Journal of Experimental Psychology:
Human Perception and Performance
2000, Vol. 26, No. 2, 568–581

0096-1523/00/$5.00 DOI: 10.1037//0096-1523.26.2.568

The Combined Effects of Plane Disorientation and Foreshortening on Picture Naming: One Manipulation or Two?

Rebecca Lawson
University of Liverpool

Glyn W. Humphreys
University of Birmingham

Pierre Jolicœur
University of Waterloo

Objects disoriented in plane away from the upright and objects rotated in depth producing foreshortening are harder to identify than canonical views. In Experiments 1 and 2, participants named pictures of familiar objects. There was no interaction between plane and depth rotation effects on initial presentation or after practice. Experiment 3 was a dual-task psychological refractory period study. Participants classified a high–low tone with a speeded keypress and then named a canonical, plane-rotated, or foreshortened view of an object. Naming was slower when the picture was presented 50 ms after the tone compared with 800 ms after the tone. Plane rotation effects were reduced (but not eliminated) at the short tone–picture stimulus onset asynchrony, but foreshortening effects were not reduced. The results implicate an early, prebottleneck locus for some processes compensating for plane rotation and a subsequent bottleneck or postbottleneck locus for compensation for foreshortening.

Rotating pictures of familiar objects in the plane away from their canonical upright orientation reliably increases response latencies in speeded naming tasks (Jolicoeur, 1985; Jolicoeur, Corballis, & Lawson, 1998; Jolicoeur & Milliken, 1989; McMullen & Jolicoeur, 1990, 1992; Murray, 1995). Similarly, increasing the depth rotation of familiar objects to produce foreshortening increases naming latencies (Humphrey & Jolicoeur, 1993; Lawson & Humphreys, 1998). For both plane and depth rotations, the disadvantage for identifying views transformed away from a canonical view reduces with practice (for plane rotation, see Jolicoeur, 1985; Jolicoeur & Milliken, 1989; Murray, 1995; for depth rotation, see Lawson & Humphreys, 1998).

Despite these similarities in the effects of plane and depth rotation on object naming, there are a priori reasons why one might anticipate that different processes are involved in compensating for plane and depth transformations away from a canonical view. Plane rotation involves a rotation about a unique axis such that there is no change in the surfaces of the object that are visible. Depth rotation produces more ecologically familiar but often apparently more visually catastrophic changes than plane rotation. For instance, depth rotation may result in surfaces and features partially or completely appearing or disappearing, and the internal spatial relations between features may alter. Such changes are often particularly striking when depth rotation foreshortens an object. Foreshortening can occlude important, distinguishing features and parts of the object, and it can severely distort the global outline shape of the object relative to the canonical view. Foreshortening has been found to impair object recognition both for normal participants (Humphrey & Jolicoeur, 1993; Lawson & Humphreys, 1998; Newell & Findlay, 1997; Srinivas, 1993, 1995) and for brain-damaged patients (Humphreys & Riddoch, 1984; Lawson & Humphreys, 1999; Warrington & Taylor, 1973, 1978), even when care is taken not to occlude distinguishing features and parts (Humphrey & Jolicoeur, 1993). The recognition of silhouettes is particularly disrupted by foreshortening (Lawson & Humphreys, 1999; Newell & Findlay, 1997), because silhouettes depend on their global outline for identification.

The aim of the three experiments reported in this article was to probe the nature of the relation between the effects of plane disorientation and foreshortening on picture identification. Specifically, we investigated whether compensation for plane and for depth transformations involves the same or different processes. This was achieved by comparing the effects of both transformations in speeded naming tasks that examined the combined effects of plane and depth rotation on initial naming (Experiment 1) and naming after practice at identifying the experimental stimuli (Experiment 2). Finally, we investigated the order of compensation for plane and depth rotations in a dual-task, psychological refractory period (PRP) paradigm (Experiment 3).

Rebecca Lawson, Department of Psychology, University of Liverpool, Liverpool, England; Glyn W. Humphreys, School of Psychology, University of Birmingham, Birmingham, England; Pierre Jolicœur, Department of Psychology, University of Waterloo, Waterloo, Ontario, Canada.

This research was supported by Grant LT-558/94 from the International Human Frontier Science Program.

We would like to thank Kevin Jordan, Hal Pashler, and an anonymous reviewer for their helpful comments on this article.

Correspondence concerning this article should be addressed to Rebecca Lawson, Department of Psychology, University of Liverpool, Eleanor Rathbone Building, Bedford Street South, Liverpool, England L69 7ZA. Electronic mail may be sent to rlawson@liverpool.ac.uk.

Experiment 1

Many familiar objects have a well-defined, unique, canonical orientation in the plane, which we term the upright view. Such objects were presented in the current series of experiments (see the Appendix). As in the experiments reported here, most studies of the effects of plane rotation have manipulated view with respect to this canonical upright view. In contrast, for most familiar objects, there is no comparable, readily identifiable, unique and canonical view in depth (Newell & Findlay, 1997). Behavioral data (e.g., Palmer, Rosch, & Chase, 1981) may indicate a favored view in depth, but this view is variable across objects and is difficult to define precisely. Instead, depth rotation has often been manipulated by rotating an object relative to the (noncanonical, poor) view that maximally foreshortens the main axis of the object (e.g., Lawson & Humphreys, 1996; Newell & Findlay, 1997; Warrington & James, 1986). This allows different, depth-rotated views of an object to be defined objectively, at least for objects that possess a clear main axis.

In Experiment 1, participants named one view only of a given object. This view could be (a) canonical, (b) plane disoriented, (c) foreshortened, or (d) both plane disoriented and foreshortened (see Figure 1). It was predicted that rotation in the plane away from the normal, upright orientation would slow naming and that depth rotation to increase foreshortening would also slow naming. The aim of Experiment 1 was to investigate whether plane and depth rotation effects on naming latencies interact in some way.

Method

Participants. Seventy-two students from the University of Birmingham (Birmingham, England) participated. In this and in the following experiments, participants were paid to take part, were native speakers of English, and had normal or corrected-to-normal vision.

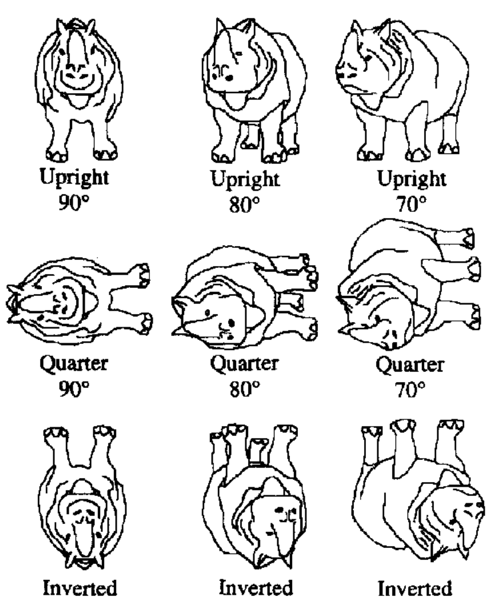

Figure 1. The nine views (three depth rotations by three plane rotations) of a rhinoceros.

Materials. A set of nine views of each of 72 familiar objects was produced (see the Appendix). All objects had a unique, familiar, canonical orientation in the plane. The objects were taken from four broadly defined categories: animals, implements, vehicles, and household items. The angle of view in depth was defined with respect to the line of sight of the viewer and the main axis of the object. The main axis was the most elongated axis or the main axis of symmetry of the object (see Lawson & Humphreys, 1999, Appendix 3). Objects were rotated about the vertical axis running through their center point to produce three different depth-rotated views of each object, at 70°, 80°, and 90°, thus, all views were partially or fully (90°) foreshortened (see Figure 1). Note that 70° views, despite being partially foreshortened, were relatively good, canonical views. The 70° views were not named significantly more slowly or less accurately than the 60° views in Experiment 2 of Lawson and Humphreys (1998), whereas participants were slower and less accurate in naming 80° relative to 70° views and 90° relative to 80° views. Three different plane rotations of each depth-rotated view were produced, each separated by a 90° rotation in plane. These plane rotations were the canonical upright, quarter-rotated, and inverted views. There were thus nine different views of each object (three depth-rotated views by three plane-rotated views).

The stimuli were line drawings produced by tracing and then scanning photographs of the objects or scale models of the objects. The photographs were taken from a position that was both vertically and horizontally aligned with the center of the object. Each picture was scaled to just fit inside a square of 6 × 6 cm.

Design. Participants completed one block of 72 trials, consisting of one view of each of the 72 objects. On each trial, a picture of an object was presented at one of the three depth-rotated views (70°, 80°, or 90°) and one of the three plane-rotated views (upright, quarter rotated, or inverted). There were nine different picture sets. In each set, 9 of the 72 objects were shown at each of the nine different possible combinations of view in depth by view in plane. The set of nine objects shown at each Plane × Depth view combination was rotated in a Latin square design across the picture sets so that, over all nine sets, each object was seen nine times, once at each Plane × Depth view combination. Eight participants were assigned to each picture set. The order of presentation of trials was random and was different for each participant.

Apparatus and procedure. A Macintosh IIci computer running the Psychlab Version 8.5 presentation package was used to display the stimuli. The experiment lasted about 10 min.

