

The present result that the availability of multiple surface cues improves the identification of objects rotated from the familiar upright is consistent with a general proposal on the role of surface cues in object recognition. That proposal is that colour and other surface cues may play a larger role in object recognition when an object’s shape alone is insufficient for identification (Biederman and Ju 1988; Price and Humphreys 1989). More specifically, the present result is consistent with the findings that colour is more beneficial for the recognition of less familiar depictions of objects (Wurm et al 1993) or objects that are structurally similar to other objects (Joseph 1997; Joseph and Proffitt 1996; Price and Humphreys 1989). More generally, the present result is consistent with findings that increasing the number of visual cues available in an image especially improves the naming of objects depicted at unfamiliar viewing angles (Humphrey and Jolicoeur 1993; Liter et al 1997). The way in which the availability of surface cues in the image improves the recognition of objects in unfamiliar orientations, however, remains to be elucidated.

One possibility is that the combination of surface cues, present in the full-cue colour images, may have aided the recognition of rotated images by facilitating low-level processes, such as contour extraction (for a similar argument see Wurm et al 1993). In turn, facilitating such processes may have helped participants to parse the rotated objects into parts. This process is fundamental to parts-based theories of object recognition, which posit that objects are coded in memory as a few volumetric parts, along with the categorical relations (eg ‘on top of’) of these parts to each other or to the object’s principal axis (Biederman 1987; Marr 1982; Marr and Nishahara 1978). Moreover, Biederman and Ju (1988) have argued that surface cues may play a larger role in defining object parts when edge information is degraded or occluded. Inconsistent with this idea is the fact that the quality of edge information is not altered when images of objects are depicted in unfamiliar orientations. It could be, however, that it was more difficult for participants to rely on object properties that potentially could have been used to parse the rotated objects into parts, such as edge symmetry (eg see Biederman 1987) or familiar edge cues (eg Cavanagh 1991; Gibson and Peterson 1994). Thus, instead of relying on cues, such as symmetry or familiar shape cues, to decompose the rotated images into parts, participants may have relied on sharp changes in luminance, texture, and/or colour to decompose these images. In addition, texture and/or shading gradients could have provided depth information, allowing participants to determine the three-dimensional structure of parts. The information available in either the greyscale images or the coloured drawings may not have been sufficient to unambiguously parse rotated objects into parts. In combination (ie full-cue colour images), however, this information may have been highly useful for determining the objects’ parts. For example, differences in colour (ie coloured drawings) could only be useful in defining the parts of certain objects—ie those in which the parts
were different in colour. Some of the manufactured objects in the current study were uniform in colour (e.g., chair). The additional texture and luminance-gradient information available in the full-cue colour images, but not present in the coloured drawings, may have made it easier to define the parts in these instances. Also, sharp changes in luminance (i.e., greyscale images) may be useful for defining parts, but such changes are also indicative of shadow borders. It may be that the colour available in the full-cue colour images, but not the greyscale images, made it easier to disambiguate these possibilities. Thus, the redundancy in visual cues may have made it easier for participants to parse the full-cue colour images of rotated objects into parts compared with parsing the greyscale images or coloured drawings.

It might also be expected, however, that the information available in greyscale images or coloured drawings of rotated objects would make these depictions easier for participants to analyse into parts than line drawings. The finding that this was not the case may indicate that the improvement in naming of rotated objects, seen with full-cue colour images, was not related to the delineation of object parts. Alternatively, this null effect may partially reflect the nature of the visual stimuli, rather than the nature of visual processes. Counter to intuition, the part information depicted in the line drawings and coloured-in line drawings may have been superior to that extracted from greyscale images and full-cue colour images by the visual system (see for discussion Sanocki et al. 1998). For instance, drawings may avoid difficulties in the extraction of edge information from the retinal image encountered by the visual system, such as failing to detect obscured edges (e.g., due to low contrast) and/or extracting false edges (e.g., due to shadows). Consistent with this notion, the accuracy rate to name colour images and line drawings of manufactured objects has been shown to differ by only a few percent (experiments 2–4; see also Brodie et al. 1991; Price and Humphreys 1989). In contrast, a 20% difference has been reported between colour images and more realistic edge-representations of manufactured objects, extracted from the images by using a computer algorithm (Sanocki et al. 1998). Thus, it may be an invalid assumption that the visual cues are additive in the stimuli used in the present set of experiments (i.e., line drawings = shape; greyscale images = shape + other surface cues, etc).

