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Does Mental Rotation Require Central Mechanisms?

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Four reaction time experiments examined the mental rotation process using a psychological refractory period paradigm. On each trial, participants made speeded responses to both a tone (S_1) and a rotated letter (S_2), presented with varying stimulus onset asynchronies (SOAs). If mental rotation of the stimulus letter can proceed while central mechanisms are busy with S_1, then the effect of orientation should decrease substantially with decreasing SOA. Contrary to these predictions, the effect of orientation was nearly constant across SOAs, suggesting that mental rotation cannot effectively proceed without help from central mechanisms. These results support the conclusion that mental rotation requires access to a single-channel mechanism and must therefore be performed serially with other operations requiring the same mechanism.

When people are asked to perform two tasks at the same time, performance is almost always degraded on at least one of the tasks, and it is of both practical and theoretical importance to understand the cognitive limitations that are responsible for this degradation. In recent years, these limitations have been studied extensively using the psychological refractory period (PRP) paradigm. In this paradigm, the stimuli for two different tasks (S_1 and S_2) are presented in rapid succession, and the participant is asked to respond to both stimuli as quickly as possible. When the time between the onsets of the two stimuli (*stimulus onset asynchrony*, or SOA) is small, responses to the second stimulus are slowed dramatically, often by several hundred milliseconds (e.g., Vince, 1948; Welford, 1952). This slowing occurs even when the two tasks do not compete for structural reasons (e.g., both require the right hand) and when the input modalities for S_1 and S_2 are different.

Bottleneck Models

Recent studies using the PRP paradigm have produced results that are generally consistent with *bottleneck models* of second-task slowing. In these models, certain mental operations (e.g., response selection) require a limited-capacity central mechanism that can be allocated to only one task at a time, and hence is referred to as the "bottleneck" mechanism (e.g., McCann & Johnston, 1992; Pashler, 1984, 1989; Pashler & Johnston, 1989; Welford, 1952). According to this model, second-task reaction time (*RT2*) is lengthened at short SOAs because operations requiring the bottleneck mechanism have to wait until this mechanism is finished with the first task. Thus, *RT2* is essentially the sum of the time spent waiting for the bottleneck and the time needed for Task 2 processing. Each millisecond of the waiting or "slack" period (cf., Schweickert, 1978) adds directly to *RT2*, because no second-task processing is accomplished during this period. As reviewed by Pashler (1993, 1994a, 1994b), the bottleneck model is strongly supported by a variety of experimental results that are difficult to reconcile with alternative models. In addition, current evidence indicates that the bottleneck mechanism is needed for response selection (McCann & Johnston, 1992; Pashler, 1984, 1989; Pashler & Johnston, 1989) and perhaps response initiation (Keele, 1973; Pashler, 1994a), and thus one can expect to observe delays in *RT2* whenever two speeded choice-RT tasks must be performed at the same time.

The paradigm introduced by Pashler (1984) provides a useful diagnostic tool for determining what operations, in addition to response selection, require the bottleneck mechanism. The basic approach, which has been described at length elsewhere (e.g., McCann & Johnston, 1992; Pashler, 1984; Pashler & Johnston, 1989), is to manipulate a factor that influences the difficulty of a specific second-task stage and then determine whether the effect of that factor de-

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creases or remains constant as SOA decreases. If the factor affects a second-task stage at or beyond the bottleneck, the factor's effect should be independent of SOA (i.e., additive with the effects of SOA). This is because SOA and the factor affect different additive components of *RT*2: SOA affects the time at which postbottleneck operations begin, whereas the factor affects the duration of postbottleneck operations.

If the factor affects a stage prior to the bottleneck, however, the factor's effect should decrease with decreasing SOA (i.e., there should be an underadditive interaction of the factor with SOA). At short SOAs, Task 2 operations that require the bottleneck (e.g., response selection) must wait until the bottleneck mechanism has completed Task 1 bottleneck processes. A factor affecting prebottleneck operations will only affect what goes on during this waiting time and therefore will have little or no effect on *RT*2, just as the speed of the check-in line at the airport has no effect on overall travel time to the destination. In sum, at short SOAs it makes no difference whether the prebottleneck operations finish earlier or later, because the postbottleneck operations have to wait for the bottleneck mechanism to become available in either case. Of course, at long SOAs the bottleneck mechanism will usually be available for Task 2 processing as soon as it is needed (i.e., there is no slack), and so the durations of prebottleneck operations will influence *RT*2. Thus, the factor will have a larger effect on *RT*2 at long SOAs than at short ones.

Carrier and Pashler (in press) used this logic to see whether information can be retrieved from long-term memory without assistance from the bottleneck mechanism. They manipulated the difficulty of memory retrieval, and the effect of this manipulation was constant across SOAs, suggesting that some memory retrieval operations occur at or after the bottleneck. These results indicate that the bottleneck mechanism is responsible for more than just the selection of responses.

The processing demands of various perceptual operations have also been examined using this paradigm. It appears that most perceptual operations, especially those involving simple visual judgments, can operate independently of the bottleneck mechanism. Pashler (1984), for example, varied the contrast of a visual stimulus (S_2) against its background. The effect of this manipulation was 58 ms when the judgment was performed alone, but only 28 ms at short SOAs, as would be expected if contrast-sensitive perceptual processing of S_2 could occur while the bottleneck mechanism was processing S_1. On the other hand, there is evidence that certain difficult perceptual discriminations do, in fact, require access to the bottleneck mechanism. McCann and Johnston (1989) asked participants to make pitch judgments (S_1) and then to discriminate between visually presented *A*s and *H*s (S_2). When the fonts used to display these letters were distorted so as to enhance their visual similarity (e.g., by making the vertical lines of the *H*s converge near the top of the letter), the effect of the distortion was nearly the same for all SOAs. Accordingly, McCann and Johnston concluded that although many perceptual operations can be carried out before the bottleneck (e.g., the operations affected by stimulus contrast, Pashler, 1984), some difficult perceptual operations do require the bottleneck mechanism.

Does Mental Rotation Require the Response-Selection Bottleneck?