The procedure for each trial was as follows: A fixation cross appeared on the screen for 500 ms, immediately followed by the picture, which was displayed until the participant responded by naming the object aloud. Response times (RTs) were recorded by the computer via a microphone and a voice-activated relay. Participants were not provided with feedback.

In this and the following studies, participants read a list of the names of the objects that would appear in the study before the start of the experiment (see the Appendix). This measure was intended to reduce word-finding difficulty and variability in naming (Srinivas, 1993). It was emphasized to participants that they were free to use alternative names (e.g., jug instead of pitcher) if they preferred. Participants were encouraged to respond as rapidly and as accurately as possible. They were given a block of practice trials before the start of the experiment; these trials involved objects not shown in the experimental trials.

Results

Response latencies of less than 300 ms or more than 5,000 ms were discarded as errors[1] (0.8% of trials). In addition, trials in which participants used an inappropriate name or in which the microphone was accidentally activated before the participant responded were discarded as errors. Participants were replaced if they had an error rate of more than 40%. Fifteen participants were replaced in Experiment 1 according to this criterion. One item, the hairclip, was dropped from the analysis because only 1 participant named it correctly. In this and the following experiments, we report the results of by-subjects and by-item analyses, using F_1 and F_2, respectively; in some of the item analyses, there were a small number of empty cells that were replaced by the mean for that condition.

An analysis of variance (ANOVA) was conducted on mean correct naming RTs. Mean correct RTs and percentage errors over participants are shown in Figure 2 and Table 1, respectively. There were two within-subject variables: plane (the plane rotation of the picture: upright, quarter rotated, or inverted) and depth (the depth rotation of the picture: 70°, 80°, or 90°).

The main effect of plane was significant: $F_1(2, 142) = 28.47$, $p < .001$, $MSE = 74{,}030$; $F_2(2, 140) = 22.75$, $p < .001$, $MSE = 112{,}681$. Inverted views were named slower than quarter-rotated views, which in turn were named slower than upright views. Depth was also significant: $F_1(2, 142) = 28.75$, $p < .001$, $MSE = 72{,}351$; $F_2(2, 140) = 26.91$, $p < .001$, $MSE = 143{,}444$. Ninety-degree views were named slower than 80° views, which in turn were named slower than 70° views. The Plane × Depth interaction was not significant: $F_1(4, 284) = 0.91$, $p > .4$, $MSE = 71{,}706$; $F_2(4, 280) = 1.45$, $p > .2$, $MSE = 104{,}728$ (see Figure 2).

An ANOVA was also performed on error scores. The main effect of plane was significant: $F_1(2, 142) = 18.25$, $p < .001$, $MSE = 1.91$; $F_2(2, 140) = 27.35$, $p < .001$, $MSE = 1.29$. Inverted and quarter-rotated views were named less accurately than upright views. Depth was also significant: $F_1(2, 142) = 171.48$, $p < .001$, $MSE = 1.47$; $F_2(2, 140) = 37.66$, $p < .001$, $MSE = 6.78$. Ninety-degree views were named less accurately than 80° views, which in turn were named less accurately than 70° views. The Plane × Depth interaction was not significant: $F_1(4, 284) = 1.78$, $p > .1$, $MSE = 1.29$; $F_2(4, 280) = 2.01$, $p > .09$, $MSE = 1.13$ (see Table 1).

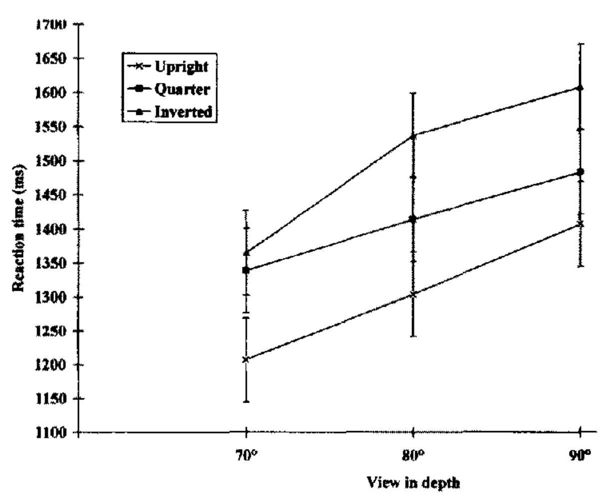

Figure 2. Mean reaction times as a function of plane rotation and depth rotation in Experiment 1, along with 95% confidence intervals based on the error term for the Plane × Depth interaction (Loftus & Masson, 1994).

Table 1
Mean Error Rates (%) as a Function of Plane Rotation and Depth Rotation in Experiment 1

	Depth rotation		
Plane rotation	70°	80°	90°
Upright	16.7	19.1	38.9
Quarter rotated	19.6	26.7	49.8
Inverted	25.9	28.8	49.0

Discussion

The results were clear. Individually, both plane and depth rotation produced strong, monotonic effects on RTs and errors. Naming latencies and errors increased when either plane disorientation or foreshortening increased. The magnitude of the plane and depth rotation effects on RTs was similar, at approximately 200 ms for the range of rotations examined. There were, however, smaller effects on error rates for plane rotation (with a 10% increase in errors for inverted relative to upright views) than for depth rotation (with a 20% increase in errors for 90° relative to 70° views). Most important, there was no interaction between the effects of plane and depth rotation on object naming for either RTs or errors.

The lack of interaction between the effects of plane and depth rotation on picture naming is consistent with an account in which normalization for plane and depth rotation is carried out in series, by successive functional stages (Sternberg, 1969; see also Miller, 1988, 1990; Roberts & Sternberg, 1993). This result is similar to that reported by Bundesen, Larsen, and Farrell (1981) and Larsen (1985). They investigated the matching of alphanumeric characters and random polygons, wherein matching pairs of stimuli could vary in plane orientation and in size. They found no interaction between the effects of plane rotation and size changes for the matching of unfamiliar stimuli. They suggested that people compensate for plane and size disparities with separate, sequential transformation processes.

[1] The box outlier procedure for eliminating outlying RTs described in this article can introduce biases into data analysis (see Van Selst & Jolicoeur, 1994b). A better outlier elimination procedure has been described by Van Selst and Jolicoeur (1994b). This outlier procedure was used to reanalyze the RT data for the picture naming trials in Experiment 3 here. The re-analysis produced the same pattern of significant results and similar mean RTs as the original analysis reported for the critical SOA × View interaction.

An account of compensation for the effects of plane and depth rotation as being undertaken by distinct, sequential processes is thus consistent with both the results of Experiment 1 and earlier research investigating compensation for plane rotation and size changes. This initial, tentative account still leaves open a number of further questions. First, if separate, sequential processes do compensate for plane and depth rotation, which rotation is compensated for first? There are no strong a priori reasons to suggest a particular order. Second, although a lack of an interaction between two factors is typically taken to indicate that the two factors influence distinct, qualitatively different processing stages, this is not necessarily so. The result may, alternatively, be produced by the same process being used iteratively. For instance, a general "image normalization" process may first compensate for one transformation and then for the other or may even alternate between partially compensating for one and then the other transformation, in no fixed order of priority.

Thus, independent effects of plane and depth rotation are consistent with either of two accounts: the involvement of two distinct processes, operating sequentially and respectively transforming views of objects rotated in plane or in depth away from a canonical view, or the same normalization process operating iteratively, compensating for both plane and depth rotation. These two accounts were examined further in Experiments 2 and 3.

Experiment 2

The results of Experiment 1 underlined the importance of the view of an object in both plane and depth in determining the efficiency of object recognition. This finding supports earlier studies in which either plane or depth rotation was manipulated individually (e.g., Humphrey & Jolicoeur, 1993; Jolicoeur, 1985; Jolicoeur & Milliken, 1989; Lawson & Humphreys, 1996, 1998, 1999). In addition, Experiment 1 indicated that the effects of plane and depth rotation did not interact. In Experiment 2, we replicated and extended these results by investigating how a third factor, practice at naming a set of views of familiar objects, modulated the combined effects of plane and depth rotation.

Clear reductions in the effects of rotation on object naming have been reported when the same objects were named repeatedly at different rotations in plane (Jolicoeur, 1985; Jolicoeur & Milliken, 1989; Murray, Jolicoeur, McMullen, & Ingleton, 1993) and at different rotations in depth (Lawson & Humphreys, 1998). For example, Jolicoeur (1985) reported that strong initial effects of plane rotation rapidly diminished with practice, although rotation effects were still reliable even after participants had named five different plane-rotated views of the same object. Most of the reduction in the rotation effects occurred from the first to the second stimulus presentation. Similarly, Lawson and Humphreys (1998) found reduced effects of depth rotation from the initial naming of a stimulus to the fourth naming of the same view of the stimulus (see their Figure 6).

Given these results, we predicted that both plane and depth rotation effects would diminish with practice in Experiment 2. If a common process compensates sequentially for both plane and depth rotations, then practice should influence the effects of both rotations in the same way, and so plane and depth rotation effects should not interact after practice. In contrast, if different compensatory processes are involved, it is possible that some divergence can be observed, with practice affecting one transformation more than the other.