Another possibility is that the combination of surface cues present in the full-cue colour images may have helped participants determine the orientation of the images. Facilitating the determination of image orientation could have been beneficial for locating object-centred reference coordinates; this has been proposed as an explanation of the effects of planar rotation on the latency to name images of objects (Hummel and Biederman 1992). More specifically, the combination of surface cues present in the full-cue colour images may have helped participants determine the categorical relations amongst object parts (e.g., ‘on top of’) or locate some salient axis of the object (e.g., the top–bottom axis). Rotation perturbs the relative orientations of parts/axes (i.e., vertical parts/axes become tilted) and the relative positions of parts (i.e., top parts may become beside parts). Assuming that the world is illuminated from above (e.g., Ramachandran 1988; Symons et al. 2000), shading gradients may have made it easier to determine the top–bottom relations amongst parts or locate the top–bottom axis. Also, characteristic features (e.g., flame on a candle), which may be more salient when depicted in colour, could be used as a heuristic to determine top–bottom relations. Again, however, this explanation predicts that there should have been some advantage in the latency to name greyscale images and coloured drawings of rotated objects compared with line drawings. The finding that the potential orientation cues, available in greyscale images or coloured drawings, do not improve the naming of rotated images is consistent with the result that pre-cueing the top of an image does not improve the naming of rotated images (McMullen et al. 1995). Thus, it may be that the linear effect
of orientation on naming latency does not reflect the time needed for participants to
determine the orientation of the object or its parts.

Another possibility is that the surface cues available in full-cue colour images may
have helped specify the objects’ material properties (e.g., sports cars often have a shiny
smooth red surface), information which participants may have used to recognise
rotated images. This idea is compatible with Jolicoeur’s (1985, 1990) suggestion that
distinctive orientation-invariant features may be used to recognise rotated images,
reducing the need for mental rotation. Given that the stimuli depicted manufactured
objects, however, it seems unlikely that information about objects’ material properties
would be distinct enough to activate only a single object representation stored in
memory. That is, although a shiny smooth red surface may be the typical material for
sports cars, it is also typical of other objects. Thus, it is not clear that a shiny smooth
red surface alone would allow an image to be uniquely identified as a sports car as
opposed to a toy wagon, for example. Alternatively, it has been argued that surface
cues may be more important for recognising objects when there is competition within
the shape domain (Joseph 1997; Joseph and Proffitt 1996; Price and Humphreys 1989).
That is, when there is no single interpretation of an object’s identity on the basis of
shape cues. In the present set of experiments, presenting images in unfamiliar orienta-
tions may have increased the number of interpretations of the objects, based on shape
cues, especially when subordinate-level identification is required (e.g., a sports car must
be discriminated from other types of cars). It may be that participants used informa-
tion about the objects’ material properties to constrain the number of interpretations
of rotated images. For example, it may be that participants used the shiny smooth
red surface to limit their responses to those objects, such as vehicles, that may possess
such material properties.

The above argument could be consistent with the alternative explanations of the
linear increase in identification latency with image orientation proposed by Corballis
1989) argued that the function of mental rotation is to rotate a visual input for the
purpose of recognition. In contrast to this argument, Corballis (1988) suggested that
objects may be recognised with an orientation-invariant process, based on shape
cues, with mental rotation subsequently being used when an object’s identity needs to
be verified. Recent research results reported by De Caro and Reeves (2000) support
Corballis’s orientation-invariant-plus-checking account of the recognition of misoriented
objects. Perhaps when information about the objects’ material properties is available
there is less competition within the shape domain. As such, participants are confident
enough in their decisions that there is no need to verify the objects’ identities (i.e., no
need for mental rotation).