Further specification of the bottleneck model will require more detailed information about the nature of the bottleneck mechanism or mechanisms. It is crucial, for instance, to determine how many bottleneck mechanisms there are and which mental operations require each bottleneck mechanism. As just reviewed, traditional choice-RT tasks involving relatively easy perceptual judgments suggest the existence of a bottleneck mechanism that is responsible for selecting responses, hereinafter referred to as the *response-selection bottleneck,* or just "the bottleneck" (McCann & Johnston, 1992; Pashler, 1984, 1989; Pashler & Johnston, 1989), but this bottleneck mechanism may also be responsible for long-term memory retrieval (Carrier & Pashler, in press) and difficult perceptual judgments (McCann & Johnston, 1989). Thus far, only a limited range of tasks have been examined, so it is too early to make precise generalizations concerning the cognitive operations for which this bottleneck mechanism is required.

The purpose of the present study was to extend our understanding of the range of processes that require the bottleneck mechanism identified in the PRP studies discussed earlier. To do this, we studied a different kind of perceptual operation—mental rotation—in the dual-task situation. The mental rotation process has been inferred from performance in imagery tasks, especially those requiring discrimination of normal from mirror-image forms presented in different orientations. In these tasks, discrimination time often increases approximately linearly with the angular difference between the orientation of the stimulus and a previously presented, preferred, or canonical orientation (e.g., Shepard & Metzler, 1971). One intriguing conceptualization of mental rotation is that it is an analog process that transforms (i.e., rotates) a mental image from one orientation to another, along the way passing through a series of intermediate states corresponding to different physical orientations (e.g., Cooper & Shepard, 1973; Pellizzer & Georgopoulos, 1993), although others have argued for somewhat different conceptualizations (e.g., Minsky, 1975; Pylyshyn, 1978).

Several properties of the mental rotation process make it an interesting candidate for study in the context of bottleneck models. First, mental rotation is more perceptual than most processes that have previously been found to require the bottleneck, such as response selection and memory retrieval. Mental rotation also differs from the type of difficult perceptual discrimination found to require the bottleneck by McCann and Johnston (1989), because the former requires manipulation of a mental image, whereas the latter requires comparison of a visible stimulus against one or more representations in memory. Thus, if mental rotation also requires the bottleneck, it will extend the range of mental operations for which the bottleneck is known to be required. Second, certain characteristics of mental rotation suggest that it might well require the bottleneck. For example, it is a comparatively difficult process, taking up to 400 ms for upside-down stimuli, and it is reasonable to suspect that the bottleneck will be required for most if not all difficult operations. Furthermore, mental rotation appears to be under conscious control (Cooper & Shepard, 1973), and the fact that conscious processing has strict capacity limits suggests that such processing might require the bottleneck (e.g., Carr, 1979; Posner, 1978). Third, mental rotation is a relatively well understood process, and its duration can be varied over a range of several hundred milliseconds. These features make it easier to discriminate among models without fear of contamination from unsuspected artifacts.

Although the operation of the mental rotation process has been studied extensively, it is not yet clear what mental mechanisms are needed to carry it out, and so the results of this study will also further our understanding of mental rotation per se. Is mental rotation performed by a dedicated module that does little or nothing else, by an imagery-specific or perception-specific processing system, or perhaps by more general-purpose cognitive mechanisms of the sort that are required for response selection and memory retrieval? Obviously, one way to begin answering this question is to find out whether mental rotation requires the bottleneck mechanism.

A variety of studies indicate that mental rotation interferes with other cognitive operations and thereby indirectly suggest that it requires bottleneck mechanisms. Bundesen, Larsen, and Farrell (1981), for example, reported that participants could not mentally rotate stimuli while they were simultaneously engaged in size scaling operations (reducing or enlarging a mental image), suggesting that the mechanism responsible for mental rotation is also used to carry out other types of operations with mental images. Ruthruff and Miller (in press), meanwhile, found that mental rotation interferes with difficult perceptual discriminations, indicating that it requires a processing capacity that is not specific to the manipulation of images. Finally, Band and Miller (1994) found that mental rotation interfered with the concurrent preparation of a response hand, and Ilan and Miller (1994) found evidence that preparation for mental rotation interferes with the maintainence of stimulus–response mappings. Taken together, these results suggest that the mechanisms engaged by mental rotation are general-purpose mechanisms responsible for many other cognitive operations and thereby raise the likelihood that the mental rotation process requires the bottleneck mechanism.

On the other hand, several findings concerning the psychophysiological correlates of mental rotation suggest that the neural hardware responsible for mental rotation is distinct from the structures involved in selecting responses, in which case mental rotation might not require the bottleneck after all. For instance, there is evidence from electrophysiological studies that mental rotation is carried out by parietal brain structures (Peronnet & Farah, 1989; Stuss, Sarazin, Leech, & Picton, 1983), whereas response selection seems primarily to involve frontal areas of the cerebral cortex (Requin, Riehle, & Seal, 1988). Furthermore, Farah and Hammond (1988) reported a patient with a frontotemporoparietal lesion who failed several mental rotation tasks but could nonetheless successfully perform visuospatial tasks of similar difficulty that did not require mental rotation. One possible explanation of such a deficit is that there was damage to a special-purpose module responsible for some aspect of mental rotation, although, as noted by Farah and Hammond, the module may also be responsible for other, untested, visuospatial operations.

Corballis (1986) provided another piece of evidence suggesting that mental rotation might not require central mechanisms. He asked participants to hold several items (8 digits or a random dot pattern) in short-term memory while mentally rotating stimulus letters and found that the rate of rotation was independent of memory load. This is consistent with the idea that mental rotation is carried out by a different set of mechanisms than those used to maintain items in short-term memory. Memory load did influence overall RT, but this finding simply indicates that holding a memory load prolongs one or more of the nonrotational processes required by the mental rotation task (e.g., perceptual identification, response selection).

Because previous experiments do not uniquely identify the mechanism or mechanisms required for mental rotation, the present experiments were designed to address this question using the PRP paradigm. On each trial, participants were first presented with a tone, which they had to classify as high or low in pitch. After a brief SOA, a stimulus letter was displayed in one of several possible orientations, and participants had to determine whether it was a normal or a mirror-image version of that letter. Virtually all previous studies using similar stimuli have found that the time required to make these mirror–normal discriminations increases monotonically (sometimes linearly) as stimulus orientation is varied from upright to upside-down.

Model Predictions

Following the logic of Pashler (1984) outlined earlier, stimulus orientation and SOA should have additive effects on RT to the letter stimulus (*RT*2) if mental rotation (or some process that precedes it) requires the bottleneck mechanism. But if the process of mental rotation takes place before the bottleneck, then stimulus orientation and SOA should produce an underadditive interaction: The effect of stimulus orientation should be reduced when SOA is short.