It is also possible that practice may undo the sequential relations between the compensation processes, leading to an interaction between the effects of plane and depth rotation. For instance, in studies examining the effects of plane rotation and size changes using shape matching, an interaction between the two factors has been observed for familiar, repeated stimuli (Kubovy & Podgorny, 1981; Larsen, 1985; although note that in these studies, participants were tested with just two familiar stimuli, each of which was presented hundreds of times). With practice, it may be that compensation processes for plane and depth rotations are run in parallel rather than sequentially.

In Experiment 2, participants completed the same block of naming trials as in Experiment 1, which was then followed by two identical blocks of trials; thus, after the third block, each participant had named the same view of an object (at a particular rotation in plane and in depth) three times. This design allowed us to investigate the effects of practice on identical repetitions of the stimuli. This task was similar to that used in Experiment 3 in Lawson and Humphreys (1998), in which the same depth-rotated view of an object was named repeatedly; note, however, that it differed from that used by Jolicoeur (1985), in which participants were presented with a different plane-rotated view of a given object on every block.

Method

Participants. Fifty-four students from the University of Birmingham (Birmingham, England) participated.

Materials. The nine views of the 72 objects presented in Experiment 1 were used.

Design. Participants completed three blocks of 72 trials, each consisting of one view of each of the 72 objects. The first block was identical to that presented in Experiment 1, except that only 6 participants were assigned to each picture set. For each participant, the second and third blocks were identical to the first block. The order of presentation of trials within a block was random and was different for each participant.

Apparatus and procedure. The apparatus and procedure were identical to those of Experiment 1. The experiment lasted about 30 min.

Results

Response latencies of less than 300 ms or more than 3,000 ms were discarded as errors (2.3% of trials; see Footnote 1). In addition, trials in which participants used an inappropriate name or in which the microphone was accidentally activated before the participant responded were discarded as errors. Finally, for RT but not error analyses, trials presenting a given picture of an object were excluded from the analysis if the participant had not named that object correctly in the preceding block. Participants were replaced if they had an error rate of more than 40% in any one block or if they had an error rate of more than 33% across the whole experiment. Eleven participants were replaced in Experiment 2 according to these criteria.

An ANOVA was conducted on mean correct naming RTs. There were three within-subject variables: plane (upright, quarter rotated, or inverted), depth (70°, 80°, or 90°), and block (1, 2, or 3).

All of the main effects were significant. For plane: $F_1(2, 106) = 32.12, p < .001, MSE = 50{,}322$; $F_2(2, 142) = 42.39, p < .001, MSE = 56{,}817$. Inverted and quarter-rotated views were named slower than upright views. For depth: $F_1(2, 106) = 21.28, p < .001, MSE = 40{,}414$; $F_2(2, 142) = 19.91, p < .001, MSE = 127{,}864$. Ninety-degree views were named slower than 80° views, which in turn were named slower than 70° views. Finally, for block: $F_1(2, 106) = 393.12, p < .001, MSE = 48{,}160$; $F_2(2, 142) = 356.74, p < .001, MSE = 96{,}135$. Participants were slower in Block 1 than in Block 2, and they were slower in Block 2 than in Block 3.

The Plane × Block interaction was significant: $F_1(4, 212) = 7.41, p < .001, MSE = 20{,}087$; $F_2(4, 284) = 5.90, p < .001, MSE = 31{,}486$ (see Figure 3). Similarly, the Depth × Block interaction was significant: $F_1(4, 212) = 6.11, p < .001, MSE = 23{,}129$; $F_2(4, 284) = 9.09, p < .001, MSE = 38{,}852$ (see Figure 4). These two interactions reflect the reduction in both plane and depth rotation effects with practice, the reduction occurring largely from the first to the second stimulus presentation.

As in Experiment 1, the Plane × Depth interaction was not significant: $F_1(4, 212) = 1.05, p > .3, MSE = 48{,}968$; $F_2(4, 284) = 1.69, p > .1, MSE = 53{,}060$ (see Figure 5). The same was true of the three-way Plane × Depth × Block

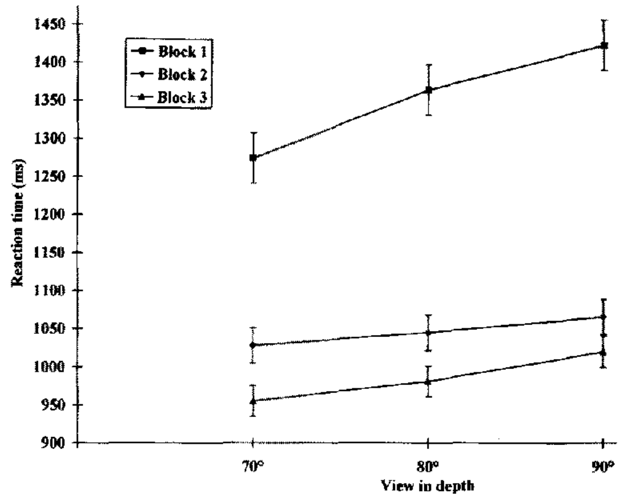

Figure 4. Mean reaction times as a function of depth rotation and block in Experiment 2, along with 95% confidence intervals based on the error term for the main effect of depth in each separate block (Loftus & Masson, 1994).

interaction: $F_1(8, 424) = 0.61, p > .7, MSE = 20{,}220$; $F_2(8, 568) = 0.80, p > .6, MSE = 31{,}081$.

An ANOVA was also performed on error scores. All of the main effects were significant. For plane: $F_1(2, 106) = 15.99, p < .001, MSE = 4.19$; $F_2(2, 142) = 25.27, p < .001, MSE = 1.99$. Inverted and quarter-rotated views were both named less accurately than upright views. For depth: $F_1(2, 106) = 166.54, p < .001, MSE = 3.23$; $F_2(2, 142) = 30.48, p < .001, MSE = 13.23$. Ninety-degree views were named less accurately than 80° views, which in turn were named less accurately than 70° views. Finally, for block: $F_1(2, 106) = 142.19, p < .001, MSE = 0.51$; $F_2(2, 142) = 75.23, p < .001, MSE = 0.729$. Participants were less

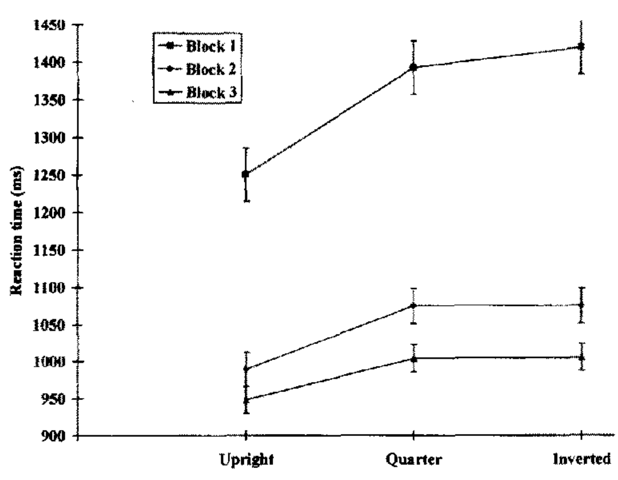

Figure 3. Mean reaction times as a function of plane rotation and block in Experiment 2, along with 95% confidence intervals based on the error term for the main effect of plane in each separate block (Loftus & Masson, 1994).

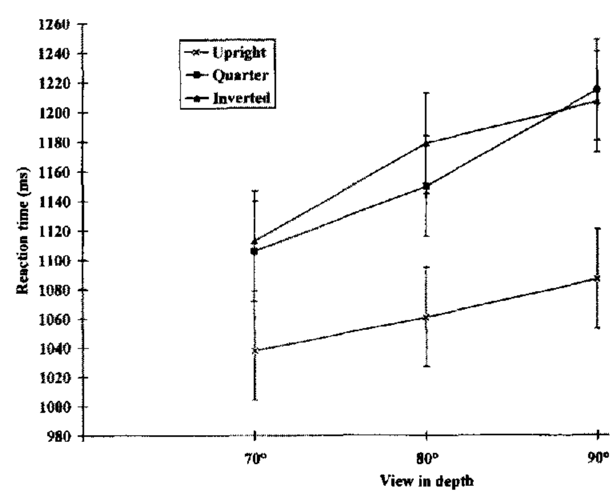

Figure 5. Mean reaction times as a function of plane rotation and depth rotation in Experiment 2, along with 95% confidence intervals based on the error term for the Plane × Depth interaction (Loftus & Masson, 1994).

accurate in Block 1 than in Block 2, and they were less accurate in Block 2 than in Block 3.

The Plane × Block interaction was significant: $F_1(4, 212) = 3.02, p < .02, MSE = 0.37$; $F_2(4, 284) = 2.93, p < .03, MSE = 0.29$ (see Table 2). As was the case for RTs, there was a reduction in plane rotation effects with practice. In contrast, the Depth × Block interaction (which was significant for RTs) was not significant for errors: $F_1(4, 212) = 0.24, p > .9, MSE = 0.40$; $F_2(4, 284) = 0.20, p > .9, MSE = 0.35$ (see Table 3).