Perrett et al. (1998) also argued that a mental-rotation process may not be needed
to explain the linear effect of planar rotation on identification latency. Instead, they
argued that the increase in latency may reflect the time needed to accumulate neuronal
evidence (i.e., number of cell discharges) favouring one interpretation of the object over
others. Consistent with this idea, cells that begin firing after the same latency to all views
of a stimulus (e.g., face), but fire at faster rates for more familiar views of the stim-
ulus (e.g., upright rather than rotated faces) have been found in the monkey temporal
cortex (e.g., Perrett et al. 1998; Tanaka et al. 1991). In addition to these shape-tuned cells,
elaborate feature cells (e.g., a cell which responds maximally to a dotted brown disk
attached to the end of a white bar) have also been found in the monkey temporal
cortex (e.g., Tanaka et al. 1991). Thus, it may be that, when multiple surface cues are
available in the visual input (i.e., full-cue colour images), this reduces competition
amongst shape representations and increases the rate at which evidence is accumulated
about an object’s identity.
The presence of colour alone (ie coloured drawings) or other surface cues without colour (ie greyscale images) were far less beneficial for naming rotated objects. This may be because the stimulus set consisted entirely of manufactured objects. The information in either the greyscale images or the coloured drawings may not have been that indicative of an object’s material properties, but in combination (ie full-cue colour images) this information may have been highly representative of such properties. For example, a shiny smooth surface is typical of vehicles, but also kitchen utensils. Likewise a red surface is typical of vehicles, but also clothing. In contrast, a shiny smooth red surface may be more typical of vehicles, than of kitchen utensils or clothing. It is not surprising that there was no advantage for naming rotated coloured drawings over line drawings. In the absence of texture and other surface cues, colour is not all that indicative of the material properties of manufactured objects. For instance, in the absence of texture cues, a brown surface could be indicative of the leather on a sofa or the wood of a coffee table. Also, in the absence of texture cues many colours other than brown could also be indicative of these materials. Further, unless the object has a unique texture, information in greyscale images may not be any more useful for identifying rotated objects than the information in line drawings. For example, in the absence of colour information, a smooth shiny surface could be indicative of the glass of a wine bottle or the metal of a bell. Although some of the objects had a unique texture in the present set of experiments, such as the wooden coffee table, most objects did not. The finding that colour and other surface cues appear to combine in a non-linear fashion is consistent with the functionality principle put forth by Schyns and Murphy (1994). They argue that, as object categories are learned, this leads to the formation of nonlinear feature units: a combination of visual cues that will distinguish members of a category from nonmembers. The present results are also consistent with findings that cells in monkey temporal cortex respond in a nonlinear fashion to combinations of object features, such as texture, colour, and simple shapes (eg Tanaka et al 1991).

Thus, there are several possible ways the combination of surface cues may have improved participants’ ability to name rotated images. The combination of surface cues may have facilitated the delineation of object parts, aided the determination of the relative position and orientation of these parts, or made it easier to extract information about the objects’ material properties. To what extent each of these factors contributed to the improved identification of rotated full-cue colour images is unclear. Further, the failure to see any improvement in other images types, especially greyscale images, over line drawings is also somewhat puzzling. It may be that the results, to some extent, reflect the nature of drawings, rather than simply the nature of visual processing. It is possible, owing to the nature of drawings, that structural information is better represented in drawings than greyscale images, while information about material properties is better represented in greyscale images than drawings. Thus, it may not be that drawings and greyscale images depict equivalent information, but rather that there is some trade-off between the information about object parts and information about material properties available to the visual system. The redundancy in visual cues available in full-cue colour images may facilitate the determination of both an object’s structure and its material properties.

7.2 The role of mental rotation and object recognition
The results of the present set of experiments suggest that mental rotation is not a critical process, nor the default process, for recognising objects in unfamiliar orientations when multiple surface cues are available in the visual input. When participants named full-cue colour images of objects rotated from the familiar upright, the initial linear increase in identification latency with orientation was shallow, at best. The initial
rotation speed (ie inverse slope $\times 1000$) for naming these images was about $2000$ deg s$^{-1}$ or faster, which would be considered too fast for mental rotation [see Jolicoeur (1985, 1990); ie probable rotation speeds are based on data from putative mental-rotation tasks such as left/right decisions]. Also, the linear effect of orientation on naming latency did not decrease across blocks, indicating that participants never used mental rotation for identifying rotated images [Jolicoeur (1990); ie there was no shift from mental rotation to a distinctive-feature process].

In contrast to full-cue colour images, the initial rotation speeds for naming line drawings, greyscale images, and coloured drawings of the same objects were less than $850$ deg s$^{-1}$, which would be more in line with mental rotation. Also, the linear effect of orientation on naming time was much shallower by the second naming block, when participants named these three types of images. This is consistent with the view that participants shifted from mental rotation to using an orientation-invariant process to identify rotated objects. Thus, although mental rotation may not be a critical process or the default process for recognising rotated objects, it may be a process that is used in instances when fewer visual cues are available in the input (eg at low levels of illumination).