Although previous investigators using this logic have typically just tested for the presence or absence of underadditive interactions, the bottleneck model also allows us to estimate the size of the underadditive interaction that should be observed if mental rotation can be carried out before the bottleneck. According to this model, mental rotation begins as soon as preliminary perceptual analysis of the letter has been completed (i.e., formation of a rotatable image). The duration of the preliminary perceptual operations and the duration of mental rotation are assumed to be independent of SOA (i.e., these processes proceed at the same rate regardless of whether or not the bottleneck mechanism is currently engaged with Task 1). Once rotation is finished, the mirror–normal judgment can be made, and then a response can be selected and executed, but only if the bottleneck mechanism is available (i.e., it has finished with Task 1 bottleneck processing).[1] The point at which the bottleneck mechanism completes Task 1 bottleneck processes is assumed to be independent of SOA and of the orientation of S_2.

According to this model, the value of $RT2$ is

$$RT2 = \max(B - SOA, MR) + C, \qquad (1)$$

where $B - SOA$ is the time—measured from the onset of S_2—needed to complete Task 1 bottleneck processes, MR is the time—also measured from the onset of S_2—at which mental rotation is completed, and C is the time required for the mirror–normal judgment and the selection and execution of a response to the stimulus letter. Essentially, this equation says that later processes, which require C milliseconds, can begin after the completion of both Task 1 bottleneck processes, which require $B - SOA$ milliseconds, and mental rotation, which requires MR milliseconds.

Consider a factorial experiment with two different SOAs, $SOA_1 < SOA_2$, and two different stimulus orientations (e.g., 0° and 180°) producing finishing times of $MR_1 < MR_2$ for the mental rotation processes. Let the $RT2$s for the four cells of the design be denoted $RT2_{11}$, $RT2_{12}$, $RT2_{21}$, and $RT2_{22}$, where the first and second subscripts indicate the levels of SOA and orientation, respectively. Note that because short SOAs produce longer RTs, $RT2_{11}$ and $RT2_{12}$ will tend to be larger than $RT2_{21}$ and $RT2_{22}$, respectively. Assuming that the values of B, MR_1, and MR_2 are constants rather than random variables (the effects of random variation on the predictions of the model are considered in the General Discussion), one measure of the interaction contrast among these four cells, I, is

$$I = RT2_{22} - RT2_{21} - RT2_{12} + RT2_{11}. \qquad (2)$$

Note that, given this definition, positive values of I represent underadditive interactions.

Predicted values of I can be computed by substituting into Equation 2 the values of Equation 1 corresponding to the four cells of the experimental design:

$$\begin{aligned} I &= \max(B - SOA_2, MR_2) - \max(B - SOA_2, MR_1) \\ &\quad - \max(B - SOA_1, MR_2) + \max(B - SOA_1, MR_1) \qquad (3) \\ &= \begin{cases} \max(B - SOA_1, MR_1) - \max(B - SOA_2, MR_1), \\ \qquad \text{when } MR_2 \geq B - SOA_1 \\ \max(B - SOA_2, MR_2) - \max(B - SOA_2, MR_1), \\ \qquad \text{when } MR_2 < B - SOA_1 \end{cases} \\ &= \begin{cases} RT2_{11} - RT2_{21}, \text{ when } MR_2 \geq B - SOA_1 \\ RT2_{22} - RT2_{21}, \text{ when } MR_2 < B - SOA_1. \end{cases} \qquad (4) \end{aligned}$$

Thus, depending on whether MR_2 is larger or smaller than $B - SOA_1$, the size of the underadditive interaction will equal either the effect of SOA for upright stimuli ($RT2_{11} - RT2_{21}$) or the effect of orientation at the longer SOA ($RT2_{22} - RT2_{21}$). This necessarily implies that either the SOA effect will vanish at the larger orientation (i.e., for upside-down stimuli) or the effect of orientation will vanish at the shorter SOA (SOA_1). Because the effects of SOA and orientation are quite large—typically about 300 to 400 ms—the prediction that one will disappear is striking. Furthermore, as shown by computations presented in the General Discussion section, these predictions change very little when the durations involved are random variables rather than constants.

Experiment 1

Experiment 1 was an initial test to determine whether mental rotation can be performed while the bottleneck mechanism is busy with Task 1, as one would expect if mental rotation does not require central mechanisms. The first task was a high–low tone discrimination, and the second task was a mirror–normal judgment concerning a visually presented letter. The tone stimulus was always presented first, and the letter appeared after a variable SOA (50 or 400 ms). The duration of mental rotation was varied by presenting the letter in different orientations.

Method

Participants. Participants ($N = 24$) were students at the University of California, San Diego, who took part to fulfill a class requirement. Six participants failed to meet our criterion of 85% correct on the mental rotation task and were therefore replaced.[2]

Stimuli. Stimuli were the letters *F, R,* and *g,* and their mirror images, presented at either 0°, 90°, or 180° clockwise from vertical. Letters were created by drawing straight line segments between points in a 5 (horizontal) by 7 (vertical) array. The letters were displayed on an NEC multisync monitor connected to an IBM-PC compatible computer and subtended approximately 1.4° horizontally and 1.9° vertically. Tones were presented for 33 ms at either 300 or 1,000 Hz using standard IBM compatible internal speakers.

Procedure. Participants were instructed to respond to low tones by pressing the *d* key and to high tones by pressing the *f* key, using the middle and index fingers of the left hand, respectively.

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[1] For ease of presentation, we are assuming that the mirror–normal judgment requires the bottleneck mechanism. The alternative assumption, that the mirror–normal judgment does not require the bottleneck mechanism, leads to an equivalent model, in which the time needed for mental rotation, at each orientation, is simply increased by a constant corresponding to the duration of the mirror–normal judgment.

[2] It is not uncommon in speeded mental rotation experiments for a substantial number of participants to produce high error rates. Requiring participants to perform two tasks per trial, as in the present experiments, exacerbates this problem. In addition to those reported later, we have conducted analyses including the participants with high error rates, and we found essentially the same results.

Participants were further instructed to respond to the letters by pressing the *j* key for normal images and the *k* key for mirror images, using the index and middle fingers of the right hand, respectively. Participants were told that both tasks were important but that they should focus on responding quickly to the tones. Whenever participants failed to respond to the tone within 1,500 ms of tone onset (less than 3% of trials for each experiment reported in this article), the trial was not recorded, and they were admonished to respond more rapidly. Trials on which response to the letter took more than 4 s (less than 3% of trials for all experiments) were also discarded, but they did not prompt a warning to respond more rapidly.