As was the case for RTs, the Plane × Depth interaction was not significant: $F_1(4, 212) = 0.29, p > .8, MSE = 3.02$; $F_2(4, 284) = 0.41, p > .8, MSE = 1.60$ (see Table 4). The same was true of the Plane × Depth × Block interaction: $F_1(8, 424) = 1.33, p > .2, MSE = 0.35$; $F_2(8, 568) = 1.07, p > .3, MSE = 0.33$.

Finally, all of the preceding RT and error item analyses were repeated after first removing the 10 least accurately named items in the experiment (these items were, with the least accurate first, hairclip, toaster, dustpan, teapot, life raft, cow, bulldozer, weighing scales, hovercraft, and boot) and then again after removing the 20 least accurately named items (the previous 10 items along with jug, mug, cassette tape, horsebox, catapult, stapler, helicopter, binoculars, tank, and cement mixer). This was done to ensure that the results were not due to a small set of particularly difficult items. Removing the worst 10 items left a maximum of 50% errors for any particular item. Removing the worst 20 items reduced this to a maximum of 35% errors for any given item. The resultant significant and nonsignificant effects from these item analyses, and the pattern of means found, were identical to those just reported for both RTs and errors. There was therefore no evidence to suggest that the results reported earlier were due to just a few difficult items.

Discussion

As in Experiment 1, there were strong effects of both plane and depth rotation on the efficiency of picture naming. Furthermore, these effects were modulated by prior experience with a particular view of an object. The effect of both plane and depth rotation on naming latencies was greatest in the first block, reducing in magnitude across the second and third blocks; most of the improvement occurred from the first to the second block. Participants thus compensated more rapidly for the transformations after experience with the stimuli. Even in the third block, however, this compensation was far from complete: Here atypical views (either inverted views or 90° depth-rotated views) were still named approximately 60 ms slower than canonical views (either upright views or 70° depth-rotated views). These results replicate those of earlier studies reporting that practice with stimuli reduces but does not eliminate the deleterious effects of plane rotation (Jolicoeur, 1985; Jolicoeur & Milliken, 1989) and depth rotation (Lawson & Humphreys, 1998).

Although practice produced similar reductions in the effects of plane and depth rotation on naming latencies, this was not the case for errors. Practice reduced plane but not depth rotation effects on errors. This was despite depth rotation having a greater influence on initial response accuracy (as in Experiment 1), with a 25% effect on errors, as compared with an 11% effect for plane rotation. The apparent similarity in the influence of practice on plane and depth rotation effects for RTs may therefore be misleading, given the different effects of practice on errors. Nevertheless, additional item analyses in Experiment 2 suggested that it was not simply overall high error rates that produced these practice effects, because removing the 10 and the 20 most difficult items revealed a pattern of results for both RTs and errors identical to that of the initial analyses.

Notwithstanding whether practice improved performance more for plane-disoriented than for foreshortened views, it is clear that with practice, participants learned to compensate more efficiently for both plane and depth rotation. Nevertheless, despite these strong effects of practice in Experiment 2, we replicated and extended the main result from Experiment 1, finding no interaction between the effects of plane and depth rotation either on initial naming of a given view of an object or after practice at naming that view.

These results strengthen the claim that plane and depth rotations are compensated for either by two distinct, sequential processes or by the same, iterated process. In addition, the finding that practice reduced plane but not depth rotation effects on errors provides rather more support for the former than for the latter account. If the same, iterated process

Table 2
Mean Error Rates (%) as a Function of Plane Rotation and Block in Experiment 2

Plane rotation	Block 1	Block 2	Block 3
Upright	28.2	22.0	20.2
Quarter rotated	34.7	29.6	25.7
Inverted	38.9	31.1	27.4

Table 3
Mean Error Rates (%) as a Function of Depth Rotation and Block in Experiment 2

Depth rotation	Block 1	Block 2	Block 3
70°	24.1	17.2	14.1
80°	29.0	22.9	20.1
90°	48.8	42.6	39.1

Table 4
Mean Error Rates (%) as a Function of Plane Rotation and Depth Rotation in Experiment 2

Plane rotation	Depth rotation 70°	80°	90°
Upright	13.7	19.3	37.5
Quarter rotated	20.2	25.3	44.5
Inverted	21.5	27.4	48.5

compensated for both plane and depth rotations, then practice would be predicted to influence the effects of both rotations in a similar manner. The nature of the processes involved in compensating for plane and depth rotations, and in particular the order in which they are employed, was investigated further in Experiment 3.

Experiment 3

In both Experiments 1 and 2, the effects of plane and depth rotation on naming performance were individually strong but did not interact with each other. This result is consistent with the involvement of distinct, functional processes that compensate for plane disorientation and foreshortening successively or with there being a single compensation process that is repeated for each transformation. However, the data do not indicate the order in which the visual system compensates for plane and depth rotations. It may even be that the order varies from trial to trial. For certain pairs of processes, the order in which they are applied may be logically apparent (for instance, stimulus encoding must precede response selection), but this is not the case here. One approach that may allow inference of the relative temporal ordering of processes is that of investigating the influence of the PRP effect on naming performance. This was done in Experiment 3. We discuss the logic used to explain PRP effects and to infer the temporal order in which processes are employed after we have outlined the methodology used here.

Experiment 3 was a dual-task study in which participants first performed a simple auditory tone discrimination task. They made a two-choice speeded keypress response as to whether a high or a low tone had been presented. After a stimulus onset asynchrony (SOA) of either 50 ms or 800 ms following the tone, a picture of a familiar object was presented, and participants had to name the object as quickly as possible. Each object could be depicted at one of three different views (see Figure 6): a canonical view (a typical, upright view of an object), a plane-disoriented view (the canonical view plane rotated by 90°), or a foreshortened view (the canonical view foreshortened by a 20° rotation in depth).

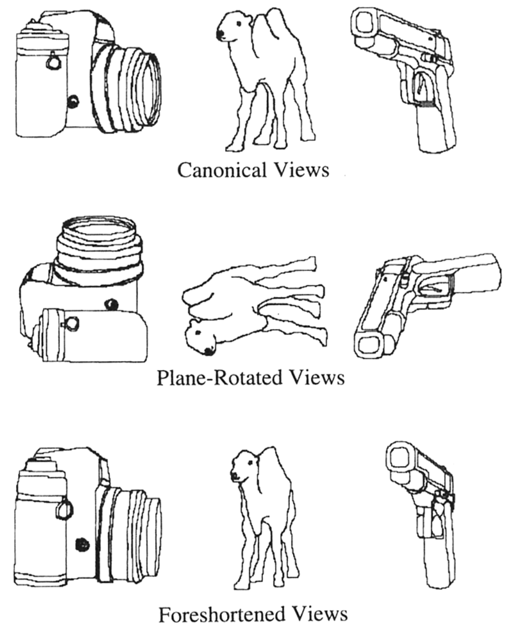

Figure 6. The canonical, plane-rotated, and foreshortened views of three of the stimuli presented in Experiment 3: camera, camel, and gun.

From the results of Experiments 1 and 2, we predicted that at the long tone–picture SOA (800 ms), naming latencies would be greater for plane-disoriented and foreshortened views than for canonical views. What was of primary interest in the current study was how these image transformation effects would be influenced by a reduction in the tone–picture SOA to just 50 ms.

1. Following the logic of Pashler (1984, 1994), if either plane or depth transformations are compensated for by relatively *early* stages of visual processing, before a central bottleneck, then the effect of the transformation at the long SOA should be reduced or even eliminated at the short, 50 ms SOA. This would result in an underadditive interaction between the effects of the transformation and SOA.

For instance, consider comparing the naming of canonical and plane-disoriented views. At the long SOA, processing of the tone would usually be complete before the picture was presented, so picture processing would not be delayed by processing on the first (tone) task. The extra processing time required to identify plane-disoriented relative to canonical views (due to time-consuming compensation for plane rotation) should therefore be reflected fully in slower naming latencies.

In contrast, at the short SOA, processing of the tone would typically not be complete before the picture was presented. Early stages of picture processing could proceed in parallel with tone processing up to a central bottleneck stage. This bottleneck stage is required for the processing of both the tone and the picture and cannot process them in parallel. Any picture processing that required the bottleneck or occurred after the bottleneck would have to be postponed until tone processing at the bottleneck was complete. Plane-disoriented views would require more early processing than canonical views and so would be slower to reach the central bottleneck. However, this additional early processing would tend to be absorbed in the postponement period if tone processing delayed picture processing for a sufficient length of time. Consequently, when the bottleneck became available for picture processing, the processing disadvantage for plane-disoriented relative to canonical views would be reduced or even eliminated.

2. Alternatively, if either plane or depth transformations are compensated for by relatively *late* stages of visual processing (at, or subsequent to, a central bottleneck), then the effect of the transformation at the short SOA should be the same as at the long SOA, resulting in additive effects of the transformation and SOA. To illustrate this, consider again the naming of canonical and plane-disoriented views. At the long SOA, the situation is identical to that in the first

account just outlined, and plane-disoriented views would be predicted to be named slower than canonical views.