Over the last decade there has been much debate over whether object recognition is mediated by orientation-dependent or orientation-invariant mechanisms and/or long-term representations (eg Biederman and Gerhardstein 1995; Tarr and Bülthoff 1995; for review see Jolicoeur and Humphrey 1998). Results showing that image orientation does not influence identification performance have been taken as evidence for an orientation-invariant mechanism. The result that planar rotation influenced the latency to name objects was a critical argument against such a view of object recognition (see Tarr and Bülthoff 1995). In experiments 2 and 3 of the present study we found no significant effect of image orientation on the latency to name full-cue colour images of objects. These findings would be consistent with an orientation-invariant recognition mechanism. In experiments 2 and 4, however, there was an effect, albeit small, of orientation on the latency to name full-cue colour images. Thus, the present results do not necessarily rule out orientation-dependent mechanisms/representations in recognition, although these results do counter the idea that the mechanism is mental rotation.

7.3 Generalising from line drawings to objects in the real world

Often, researchers exploring the processes involved in object constancy use line drawings of objects as stimuli. Real-world objects, however, are markedly different from line drawings of objects. Such objects possess surface cues, such as colour, shading, texture, and brightness, in addition to the edge cues depicted in line drawings. Moreover, in the present series of experiments we have shown that using more realistic images of objects results in markedly different effects on recognition tasks than using line drawings (ie which lead to different theoretical accounts of object constancy). Thus, to fully understand the recognition of objects in the real world, differences between stimuli used in the perception laboratory and real-world objects need to be considered.

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References


Corballis M C, 1988 “Recognition of disoriented shapes” Psychological Review 95 115 – 123
Jolicoeur P, 1985 “The time to name disoriented natural objects” Memory & Cognition 13 289 – 303
Marr D, 1982 Vision (San Francisco, CA: Freeman)
Surface cues reduce the latency to name rotated images of objects
### APPENDIX A

#### Table A1. Names of objects used as stimuli in experiments 1–3.

<table>
<thead>
<tr>
<th>Stimuli</th>
<th>Hats</th>
<th>Cars</th>
<th>Chairs</th>
<th>Shoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>clock</td>
<td>dress</td>
<td>trashcan</td>
<td>blender</td>
<td>television</td>
</tr>
<tr>
<td>barrel</td>
<td>desk</td>
<td>phone</td>
<td>rollerblade</td>
<td>motorbike</td>
</tr>
<tr>
<td>bell</td>
<td>drum</td>
<td>wine glass</td>
<td>helicopter</td>
<td>chair</td>
</tr>
<tr>
<td>bike</td>
<td>car</td>
<td>plane</td>
<td>lamp</td>
<td>door</td>
</tr>
<tr>
<td>barn</td>
<td>bed</td>
<td>shelf</td>
<td>pot</td>
<td>watercan</td>
</tr>
<tr>
<td>couch</td>
<td>suitcase</td>
<td>table</td>
<td>iron</td>
<td>wagon</td>
</tr>
<tr>
<td>candle</td>
<td>stool</td>
<td>sailboat</td>
<td>windmill</td>
<td>pitcher</td>
</tr>
<tr>
<td>cup</td>
<td>hat</td>
<td>salt shaker</td>
<td>stove</td>
<td>fridge</td>
</tr>
<tr>
<td>dish soap*</td>
<td>plant*</td>
<td>vase*</td>
<td>lightbulb*</td>
<td>glasses*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>toaster*</td>
</tr>
</tbody>
</table>

*These items were not used in experiment 1.