On half of the trials the SOA was 50 ms, and on the other half the SOA was 400 ms. Stimuli and SOAs were chosen randomly with the restriction that each combination of letter identity, version (mirror vs. normal), orientation, and SOA occurred equally often within each block of trials.

Each trial began with the presentation of a fixation cross for 800 ms, followed by a blank screen for 300 ms and then a tone for 33 ms. The stimulus letter was presented either 50 or 400 ms after the onset of the tone and was displayed until the participant responded to it. If the participant responded incorrectly to either the tone or the letter, an error message was displayed for 2 s; no feedback was given for correct responses. The next trial began 2 s later.

Participants first completed a practice block of 74 trials and then completed six experimental blocks of 74 trials each. The first two trials of each block were considered warm-up trials and were not recorded. Participants were allowed to take a short break at the middle and end of each block. The entire session lasted about 50 min.

Results and Discussion

Mirror-normal task. Figure 1 shows mean *RT*1 as a function of SOA and mean *RT*2 as a function of SOA and stimulus orientation, for trials on which the correct mirror–normal response was made; Table 1 shows the mean error rates.

A three-way repeated-measures analysis of variance (ANOVA)[3] was conducted on correct *RT*2s[4] and error rates from the mirror–normal task. The main effect of orientation was significant for both *RT*2, $F(2, 46) = 43.62$, $p < .001$, and for error rates, $F(2, 46) = 27.24$, $p < .001$. The main effect of SOA on *RT*2 was also significant, $F(1, 23) = 545.25$, $p < .001$. Participants responded faster to normal ($M = 1108$ ms) than to mirror-image stimuli ($M = 1{,}200$-ms), $F(1, 23) = 30.09$, $p < .001$, as is commonly found (e.g., Cooper & Shepard, 1973). However, participants also responded less accurately to normal than to mirror-image stimuli, $F(1, 23) = 10.78$, $p < .01$, suggesting that some of the *RT*2 difference may have been due to a speed–accuracy tradeoff.

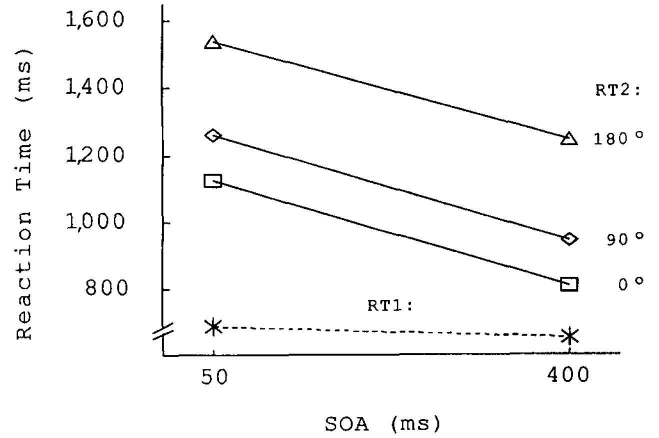

Figure 1. Experiment 1: Mean *RT*1 (tone task) as a function of stimulus onset asynchrony (SOA), and mean *RT*2 (mirror–normal task) as a function of SOA and stimulus orientation.

Table 1

Mean Task 2 Error Rates for Experiments 1 and 2 as a Function of Orientation, Stimulus Onset Asynchrony (SOA), and Version (Mirror vs. Normal)

		Orientation				
SOA (ms)	Version	0°	45°	90°	135°	180°
		Experiment 1				
50	N	4.0		3.2		16.8
	M	5.9		5.8		7.9
400	N	4.3		5.9		15.5
	M	3.0		3.3		8.0
		Experiment 2				
33	N	3.1	2.9	3.0	10.6	13.8
	M	6.0	4.7	5.1	7.8	9.3
400	N	3.4	5.0	4.4	10.4	13.3
	M	5.5	3.6	3.8	6.9	8.1

Note. N = normal; M = mirror.

As shown in Figure 1, the effects of orientation and SOA on *RT*2 were approximately additive, with effects of orientation (0° vs. 180°) of 413 and 442 for SOAs of 50 and 400 ms, respectively. The small underadditive interaction of orientation and SOA was marginally significant, however, $F(2, 46) = 2.69$, $p < .10$.

Overall, the approximate additivity of orientation and SOA suggests that mental rotation did not begin until after Task 1 operations requiring the bottleneck had finished, consistent with models in which mental rotation takes place at or after the bottleneck rather than before it. For one thing, the interaction was not statistically reliable at the standard $p < .05$ cutoff. More important, even if there really were an underadditive interaction, it was far too small to be consistent with the hypothesis that mental rotation of S_2 can be carried out while the bottleneck mechanism is engaged with

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[3] In all of the analyses reported in this article, *p* values have been adjusted using the Greenhouse-Geisser (1959) correction where appropriate.

[4] We report statistical analyses of the means of individual-participant mean RTs. Comparable analyses were conducted using individual-participant median RTs, and these yielded similar results, ruling out the possibility of outlier-based artifacts. In addition, all of the reported RT analyses are based only on trials in which a correct response was made to Task 2, regardless of the accuracy of the tone response. We conducted additional analyses including both correct and incorrect responses to Task 2 and found nearly identical results.

S_1. As discussed in the introduction and considered further in the General Discussion, models that allow such parallel processing must predict either that the SOA effect should disappear for upside-down stimuli or that the orientation effect should disappear at the 50 ms SOA. Ninety-five percent confidence intervals indicate that the former effect is 287 ± 38 ms, and the latter is 413 ± 142 ms, so it is evident that neither effect disappeared. Clearly, then, the data rule out the hypothesis that mental rotation can proceed normally without waiting for the bottleneck mechanism.

There was also a significant underadditive interaction between orientation and stimulus version (mirror vs. normal) on *RT2*, $F(2, 46) = 24.19$, $p < .001$. The commonly found advantage for normal over mirror-image stimuli decreased as orientation (in degrees from upright) increased. The interaction between these two factors on error rates was also significant, $F(2, 46) = 11.32$, $p < .001$; whereas participants responded roughly equally accurately to normal and mirror image stimuli that were upright or rotated 90°, they responded more accurately to upside-down stimuli that were mirror images. One interpretation of this pattern is that participants were biased toward interpreting upside-down stimuli as mirror images and were thus especially fast and accurate when responding to upside-down mirror images.