At the short SOA, picture processing should continue in parallel with tone processing up to the central bottleneck stage. At this point, picture processing would be postponed until tone processing at the central bottleneck stage was complete (as in the first account just outlined). In contrast to the situation outlined in the first account, compensation for plane disorientation is here assumed to require relatively late bottleneck or postbottleneck processing, so processing of both plane-disoriented and canonical views would be postponed at the central bottleneck at the same time, after the same amount of initial, early processing. Tone task processing at the central bottleneck must be complete before processing to compensate for plane disorientation can begin. Hence, the time taken for this compensation would simply add to the time taken due to postponement by the tone task at the short SOA; the disadvantage for plane-disoriented relative to canonical views should therefore be the same at the short SOA as at the long SOA.

Recently, Van Selst and Jolicoeur (1994a) and Ruthruff, Miller, and Lachmann (1995) conducted a series of dual-task PRP studies that required tone discriminations followed by a mirror-normal discrimination of plane-disoriented characters. They reported a reduction of the effects of plane disorientation at short relative to long SOAs (although only a small reduction was found in Ruthruff et al.'s studies).

Although mirror-normal judgments about plane-disoriented stimuli are generally assumed to require mental rotation (Jolicoeur, 1990), recent evidence suggests that identification does not (Jolicoeur et al., 1998; Lawson, 1999; see also Farah & Hammond, 1988; McMullen & Jolicoeur, 1990; Pashler, 1990; but see Murray, 1997). Therefore, the studies by Van Selst and Jolicoeur (1994a) and by Ruthruff et al. (1995) do not allow one to predict whether the effects of plane disorientation on speeded naming will combine additively or underadditively with SOA. This was tested in Experiment 3.

Experiment 3 also examined whether there was an interaction between SOA and the effects of depth rotation. If both plane and depth rotation effects combine either underadditively or additively with SOA, this would not provide information on the temporal ordering of the processes involved in compensating for rotation effects (although it would indicate whether compensation for both required relatively early or relatively late processing respectively). In contrast, if only plane or only depth rotation effects combined underadditively with SOA, this would suggest that processing required to compensate for that transformation started before processing to compensate for the other transformation.

Method

Participants. Seventy-two students at the University of Waterloo (Waterloo, Ontario, Canada) participated.

Materials. Two tones, each lasting 100 ms, were used. The high tone was 1200 Hz, and the low tone was 400 Hz. These very different frequencies were selected to ensure that the tones were readily discriminable.

Three different views of each of the 72 familiar objects presented in Experiments 1 and 2 were used (see the Appendix). These were canonical (upright, 60°), foreshortened (upright, 80°), and plane disoriented (quarter-rotated, 60°) views (see Figure 6). The canonical and plane-disoriented views (which were not presented in Experiments 1 and 2) were produced in the same way as the foreshortened views (which were presented in Experiments 1 and 2). The foreshortened view was chosen to be the 80° rather than the 90° view because the 90° view was found to be extremely difficult to identify in Experiments 1 and 2. To maximize any disadvantage for foreshortening, we chose the canonical view to be the 60° rather than the 70° view, because in the study by Lawson and Humphreys (1998) there was a trend for the 60° view to be named both faster and more accurately than the 70° view.

Design. Participants completed four experimental blocks of 72 trials. In each block, they named a full picture set that consisted of one view of each of the 72 objects. There were 12 different picture sets. The 72 objects were divided into 12 groups of 6 objects. The experimental conditions (canonical, plane-disoriented, or foreshortened view; short or long SOA; and high or low tone) assigned to a given group of objects were rotated in a Latin square across the 12 picture sets. Thus, for each picture set, 4 groups (24 objects) were presented at each of the three different views: canonical, plane disoriented, and foreshortened. Of these 24 objects, half (two groups; 12 objects) were presented at a short, 50-ms SOA and half at a long, 800-ms SOA. Of each group of 12 objects, 6 (one group) were preceded by a high tone and 6 by a low tone.

Six participants were randomly assigned to each picture set for the first block of trials. Participants were assigned to a different picture set in each of the three subsequent blocks. Across the 72 participants, all objects were depicted an equal number of times at all views, in all blocks, at both SOAs, and preceded by high and low tones. The order of presentation of trials was random and was different for each participant.

Apparatus and procedure. A Power Macintosh 6100 computer running the Psyscope Version 1.0.2b4 presentation package was used to display the stimuli. Auditory responses were recorded by the computer via a microphone and a voice-activated relay. The experiment lasted about 50 min.

The procedure for each experimental trial was as follows: A central fixation cross appeared on the screen for 300 ms and then, after a further 100 ms, a high (1200-Hz) or low (400-Hz) tone was presented for 100 ms. Participants responded to the tone by making a speeded keypress response of either "a" (high tones) or "z" (low tones). Either 50 ms (short SOA) or 800 ms (long SOA) after the onset of the tone, a picture of an object was presented at fixation. The picture was removed as soon as the participant had made a speeded auditory response to name it. After an additional 100 ms, participants saw the name of the object presented at fixation in uppercase letters. This feedback was displayed until the experimenter made a keypress to record the accuracy of the participant's picture naming response.

It was emphasized strongly to participants that very rapid and accurate performance on the tone task was essential and that they should not trade off better performance on the picture naming task for inaccurate or delayed performance on the tone task. Participants were told:

> On each trial, you will first hear the tone and then very shortly afterwards the picture of the object will appear. DO NOT wait for the picture to appear before responding to the tone, it is very important that you respond to the tone immediately, and as fast as you can. When you have done that, name the picture as fast as you can.

Participants were reminded of these instructions whenever necessary throughout the course of the experiment.

There were at least two practice blocks before the experimental blocks. Practice trials were identical to experimental trials, except that different objects were presented. In addition, in the first practice block only, participants were required only to respond to the tones. Participants practiced the tone task by itself until they were performing rapidly and accurately, typically after between 15 and 30 trials. They then completed the second practice block of 72 trials, in which they performed both the tone task and the picture task. Participants were required to repeat this practice block if they had particular difficulty in combining the two tasks or if they were concentrating on the picture task at the expense of the tone task.

Results

Response latencies outside the cutoffs of 250–1,000 ms for the tone task (3.5% of trials) and 300–3,000 ms for picture naming (2.5% of trials) were discarded as errors (see Footnote 1). In addition, naming trials in which participants used an inappropriate name or in which the microphone was accidentally activated before the participant responded were discarded as errors. For RT but not error analyses, trials presenting a given picture of an object were excluded from the analysis if the participant had not named that object correctly in the preceding block. Finally, for the analysis of the picture naming task only, trials on which errors were made in the tone task or in which participants responded to the picture before they responded to the tone were discarded as errors.

All participants with error rates above 20% in the experiment were replaced; errors included those made in either the tone task or the picture task on a given trial. Seventeen participants were replaced according to this criterion. Separate ANOVAs were conducted on the results from the picture naming task and the tone task.

Picture naming task. An ANOVA was conducted on the mean duration required for a correct response. There were three within-subject variables: view of the object (canonical, plane disoriented, or foreshortened), SOA (50 ms or 800 ms), and block (1, 2, 3, or 4). Note that responses for high and low tone trials were combined, because this variable was not of interest in the current study.

All of the main effects were significant. For view: $F_1(2, 142) = 69.27, p < .001, MSE = 16{,}138$; $F_2(2, 142) = 33.56, p < .001, MSE = 42{,}225$. Responses were slower to foreshortened (1,150 ms) and plane-disoriented (1,143 ms) views than to canonical views (1,071 ms). For SOA: $F_1(1, 71) = 211.68, p < .001, MSE = 65{,}797$; $F_2(1, 71) = 484.34, p < .001, MSE = 28{,}832$. Responses were slower on short SOA trials (1,211 ms) than on long SOA trials (1,032 ms). Finally, for block: $F_1(3, 213) = 295.91, p < .001, MSE = 22{,}998$; $F_2(3, 213) = 190.21, p < .001, MSE = 42{,}005$. Naming latencies decreased from Block 1 (1,297 ms) to Block 2 (1,119 ms), Block 3 (1,060 ms), and Block 4 (1,009 ms).

There were two significant interactions. First, the View × SOA interaction was significant: $F_1(2, 142) = 5.95, p < .004, MSE = 14{,}349$; $F_2(2, 142) = 4.21, p < .02, MSE = 17{,}848$ (see Figure 7; see also Figure 8). Relative to the naming of canonical views, foreshortened views were named 82 ms slower at the long SOA and a similar 77 ms slower at the short SOA. In contrast, again relative to the naming of canonical views, plane-disoriented views were named 95 ms slower at the long SOA but only 51 ms slower at the short SOA. Thus, the disadvantage in naming foreshortened views was only minimally reduced at the short SOA, but the disadvantage in naming plane-disoriented views was reduced by approximately 50%.