#### Table A2. Names of objects, and their categories, used in experiment 4.

<table>
<thead>
<tr>
<th>Stimuli</th>
<th>Hats</th>
<th>Cars</th>
<th>Chairs</th>
<th>Shoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimuli</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>clock</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>barrel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bell</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>bike</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>barn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>couch</td>
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<td></td>
</tr>
<tr>
<td>candle</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>cup</td>
<td></td>
<td></td>
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<td>dish soap*</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mismatch names*</td>
<td>football</td>
<td>station wagon</td>
<td>folding chair</td>
<td>soccer cleat</td>
</tr>
<tr>
<td></td>
<td>helmet</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>farmer's</td>
<td>hearse</td>
<td>barber chair</td>
<td>penny loafer</td>
</tr>
<tr>
<td></td>
<td>hat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>pilot's</td>
<td>model T</td>
<td>park bench</td>
<td>figure skate</td>
</tr>
<tr>
<td></td>
<td>helmet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>beret</td>
<td>taxi</td>
<td>highchair</td>
<td>hiking boot</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>baseball</td>
<td>minivan</td>
<td>beanbag chair</td>
<td>roller skate</td>
</tr>
<tr>
<td></td>
<td>cap</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cowboy</td>
<td>hatchback</td>
<td>foot stool</td>
<td>slipper</td>
</tr>
<tr>
<td></td>
<td>hat</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The last six objects in each category were not presented as images, but only as object names on mismatch trials.
### APPENDIX B

#### Table B1. Error rates for experiment 1. Error rates (%) as a function of orientation and naming block for colour-constant and colour-varied images.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Colour constant</th>
<th>Colour varied</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>8.0 10.0 10.0</td>
<td>5.9 6.3 10.0</td>
</tr>
<tr>
<td>60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block 2</td>
<td>8.3 5.2 8.0</td>
<td>9.7 4.5 6.6</td>
</tr>
<tr>
<td>Block 3</td>
<td>7.3 4.2 3.1</td>
<td>6.6 6.3 4.2</td>
</tr>
</tbody>
</table>

#### Table B2. Error rates for experiment 2. Error rates (%) as a function of orientation and naming block for line drawings, greyscale images, and full-cue colour images.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Line drawings</th>
<th>Greyscale images</th>
<th>Colour images</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>10.2 13.4 10.6</td>
<td>6.0 5.6 8.3</td>
<td>6.0 5.1 10.2</td>
</tr>
<tr>
<td>60°</td>
<td></td>
<td>3.2 3.2 4.2</td>
<td>5.6 6.0 5.6</td>
</tr>
<tr>
<td>120°</td>
<td></td>
<td>4.2 3.7 3.2</td>
<td>4.6 3.7 3.7</td>
</tr>
<tr>
<td>Block 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block 2</td>
<td>5.6 5.1 11.1</td>
<td>3.2 3.2 4.2</td>
<td>5.6 6.0 5.6</td>
</tr>
<tr>
<td>Block 3</td>
<td>4.6 4.2 6.5</td>
<td>4.2 3.7 3.2</td>
<td>4.6 3.7 3.7</td>
</tr>
</tbody>
</table>

#### Table B3. Error rates for experiment 3. Error rates (%) as a function of orientation and block for line drawings, coloured drawings, and full-cue colour images.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Line drawings</th>
<th>Coloured drawings</th>
<th>Colour images</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>8.8 10.6 7.9</td>
<td>3.2 4.2 8.8</td>
<td>7.6 5.6 4.6</td>
</tr>
<tr>
<td>60°</td>
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<td>6.5 4.6 4.6</td>
<td>4.2 4.2 2.3</td>
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<tr>
<td>120°</td>
<td></td>
<td>2.8 4.2 4.6</td>
<td>2.8 3.2 3.7</td>
</tr>
<tr>
<td>Block 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block 2</td>
<td>4.6 6.5 6.0</td>
<td>6.5 4.6 4.6</td>
<td>4.2 4.2 2.3</td>
</tr>
<tr>
<td>Block 3</td>
<td>6.9 6.0 5.1</td>
<td>2.8 4.2 4.6</td>
<td>2.8 3.2 3.7</td>
</tr>
</tbody>
</table>

#### Table B4. Error rates for experiment 4. Error rates (%) as a function of orientation and trial type for the line–same, line–different, colour–same, and colour–different groups.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Line drawings</th>
<th>Full-cue colour images</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>6.8 11.0 13.0</td>
<td>4.2 7.8 13.0</td>
</tr>
<tr>
<td>60°</td>
<td>7.8 7.8 9.9</td>
<td>4.2 7.8 13.0</td>
</tr>
<tr>
<td>120°</td>
<td>8.3 7.3 7.8</td>
<td>8.3 7.3 7.8</td>
</tr>
<tr>
<td>Block 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block 2</td>
<td>6.3 8.9 9.4</td>
<td>2.6 1.6 1.6</td>
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<tr>
<td>Block 3</td>
<td>6.9 6.0 5.1</td>
<td>2.8 4.2 4.6</td>
</tr>
</tbody>
</table>