Tone task. The same ANOVA was performed on the *RT1* data from the tone task. The only significant effect was that of SOA, $F(1, 23) = 9.80$, $p < .01$; participants responded slightly more slowly when the SOA was 50 ms ($M = 687$ ms) than when it was 400 ms ($M = 654$ ms). Because participants made very few errors to the tone task (less than 2%), tone-task error rate data were not analyzed.

Correlations of RT1 and RT2. As discussed by Pashler (1984), bottleneck models also predict positive correlations of *RT1* and *RT2*, particularly at short SOAs. This is because *RT1* and *RT2* are affected in the same way by random variations in the durations of Task 1 stages at or before the bottleneck, at least when SOA is small. To test for the predicted pattern of correlations, we computed correlations of *RT1* and *RT2* across the six trials for each combination of participant, block, and condition. To summarize these correlations, we first transformed each one to a z value using Fisher's r-to-z transformation (e.g., Marascuilo, 1971) and then performed statistical analyses (e.g., averaging, ANOVA) on these z values. Average z values across participants and blocks were transformed back into correlations using the inverse transformation, and the resulting "mean correlations" are shown in Table 2 as a function of orientation, SOA, and version. (This procedure was used to calculate average correlations throughout this article.) As predicted, correlations were higher with an SOA of 50 ms than with an SOA of 400 ms, $F(1, 23) = 50.03$, $p < .001$, consistent with the claim that the *RT2*s were delayed by a central bottleneck at an SOA of 50 ms.

Table 2
Mean RT1–RT2 Correlations in Experiment 1, as a Function of Orientation, Stimulus Onset Asynchrony (SOA), and Version (Mirror vs. Normal)

		Orientation		
SOA (ms)	Version	0°	90°	180°
50	N	.91	.83	.65
	M	.79	.75	.61
400	N	.64	.53	.31
	M	.63	.46	.38

Note. N = normal; M = mirror.

Control Experiment 1. In the main experiment, participants were instructed to emphasize the tone task and were warned to respond more rapidly whenever they failed to respond to the tone within 1,500 ms. Because of the emphasis on the speed of *RT1*, it is conceivable that participants intentionally deferred mental rotation until Task 1 response selection had been completed. According to this explanation, participants were capable of performing mental rotation while the bottleneck mechanism was busy with Task 1—they simply chose not to, because doing so might have slowed *RT1*. To investigate this possibility, we tested 12 new participants, instructing them to respond quickly and accurately to both stimuli so that they would give approximately equal emphasis to the two tasks. In addition, participants were never told that their tone responses were too slow. The results are shown in Figure 2, with mean *RT1* and *RT2* plotted as a function of SOA and orientation. The data from the mirror–normal task do not show underadditivity, $F(2, 22) < 1$, thereby strengthening the conclusion that mental rotation does not begin until the bottleneck mechanism becomes available.

Without instructions to emphasize the first task, participants have previously been observed to "group" their responses (i.e., press both response keys at approximately the same time; cf., Pashler, 1984; Pashler & Johnston, 1989), and it is interesting to ask whether they did this in the present control experiment. Although the average correlations between *RT1* and *RT2* were higher in this control experiment ($r = .80$) than in the main experiment ($r = .66$), $F(1, 34) = 7.39$, $p < .01$, the average interresponse interval

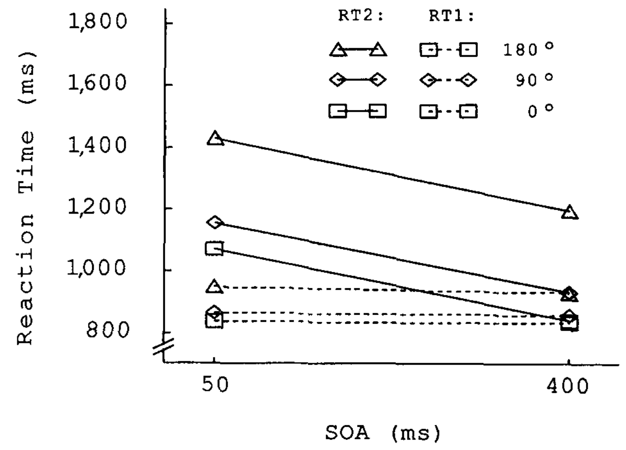

Figure 2. Control Experiment 1: Mean *RT1* (tone task) and *RT2* (mirror–normal task) as a function of stimulus orientation and stimulus onset asynchrony (SOA).

($M = 451$ ms) was much larger than one would expect if participants were simply grouping their responses. The high correlations and the significant effect of orientation on *RT1*, $F(2, 22) = 8.14$, $p < .01$, on the other hand, suggest that participants did at least occasionally defer the execution of *RT1* until mental rotation had been completed. One reason this task might have discouraged the consistent use of a grouping strategy is that *RT2* took much longer than *RT1* (especially with upside-down stimuli), and thus grouping would result in unreasonably long delays of *RT1*.

Control Experiment 2. Another possibly important feature of the main experiment was that stimulus letters remained on the screen until participants responded to them. Under these conditions, it was possible for participants to defer perceptual processing of the letters until the bottleneck mechanism had completed Task 1 operations.[5] Naturally, if participants defer perceptual operations, then they must also defer mental rotation. To test this explanation of the results, we tested 12 new participants in a second control experiment using 100-ms letter displays; with such brief displays, it is unlikely that participants can defer perceptual processing of the letters. Figure 3 shows the obtained mean *RT1* as a function of SOA and mean *RT2* as a function of orientation and SOA. The interaction between orientation and SOA on *RT2* again was nearly additive and failed to reach significance, $F(2, 22) < 1$, suggesting that the long display durations were not responsible for the lack of underadditivity observed in Experiment 1.

Experiment 2

One limitation of Experiment 1 is that stimuli were presented in only three different orientations: upright, 90° clockwise, and upside-down. Because previous studies of mental rotation have typically used six or more different orientations, it seemed appropriate to replicate our results with additional orientations, just to make sure that the limited set of orientations did not encourage the use of a special, bottleneck-dependent strategy. Clearly, increasing the number of orientations reduces the likelihood that participants can develop strategies specific to any one orientation (i.e., strategies that do not involve mental rotation). Thus we replicated Experiment 1 with eight different orientations spaced 45° apart: 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° from vertical.