We went on to examine whether picture naming trials for which there had been a longer tone task response would reveal a greater reduction of the plane disorientation effect at

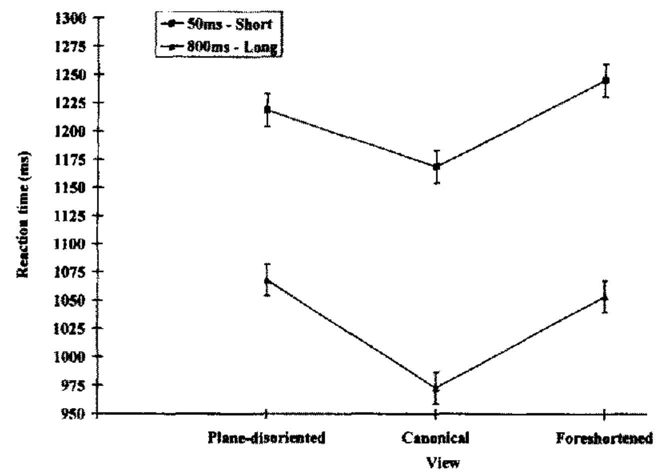

Figure 7. Mean reaction times as a function of view and stimulus onset asynchrony (SOA) in Experiment 3, along with 95% confidence intervals based on the error term for the main effect of view for 50-ms and 800-ms SOAs separately (Loftus & Masson, 1994).

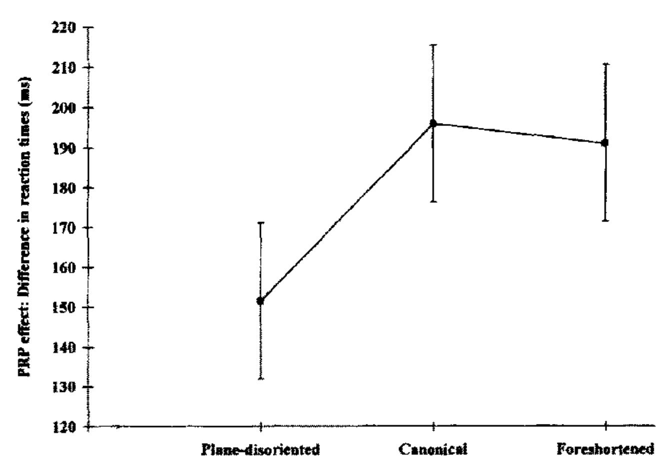

Figure 8. Mean reaction times (RTs) as a function of the psychological refractory period (PRP) effect (RT at the 50-ms stimulus onset asynchrony [SOA] − RT at the long, 800-ms SOA) for each view in Experiment 3, along with 95% confidence intervals based on the error term for the PRP effect (Loftus & Masson, 1994).

the short SOA. This would be predicted if the PRP effect on some trials was too short to allow all variation in prebottleneck processing time to be absorbed. We conducted median split analyses on the picture naming RTs based on the speed of participants' tone task RTs on that trial. Trials with slow tone RTs should have a larger PRP, so there should be a longer period of postponement on such trials. This would potentially allow more of the plane disorientation effect to be absorbed while the bottleneck was occupied by tone task processing. However, the median split analysis did not support such an account. For slow tone task trials, relative to the naming of canonical views, plane-disoriented views were named 95 ms slower at the long SOA but only 49 ms slower at the short SOA. This result is similar to that found earlier when both fast and slow tone trials were included in the analysis. It suggests that the plane disorientation effect cannot be much further reduced at the short SOA by increasing the length of the PRP. Instead, the results suggest that only approximately 50% of the plane rotation effect is compensated for by early, prebottleneck processing and that later bottleneck or postbottleneck processing is responsible for compensating for the remaining effects of plane disorientation.

Second, the View × Block interaction was significant: $F_1(6, 426) = 2.37, p < .03, MSE = 19{,}844$; $F_2(6, 426) = 5.52, p < .001, MSE = 23{,}601$ (see Figure 9). Relative to canonical views, the disadvantage in naming both foreshortened and plane-disoriented views reduced as participants gained experience in naming the objects in the experiment. Relative to the naming of canonical views, the foreshortened view disadvantage was 121 ms, 89 ms, 66 ms, and 41 ms, and the plane-disoriented view disadvantage was 92 ms, 93 ms, 62 ms, and 44 ms, in Blocks 1, 2, 3, and 4, respectively.

An ANOVA was also conducted on error scores in the picture naming task only. The main effect of view was significant: $F_1(2, 142) = 11.66, p < .001, MSE = 108$; $F_2(2, 142) = 4.91, p < .009, MSE = 258$. More errors were made

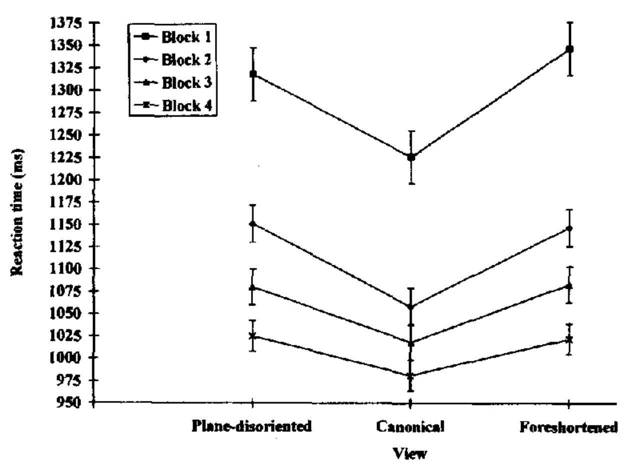

Figure 9. Mean reaction times as a function of view and block in Experiment 3, along with 95% confidence intervals based on the error term for the main effect of view in each separate block (Loftus & Masson, 1994).

Table 5
Mean Error Rates (%) as a Function of View and Block in Experiment 3

View	Block 1	2	3	4
Canonical	23.3	13.7	12.4	10.6
Plane disoriented	25.1	15.3	10.6	10.3
Foreshortened	30.4	15.9	12.8	11.8

to foreshortened views (17.7%) than to plane-disoriented views (15.3%) or canonical views (15.0%). The main effect of SOA was not significant: $F_1(1, 71) = 1.54, p > .2, MSE = 128$; $F_2(1, 71) = 2.23, p > .1, MSE = 88$. However, the main effect of block was significant: $F_1(3, 213) = 191.2, p < .001, MSE = 112$; $F_2(3, 213) = 61.77, p < .001, MSE = 347$. Errors decreased from Block 1 (26%) to Block 2 (15%), Block 3 (12%), and Block 4 (11%).

The only significant interaction was that of view and block: $F_1(6, 426) = 3.33, p < .004, MSE = 118$; $F_2(6, 426) = 2.88, p < .01, MSE = 137$ (see Table 5). Relative to canonical views, the disadvantage in naming foreshortened and, to a lesser extent, plane-disoriented views reduced as participants gained experience in naming the objects. Relative to the naming of canonical views, the foreshortened view disadvantage was 7.1%, 2.1%, 0.4%, and 1.2%, and the plane-disoriented view disadvantage was 1.7%, 1.6%, −1.8%, and −0.3%, in Blocks 1, 2, 3, and 4, respectively. Note that the View × SOA interaction was not significant: $F_1(2, 142) = 0.66, p > .5, MSE = 119$; $F_2(2, 142) = 0.84, p > .4, MSE = 94$ (see Table 6).

Tone discrimination task. An ANOVA was conducted on the mean duration required for a correct response to the tone. Responses were measured from the onset of the tone until an "a" or "z" keypress was recorded. There were three within-subject variables: view of the object (canonical, plane disoriented, or foreshortened), SOA (50 ms or 800 ms), and block (1, 2, 3, or 4). Note that responses for high and low tone trials were combined, because this variable was not of interest in the current study.

All of the main effects were significant. For view: $F_1(2, 142) = 3.85, p < .03, MSE = 1{,}394$; $F_2(2, 142) = 2.66, p < .08, MSE = 1{,}707$. Tone responses were slower on foreshortened view trials (547 ms) than on plane-disoriented (543 ms) or canonical (541 ms) view trials. For SOA: $F_1(1, 71) = 99.88, p < .001, MSE = 5{,}037$; $F_2(1, 71) = 342.29, p < .001, MSE = 1{,}445$. Tone responses were slower on short

Table 6
Mean Error Rates (%) as a Function of View and Stimulus Onset Asynchrony (SOA) in Experiment 3

View	SOA Short	Long
Canonical	14.3	15.7
Plane disoriented	15.0	15.7
Foreshortened	17.8	17.7

SOA trials (561 ms) than on long SOA trials (526 ms). Finally, for block: $F_1(3, 213) = 83.96$, $p < .001$, $MSE = 3{,}403$; $F_2(3, 213) = 208.12$, $p < .001$, $MSE = 1{,}295$. Tone responses decreased from Block 1 (578 ms) to Block 2 (547 ms), Block 3 (532 ms), and Block 4 (518 ms). There were no significant interactions.

An ANOVA was also conducted on the error scores in the tone task only. The main effect of view was marginally significant: $F_1(2, 142) = 2.76$, $p < .07$, $MSE = 42$; $F_2(2, 142) = 2.42$, $p < .1$, $MSE = 48$. Tone responses tended to be less accurate on canonical view trials (6.9% errors) than on foreshortened (6.2%) or plane-disoriented (6.1%) view trials. The main effect of SOA was significant: $F_1(1, 71) = 71.61$, $p < .001$, $MSE = 94$; $F_2(1, 71) = 127.33$, $p < .001$, $MSE = 53$. More tone task errors were made on short SOA trials (8.4% errors) than on long SOA trials (4.5%). Finally, the main effect of block was significant: $F_1(3, 213) = 15.13$, $p < .001$, $MSE = 94$; $F_2(3, 213) = 32.89$, $p < .001$, $MSE = 43$. Tone task errors decreased from Block 1 (8.9% errors) to Block 2 (6.7%), Block 3 (5.3%), and Block 4 (4.8%).