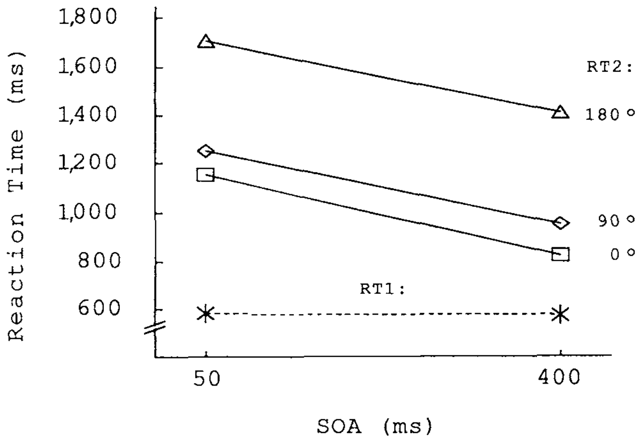

Figure 3. Control Experiment 2: Mean *RT1* (tone task) as a function of stimulus onset asynchrony (SOA), and mean *RT2* (mirror–normal task) as a function of SOA and stimulus orientation.

A further reason for examining additional orientations is that mental rotation may require the bottleneck at some orientations but not others. For example, smaller rotations (e.g., for stimuli 45° from upright) might involve qualitatively different processes than those used with 90° and 180° stimuli and might therefore be handled without the bottleneck mechanism.

Method

Except where noted, the methods were identical to those of Experiment 1.

Participants. Participants ($N = 36$) were students at the University of California, San Diego, who took part to fulfill a class requirement; none of them participated in any other experiment reported in this article. Four participants failed to meet our criterion of 85% correct and were therefore replaced.

Stimuli. Letters were presented at either 0°, 45°, 90°, 135°, 180°, 225°, 270°, or 315° from vertical.

Procedure. The SOAs used in this experiment were 33 and 400 ms. Participants completed one practice block of 74 trials (as in the previous two experiments), and then five experimental blocks of 82 trials, divided equally among conditions. The first two trials were again used as warm-up trials and were not recorded. Stimulus letters were selected randomly on each trial.

Results and Discussion

Mirror-normal task. Because the direction of rotation had negligible effects on *RT2*, data from equivalent clockwise and counterclockwise orientations have been combined. Figure 4 displays mean *RT1* as a function of SOA and mean *RT2* as a function of stimulus orientation and SOA for correct responses; Table 1 shows mean error rates.

The effect of orientation was significant both for *RT2*, $F(4, 140) = 116.23$, $p < .001$, and error rates, $F(4, 140) = 24.14$, $p < .001$. The effect of SOA on *RT2* was also significant, $F(1, 35) = 654.43$, $p < .001$, and participants again responded faster to normal stimuli ($M = 1{,}089$ ms) than to mirror image stimuli ($M = 1{,}227$ ms), $F(1, 35) = 63.44$, $p < .001$.

The interaction between orientation and SOA did not approach significance for *RT2*, $F(4, 140) = 1.88$, $p > .1$, or for error rates, $F(4, 140) < 1$. Thus, the data are once again consistent with the assertion that mental rotation cannot proceed while the bottleneck mechanism is busy with another task, and this appears to be true for small deviations from upright (45°) as well as large ones.

The interaction between orientation and version, present

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[5] This idea was suggested to us by Mark Van Selst.

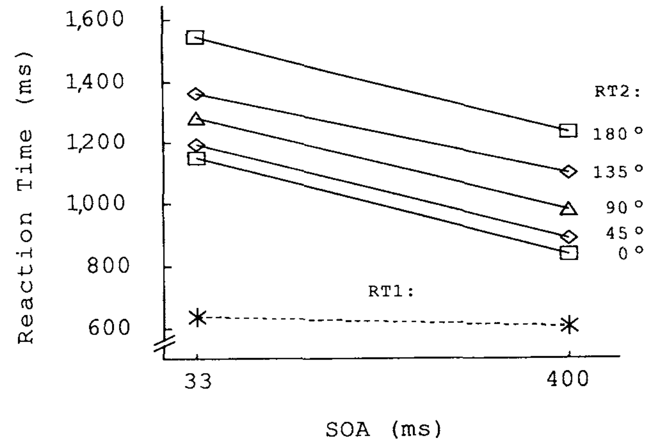

Figure 4. Experiment 2: Mean *RT*1 (tone task) as a function of stimulus onset asynchrony (SOA), and mean *RT*2 (mirror–normal task) as a function of SOA and stimulus orientation.

in the previous experiments, was again significant for *RT*2, $F(4, 140) = 6.20$, $p < .01$, and error rates, $F(4, 140) = 5.75$, $p < .01$. The patterns of results were similar to, although perhaps less pronounced than, those observed in Experiment 1: Relative to normal stimuli, responses to mirror-image stimuli became faster and more accurate as orientation (in degrees from vertical) increased, as would be expected if participants had a bias toward interpreting upside-down stimuli as mirror images.

Tone task. As in Experiment 1, mean *RT*1 was slightly greater at short SOAs ($M = 636$ ms) than at long SOAs ($M = 602$ ms), $F(1, 35) = 13.31$, $p < .01$. The only other significant effect on *RT*1 was the three-way interaction between orientation, version, and SOA, $F(4, 140) = 2.78$, $p < .05$. Because this interaction was nonmonotonic across orientations and was not observed in the other experiments reported in this article, we believe it was a Type I error. In any case, mean *RT*1, across conditions, varied over a range of only 31 ms, so the interaction was not very large even if it was real. There were not enough errors on the tone task to warrant analyses. Within-condition correlations of *RT*1 and *RT*2 were again positive, particularly at the short SOA.

Experiment 3

The results of Experiments 1 and 2 are consistent with the claim that mental rotation does not proceed while the bottleneck mechanism is busy with Task 1 operations. One possibility worth considering, however, is that our participants were capable of rotating while the bottleneck mechanism was occupied with Task 1 but simply opted to perform these operations serially, perhaps to reduce effort. We have already examined a version of this hypothesis to some extent through a control experiment reported in conjunction with Experiment 1. In that control experiment, participants were instructed to place equal emphasis on both tasks, but the results nevertheless supported the claim that mental rotation was not performed during Task 1 bottleneck operations. The purpose of Experiment 3 was to provide a more sensitive test of this hypothesis, by attempting to further encourage participants to work on both tasks at the same time.

Several major changes were made to the experimental methods used in Experiments 1 and 2. The first change was to place equal emphasis on the two tasks (as in the control experiment discussed earlier). Thus, participants were not encouraged to defer Task 2 operations in favor of Task 1. Next, we provided participants with an explicit payoff system, described later, that encouraged fast and accurate responding. Because participants earned more money by responding more quickly, they were motivated to perform both tasks efficiently. Also, to specifically encourage parallel processing in the two tasks, participants were informed that the payoffs for fast responses were based on the time required to complete both responses, and that the time to make the first response was irrelevant. The most effective strategy under these conditions, arguably, would be to perform mental rotation and Task 1 operations at the same time, if possible. In contrast, a bottleneck strategy would presumably just speed up one response at the expense of slowing the other. To help them find an optimal strategy, participants were given feedback after each trial indicating the number of points they earned for that trial and the total number of points they had so far accumulated.

Also, instead of randomly mixing SOA conditions within a block of trials, SOA conditions (0 and 400 ms) were blocked in the current experiment. Because SOAs were mixed in Experiments 1 and 2, the letter to be rotated occasionally appeared 400 ms after the tone. Rather than always prepare to process the letter immediately after detecting the tone (i.e., in case the SOA was short), participants may have deliberately waited several hundred milliseconds. This strategy might reduce cognitive effort and, in many cases (i.e., when SOA is long) would not slow their responses. By blocking SOAs, we ensured that participants would have a clear incentive to prepare to process both S_1 and S_2 when SOA was short.

Furthermore, in Experiments 1 and 2 the tone always sounded before the letter appeared, and it is possible that this encouraged participants to start by processing Task 1 exclusively. Thus, to further discourage participants from deferring Task 2 processing, the current experiment used an SOA of 0 ms in some blocks of trials. Presenting the letter and tone simultaneously should encourage participants to process them in parallel as much as possible.

Finally, participants responded to the tones by making vocal responses ("high" or "low") rather than manual responses. The decision of whether to press the left or right key in Experiments 1 and 2 may have interfered with mental rotation because these operations perhaps involve conflicting spatial relationships. Vocal responses seem much less likely to interfere with mental rotation, because they are not inherently spatial. Furthermore, vocal responses to tones seem to be more natural, and may therefore leave more capacity in reserve for mental rotation.

Method

Except where noted, the methods were identical to those of Experiment 1.

Participants. Participants ($N = 16$) were students at the University of California, San Diego, who took part to fulfill a class requirement; none of them participated in any other experiment reported in this article. Two participants failed to meet our criterion of 85% correct and were replaced.

Stimuli. Letters were presented at either 0°, 60°, 120°, 180°, 240°, or 300° from vertical.

Procedure. Participants were instructed to respond to low tones (300 Hz) by saying the word "low" and to respond to high tones (900 Hz) by saying "high." Vocal response latencies were determined by a Hunter model 320S voice key.

Participants completed one practice block of 74 trials (as in the previous experiments), and then eight experimental blocks of 50 trials, divided equally among conditions. The first two trials of each block were again used as warm-up trials and were not recorded. Stimulus letters were selected randomly on each trial.

The SOAs used in this experiment were 0 and 400 ms. Half of the participants completed five 0-ms SOA blocks (the first of which was the practice block), followed by four 400-ms SOA blocks. The remaining participants began with five 400-ms SOA blocks, followed by four 0-ms SOA blocks.

Results and Discussion

Mirror-normal task. Because the direction of rotation had negligible effects on *RT*2, data from equivalent clockwise and counterclockwise orientations have been combined. Figure 5 displays mean *RT*1 and mean *RT*2 as a function of stimulus orientation and SOA; Table 3 shows mean error rates.

The effect of orientation was significant both for *RT*2, $F(3, 42) = 66.51$, $p < .001$, and error rates, $F(3, 42) = 54.98$, $p < .001$. The effect of SOA on *RT*2 was also significant, $F(1, 14) = 31.34$, $p < .001$, and participants again responded faster to normal stimuli ($M = 1043$ ms) than to mirror-image stimuli ($M = 1208$ ms), $F(1, 14) = 39.52$, $p < .001$.

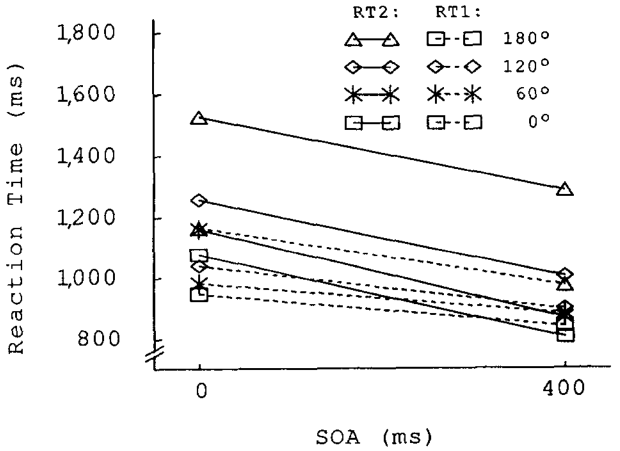

Figure 5. Experiment 3: Mean *RT*1 (tone task) as a function of *stimulus onset asynchrony (SOA), and mean RT*2 (mirror–normal task) as a function of SOA and stimulus orientation.

Table 3

Mean Task 2 Error Rates for Experiment 3 as a Function of Orientation and Stimulus Onset Asynchrony (SOA)

	Orientation			
SOA (ms)	0°	60°	120°	180°
0	3.7	3.1	5.1	13.0
800	4.3	4.9	6.1	14.9

The interaction between orientation and SOA did not approach significance for *RT*2, $F(3, 42) < 1$, or for error rates, $F(3, 42) < 1$. Although there was again a trend toward underadditivity in this experiment, the trend was no larger than in previous experiments. These results indicate that participants do not freely rotate the stimulus letters while the bottleneck is occupied with Task 1, even when the experimental design encourages them to do so. Of course, it is still possible that participants can rotate stimulus letters while Task 1 engages the bottleneck and that we did not do enough to encourage simultaneous processing. Although this hypothesis can never be ruled out entirely, there is nothing to support it in the data available to this point. Therefore, the present results suggest that the processing bottleneck is a necessary consequence of the cognitive architecture, rather than a strategical choice made by the participant (see Pashler, 1994b).