The only significant interaction was that for SOA and block: $F_1(3, 213) = 4.05$, $p < .008$, $MSE = 48$; $F_2(3, 213) = 4.18$, $p < .007$, $MSE = 47$. The increase in errors for short relative to long SOA trials was greatest in Block 1, at 5.6%, and subsequently reduced to 4.5% in Block 2, 3.2% in Block 3, and 2.5% in Block 4.

Thus, there were clear effects of SOA on tone task performance. Strenuous attempts were made to have participants prioritize performance on the tone task, with clear instructions, extensive practice, and regular reminders to respond rapidly and accurately to the tone. Nevertheless, participants' tone responses were still adversely affected at short relative to long SOAs, with an increase in latencies of 35 ms and an increase in errors of 3.9%. In addition, the view of the picture had a weak effect: On foreshortened view trials, tone task responses were approximately 6 ms slower (but 0.7% more accurate) than on canonical view trials. Clearly, though, these SOA and view effects were small relative to those found in the picture naming task, and so the assumptions underlying the locus-of-slack logic were reasonably well met (Pashler, 1984, 1994).

Discussion

Replicating Experiments 1 and 2, in Experiment 3 we found that both foreshortening and plane disorientation had clear, deleterious effects on the speed and accuracy of picture naming. Replicating Experiment 2, the disadvantage for both types of rotation decreased, but was not eliminated, with practice.

Most interestingly, there was an interaction between the effects of SOA and view on picture naming. Plane disorientation effects were approximately halved at the short relative to the long SOA. In contrast, the foreshortening disadvantage was additive with the effects of SOA.

As outlined earlier, the underadditive interaction between plane rotation and SOA suggests that normalization for plane rotation is performed at least in part by relatively early (prebottleneck) visual processes. These early processes can apparently proceed in parallel with tone task processing, resulting in reduced effects of plane disorientation at the short relative to the long SOA.

In contrast, the additive effects of foreshortening and SOA suggest that normalization for foreshortening requires later (bottleneck or postbottleneck) visual processes. These processes must be postponed until tone processing at the central bottleneck stage is complete, and so the effects of foreshortening are the same at short and at long SOAs.

Note that the difference in the influence of SOA on plane rotation effects and depth rotation effects is probably not due to differences in the difficulty of compensating for the two transformations. At the long SOA here, RTs to plane-disoriented views were as slow as those to foreshortened views.

Note further that plane rotation effects were reduced, but not eliminated, at the short SOA. The PRP effect was about 200 ms for canonical views (see Figure 8), whereas the disadvantage for plane-disoriented relative to canonical views was only about 100 ms at the long SOA. There was, therefore, potentially sufficient postponement of picture processing at the short SOA for all of the plane disorientation effect to have been absorbed. This did not occur. In addition, the median split analyses revealed that when tone responses on a given trial were slower than usual (and so when tone processing at the central bottleneck may have taken longer, thus increasing the PRP), there was almost no further reduction of the plane disorientation effect on picture naming at the short SOA. It is therefore unlikely that the plane disorientation effect would have been entirely eliminated if the PRP effect had been greater. Instead, the results suggest that there are two loci for the processes involved in compensating for effects of plane rotation: an early prebottleneck locus and a subsequent bottleneck or postbottleneck locus.

The PRP results indicate that the compensatory processes mediating the identification of plane-disoriented and foreshortened views can be separated (although normalization for both transformations may also involve common bottleneck or postbottleneck processes). The data are consistent with the proposal that different compensatory operations are required for plane and depth transformations and that the operations are carried out sequentially. The results of Experiment 3 further suggest that normalization for plane disorientation begins before normalization for foreshortening.

General Discussion

As far as we are aware, the three studies described here are the first to orthogonally manipulate plane and depth rotation to investigate how these transformations combine to influence the recognition of familiar objects. The results provide insights into the nature and the order of the processes involved in compensating for plane disorientation and foreshortening. Our findings challenge the common assumption that the visual system uses the same processes to compensate for plane and depth rotations, instead suggesting that compensation for plane rotations involves separate, earlier processes than compensation for depth rotations.

We found no interaction between the effects of plane and depth rotation, either on initial naming (Experiments 1 and 2) or after practice at naming the experimental stimuli (Experiment 2). These results are consistent with there being distinct, sequentially organized, functional processes to compensate for the effects of these transformations (Sternberg, 1969; see also Miller, 1988, 1990; Roberts & Sternberg, 1993). In a dual-task PRP study (Experiment 3), we found partially underadditive effects of plane rotation and SOA but additive effects of depth rotation and SOA. This suggests that the deleterious effects of plane disorientation can begin to be compensated for by processes operating before a central bottleneck (Pashler, 1984, 1994), but further bottleneck or postbottleneck processing is probably also required to compensate fully for plane disorientation. In contrast, all compensation for foreshortening appears to require bottleneck or postbottleneck processing. Together, the results of the three studies point to a model in which compensation for plane rotation starts relatively early in processing, before compensation for depth rotation has begun. The probable features of the processes involved in compensating for plane and depth rotation are, therefore, each discussed separately.

Recent evidence suggests that identification (as opposed to mirror-image judgments) of plane-disoriented views of objects does not involve mental rotation to transform internal representations in a manner analogous to a physical rotation (Jolicoeur et al., 1998; Lawson, 1999). Alternative accounts to that of mental rotation have been proposed to explain the effects of plane disorientation on identification, including image alignment (Ullman, 1989) and view interpolation (Bülthoff & Edelman, 1992, 1993; Ullman & Basri, 1991); as yet, however, there is insufficient evidence to assess them. The extraction of orientation-invariant features can account for the reduction in plane rotation effects with practice (Jolicoeur, 1990), but this hypothesis does not explain why plane rotation effects are ever observed, because no effects of plane disorientation are predicted if all stimuli are identified via orientation-invariant features.

Alternatively, plane-rotated stimuli may actually be processed differently from upright stimuli, as has recently been proposed for face recognition (Leder & Bruce, 1998). For example, spatial relations between features may be harder to extract for plane-disoriented views of familiar objects, whereas local features may be analyzed equally efficiently at all plane rotations.

Finally, it is likely that certain perceptual attributes can be extracted at a relatively early stage of visual processing, before the identification of an object. These attributes might include the orientation of any axes of symmetry, the main axis of extension of the object, and the likely base of the object. Such attributes could provide important information about the probable orientation of the object in the plane. This, in turn, is likely to be a central component of the process of compensating for plane disorientation in order to identify an object. In contrast, these same attributes may not be as informative about the depth orientation of an object. In addition, knowledge of an object's orientation in depth may not be particularly helpful in compensating for the effects of depth rotation (Lawson & Humphreys, 1998).

The results of Experiment 3 indicated that processing to normalize foreshortened views was fully delayed by a processing bottleneck at short SOAs. Prior studies on the PRP suggest that, in dual-task performance, different operations are associated with a processing bottleneck. One such operation is response selection (Broadbent & Gregory, 1967; Pashler & Johnston, 1998). Varying the difficulty of the stimulus–response mapping in the first of two tasks in a PRP procedure slows RTs in a second task (Pashler, 1984; Smith, 1969), and manipulating the "naturalness" of the stimulus–response mapping in the second task produces additive effects with SOA (McCann & Johnston, 1992). However, in Experiment 3, it seems unlikely that response selection was more difficult for foreshortened than for canonical views of familiar objects.

Alternative operations that have also been implicated in a processing bottleneck have involved memory retrieval (Carrier & Pashler, 1995) and some stimulus analyses, although not stimulus identification (Pashler & Johnston, 1998). Delay to such operations appears to provide a more plausible account of the additive effects of foreshortening and SOA reported in Experiment 3 here. The operation(s) involved in the processing bottleneck for foreshortened stimuli could include additional perceptual processing of foreshortened stimuli (if a more accurate representation of foreshortened relative to canonical stimuli was required for identification) or prolonged memory retrieval for foreshortened views (if, for example, only fragments of foreshortened views could initially be identified, decreasing the efficiency of matching to stored representations). Further studies will clearly be necessary before the exact nature of the bottleneck in the processing of foreshortened views can be specified.

The current results appear to be inconsistent with Hummel and Biederman's (1992) model of object recognition (see also Biederman & Gerhardstein, 1993). Their model produces a monotonic decline in performance for views that are plane disoriented over the range 0° to 135°. In contrast, the model shows nearly complete invariance to rotations in depth. This is a consequence of compensation for depth rotation occurring within the model. In contrast, compensation for plane rotation is not addressed by the model. If, as these results suggest, such compensation is assumed to occur at a later stage of visual processing than compensation for depth rotation, this contradicts our findings, which point to the opposite order of compensation for plane and depth rotation. Alternatively, if no process of compensation for plane rotation is proposed, then, on Hummel and Biederman's model, high error rates would always be predicted for the identification of plane-disoriented views. This again contradicts human empirical data.

Hummel and Biederman's (1992) model could, though, be modified to accommodate compensation for plane rotation. For example, if a plane-rotated stimulus failed to be identified when it was initially processed (because the above–below–beside spatial relations between parts of the objects were assigned with respect to the input orientation of the stimulus, which was assumed, by default, to be upright, hence producing a mismatch with the set of stored spatial relations for that object), then spatial relations of the object might be systematically recoded. The stimulus might then be successfully matched to a stored, object representation, once a different, nonupright stimulus orientation was assumed. Nevertheless, even for such a modified model, it is not clear that compensation for plane rotation would begin before compensation for depth rotation.

The current results place important constraints on theoretical accounts of the achievement of object constancy over plane and depth rotation, with respect to both the number of processes involved and their temporal relations to each other. Our findings indicate that at least two sequential and dissociable processes are involved, with compensation for plane rotation starting before compensation for depth rotation. In addition, practice reduces, but does not eliminate, the disadvantage in identifying both plane-disoriented and foreshortened views of objects. Current theoretical accounts of object identification either fail to account for these results or are too vague, such that clear predictions cannot be derived from them in regard to these issues.

References

Biederman, I., & Gerhardstein, P. C. (1993). Recognizing depth-rotated objects: Evidence for 3-D viewpoint invariance. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1162–1182.

Broadbent, D. E., & Gregory, M. (1967). Psychological refractory period and the length of time required to make a decision. *Proceedings of the Royal Society B, 168,* 181–193.

Bülthoff, H. H., & Edelman, S. (1992). Psychophysical support for a 2-D view interpolation theory of object recognition. *Proceedings of the National Academy of Sciences, USA, 89,* 60–64.

Bülthoff, H. H., & Edelman, S. (1993). Evaluating object recognition theories by computer graphics psychophysics. In T. A. Poggio & D. A. Glaser (Eds.), *Exploring brain functions: Models in neuroscience* (pp. 139–164). New York: Wiley.

Bundesen, C., Larsen, A., & Farrell, J. E. (1981). Mental transformations of size and orientation. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 279–294). Hillsdale, NJ: Erlbaum.

Carrier, L. M., & Pashler, H. (1995). Attentional limits in memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 1339–1348.

Farah, M. J., & Hammond, K. M. (1988). Mental rotation and orientation-invariant object recognition: Dissociable processes. *Cognition, 29,* 29–46.

Hummel, J. E., & Biederman, I. (1992). Dynamic binding in a neural network for shape recognition. *Psychological Review, 99,* 480–517.

Humphrey, G. K., & Jolicoeur, P. (1993). An examination of the effects of axis foreshortening, monocular depth cues, and visual field on object identification. *Quarterly Journal of Experimental Psychology, 46A,* 137–159.

Humphreys, G. W., & Riddoch, M. J. (1984). Routes to object constancy: Implications from neurological impairments of object constancy. *Quarterly Journal of Experimental Psychology, 37A,* 493–495.

Jolicoeur, P. (1985). The time to name disoriented natural objects. *Memory & Cognition, 13,* 289–303.

Jolicoeur, P. (1990). Identification of disoriented objects: A dual systems theory. *Mind and Language, 5,* 387–410.

Jolicoeur, P., Corballis, M. C., & Lawson, R. (1998). The influence of perceived rotary motion on the recognition of rotated objects. *Psychonomic Bulletin & Review, 5,* 140–146.

Jolicoeur, P., & Milliken, B. (1989). Identification of disoriented objects: Effects of context of prior presentation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 200–210.

Kubovy, M., & Podgorny, P. (1981). Does pattern matching require the normalization of size and orientation? *Perception & Psychophysics, 30,* 24–28.

Larsen, A. (1985). Pattern matching: Effects of size ratio, angular difference in orientation, and familiarity. *Perception & Psychophysics, 38,* 63–68.

Lawson, R. (1999). Achieving visual object constancy across plane rotation and depth rotation. *Acta Psychologica, 102,* 221–245.

Lawson, R., & Humphreys, G. W. (1996). View specificity in object processing: Evidence from picture matching. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 395–416.

Lawson, R., & Humphreys, G. W. (1998). View-specific effects of depth rotation and foreshortening on the initial recognition and priming of familiar objects. *Perception & Psychophysics, 60,* 1052–1066.

Lawson, R., & Humphreys, G. W. (1999). The effects of view in depth on the identification of line drawings and silhouettes of familiar objects: Normality and pathology. *Visual Cognition, 6,* 165–195.

Leder, H., & Bruce, V. (1998). Local and relational aspects of face distinctiveness. *Quarterly Journal of Experimental Psychology, 51A,* 449–473.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subjects designs. *Psychonomic Bulletin & Review, 1,* 476–490.

McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 471–484.

McMullen, P. A., & Jolicoeur, P. (1990). The spatial frame of reference in object naming and discrimination of left-right reflections. *Memory & Cognition, 18,* 99–115.

McMullen, P. A., & Jolicoeur, P. (1992). The reference frame and effects of orientation on finding the top of rotated objects. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 807–820.

Miller, J. (1988). Discrete and continuous models of human information processing: Theoretical distinctions and empirical results. *Acta Psychologica, 67,* 190–257.

Miller, J. (1990). Discreteness and continuity in models of human information processing. *Acta Psychologica, 74,* 297–318.

Murray, J. E. (1995). Imagining and naming rotated natural objects. *Psychonomic Bulletin & Review, 2,* 239–243.

Murray, J. E. (1997). Flipping and spinning: Spatial transformation procedures in the identification of rotated natural objects. *Memory & Cognition, 25,* 96–105.

Murray, J. E., Jolicoeur, P., McMullen, P. A., & Ingleton, M. (1993). Orientation-invariant transfer of training in the identification of rotated natural objects. *Memory & Cognition, 21,* 604–610.

Newell, F. N., & Findlay, J. M. (1997). The effect of depth rotation on object identification. *Perception, 26,* 1231–1257.

Palmer, S., Rosch, E., & Chase, P. (1981). Canonical perspective and the perception of objects. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 135–151). Hillsdale, NJ: Erlbaum.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 358–377.

Pashler, H. (1990). Co-ordinate frame for symmetry detection and object recognition. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 150–163.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116,* 220–224.

Pashler, H., & Johnston, J. C. (1998). Attentional limitations in dual-task performance. In H. Pashler (Ed.), *Attention* (pp. 155–190). London: Psychology Press.

Roberts, S., & Sternberg, S. (1993). The meaning of additive reaction-time effects: Tests of three alternatives. *Attention and Performance, 14,* 611–653.

Ruthruff, E., Miller, J., & Lachmann, T. (1995). Does mental rotation require central mechanisms? *Journal of Experimental Psychology: Human Perception and Performance, 21,* 552–570.

Smith, M. C. (1969). The effect of varying information on the psychological refractory period. *Acta Psychologica, 30,* 220–231.

Srinivas, K. (1993). Perceptual specificity in nonverbal priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 582–602.

Srinivas, K. (1995). Representation of rotated objects in explicit and implicit memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 1019–1036.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica, 30,* 276–315.

Ullman, S. (1989). Aligning pictorial descriptions: An approach to object recognition. *Cognition, 32,* 193–254.

Ullman, S., & Basri, R. (1991). Recognition by linear combination of models. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 13,* 992–1006.

Van Selst, M., & Jolicoeur, P. (1994a). Can mental rotation occur before the dual-task bottleneck? *Journal of Experimental Psychology: Human Perception and Performance, 20,* 905–921.

Van Selst, M., & Jolicoeur, P. (1994b). A solution to the effect of sample size on outlier elimination. *Quarterly Journal of Experimental Psychology, 47A,* 631–650.

Warrington, E. K., & James, M. (1986). Visual object recognition in patients with right-hemisphere lesions: Axes or features? *Perception, 15,* 355–366.

Warrington, E. K., & Taylor, A. M. (1973). The contribution of the right parietal lobe to object recognition. *Cortex, 9,* 152–164.

Warrington, E. K., & Taylor, A. M. (1978). Two categorical stages of object recognition. *Perception, 7,* 695–705.

Appendix

The 72 Objects Presented in Experiments 1, 2, and 3

Animals	Implements	Vehicles	Household
bird	binoculars	airplane	boot
camel	calculator	bicycle	cassette tape
cow	camera	bulldozer	catapult
crocodile	can opener	bus	clothes-peg
deer	clock	cannon	compasses
dinosaur	corkscrew	car	dustpan
dog	gun	caravan	hairclip
elephant	hole punch	cement mixer	ink jar
giraffe	iron	life raft	jug
hippopotamus	kettle	forklift truck	mug
horse	lamp	helicopter	oilcan
kangaroo	lighter	horsebox	paperclip
pig	radio	hovercraft	pint glass
rhinoceros	weighing scales	lorry	saucepan
sheep	stapler	steamroller	shoe
tortoise	telephone	tank	teapot
walrus	toaster	tractor	trophy
whale	whisk	train	wardrobe

Received May 27, 1998
Revision received December 30, 1998
Accepted April 23, 1999 ■