Two higher order interactions reached significance. SOA interacted with the order of presentation of SOA conditions, $F(1, 14) = 15.10$, $p < .01$; the difference in mean *RT*2 between the 0- and 400-ms SOA blocks was greater for participants who completed the 0-ms SOA block first. Presumably, this was because performance improved with practice, and therefore participants responded faster in the SOA block that they completed last. There was also an interaction between orientation, SOA, and the order of presentation of SOAs, $F(3, 42) = 5.14$, $p < .05$. The interaction between orientation and SOA tends to be overadditive when participants complete the 400-ms SOA block first and underadditive when they first complete the 0-ms SOA block. This may be because rotation rates decrease somewhat with practice—especially over the first few blocks—so the effect of orientation is smaller or greater for one SOA condition or the other, depending on which is completed first. Consistent with this interpretation, the three-way interaction between orientation, SOA, and the order of presentation of SOA blocks was not significant, $F(3, 42) = 1.83$, $p > .10$, in an analysis restricted to the last four blocks of the experiment, where practice effects are greatly diminished.

Tone task. Mean *RT*1 was affected by both orientation, $F(3, 42) = 12.14$, $p < .01$, and version, $F(1, 14) = 10.75$, $p < .01$. The directions of these effects were similar to the effects on mean *RT*2, although reduced in magnitude. As discussed earlier, one plausible explanation of these effects is that participants occasionally group their responses when the speed of Task 1 responses is not emphasized; that is, they tend to initiate both responses at the same time (Pashler, 1984; Pashler & Johnston, 1989). When participants use this strategy, a variable that slows *RT2* will also tend to slow *RT1*. One higher order interaction, between SOA and the order of presentation of the SOAs, $F(1, 14) = 5.77, p < .05$, was observed on mean *RT1*; participants responded more slowly to the tones in the 0-ms SOA condition relative to the 400-ms SOA condition when they completed the 0-ms SOA block first, and vice versa. As noted above with respect to *RT2*, this is probably because participants respond more slowly early in the session.

Experiment 4

After our initial experiments had been conducted, we learned of a similar set of experiments by Van Selst and Jolicoeur (1992; see also Van Selst & Jolicoeur, 1994) yielding somewhat different results. In one of their experiments, participants made high or low pitch judgments in response to a tone and made mirror or normal judgments in response to stimulus letters rotated either 0°, 30°, or 60° clockwise from vertical. They found significant underadditivity between orientation and SOA, and, using the same basic logic as the present experiments, concluded that mental rotation does not require the bottleneck mechanism. The purpose of Experiment 4 was to examine some methodological differences that might account for the discrepancies between their results and ours.

One potentially important difference between our methods and those of Van Selst and Jolicoeur (1992) concerned the range of orientations used. They used only a small range of orientations (0°–60° clockwise from upright), whereas the present experiments used orientations ranging from upright to upside down. It is possible, for example, that different types of mental rotation are used with small versus large deviations from upright and that only the type used with large deviations requires the bottleneck.

A second potentially important difference is the duration of the stimulus displays: Van Selst and Jolicoeur (1992) displayed letters for only 83 ms, whereas we used response-terminated displays except in a single control experiment carried out in conjunction with Experiment 1. The purpose of that control experiment was to test the hypothesis that display duration affects the additivity versus underadditivity of orientation and SOA, and the results provided no support for that hypothesis. In light of the different results obtained by Van Selst and Jolicoeur and the possibility that our earlier control experiment had insufficient power, it seemed worth pursuing this hypothesis further here.

To examine the influence of these methodological differences on the additivity versus underadditivity of orientation and SOA, two different experimental factors were manipulated. First, the range of orientations was either very small (0°, 30°, or 60°) or relatively large (0°, 60°, 120°, 240°, or 300° from upright). Second, the displays were either brief (lasting 85 ms) or were terminated only once the participant had responded. To avoid possible carryover effects and thus conduct more exact replications of both our initial experiments and those of Van Selst and Jolicoeur (1992), these two factors were manipulated in a between-subjects factorial design.

One additional change in procedure was made relative to our earlier experiments. Specifically, we increased the longest SOA to 800 ms, because Van Selst and Jolicoeur (1992) used long SOAs of approximately this length. Although we know of no theoretical basis for predicting that the length of the longest SOA should have a large effect on the amount of underadditivity, we adopted this longer SOA in order to try to replicate conditions in which underadditivity had previously been observed.

Method

Except where noted, the methods were identical to those of Experiment 1.

Participants. Participants were 112 students at the University of California, San Diego, who took part to fulfill a class requirement; none of them participated in any other experiment reported in this article. Seven participants failed to meet our criterion of 85% correct and were therefore replaced.

Stimuli. Stimulus letters were *F, R, g,* and *J*, and the number 2, randomly selected on each trial with the exception that no stimulus was presented on two consecutive trials.

Procedure. For half of the participants, letters were presented for 85 ms and then removed; for the other half, letters were presented until the participant made the mirror–normal response. In addition, for half of the participants, letters were presented at 0°, 30°, or 60° from vertical, clockwise. For the remaining participants, letters were presented at either 0°, 60°, or 120° from vertical, clockwise or counterclockwise.

The SOA was either 50 or 800 ms, varying randomly across trials. Participants again responded to mirror and normal image stimuli by pressing the *j* and *k* keys. However, in this experiment the mapping of mirror and normal images to the two response keys was counterbalanced across participants. The purpose of this counterbalancing was to ensure that the particular mapping used in Experiments 1 through 3 was not responsible for any of the important aspects of our results.

Results and Discussion

Mirror-normal task. The direction of rotation again had negligible effects on *RT2*, so data from equivalent clockwise and counterclockwise orientations have been combined. The data of main interest are the interactions of orientation and SOA obtained in each of the four groups (2 display durations and 2 ranges of orientation).

Figure 6 displays mean *RT1* as a function of SOA and mean *RT2* as a function of stimulus orientation and SOA, separately for the four groups of participants differing in orientation range and display duration. Table 4 shows the error rates for Task 2.

ANOVAs were conducted with factors of Orientation, SOA, Version, and Display Duration. Separate ANOVAs were carried out for groups differing in orientation range, because the levels of the orientation factor were different across these groups. In both ANOVAs, the usual effects of orientation, version, and SOA on *RT2* were significant ($p < .05$), as were the usual effects of orientation and SOA on Task 2 error rates.

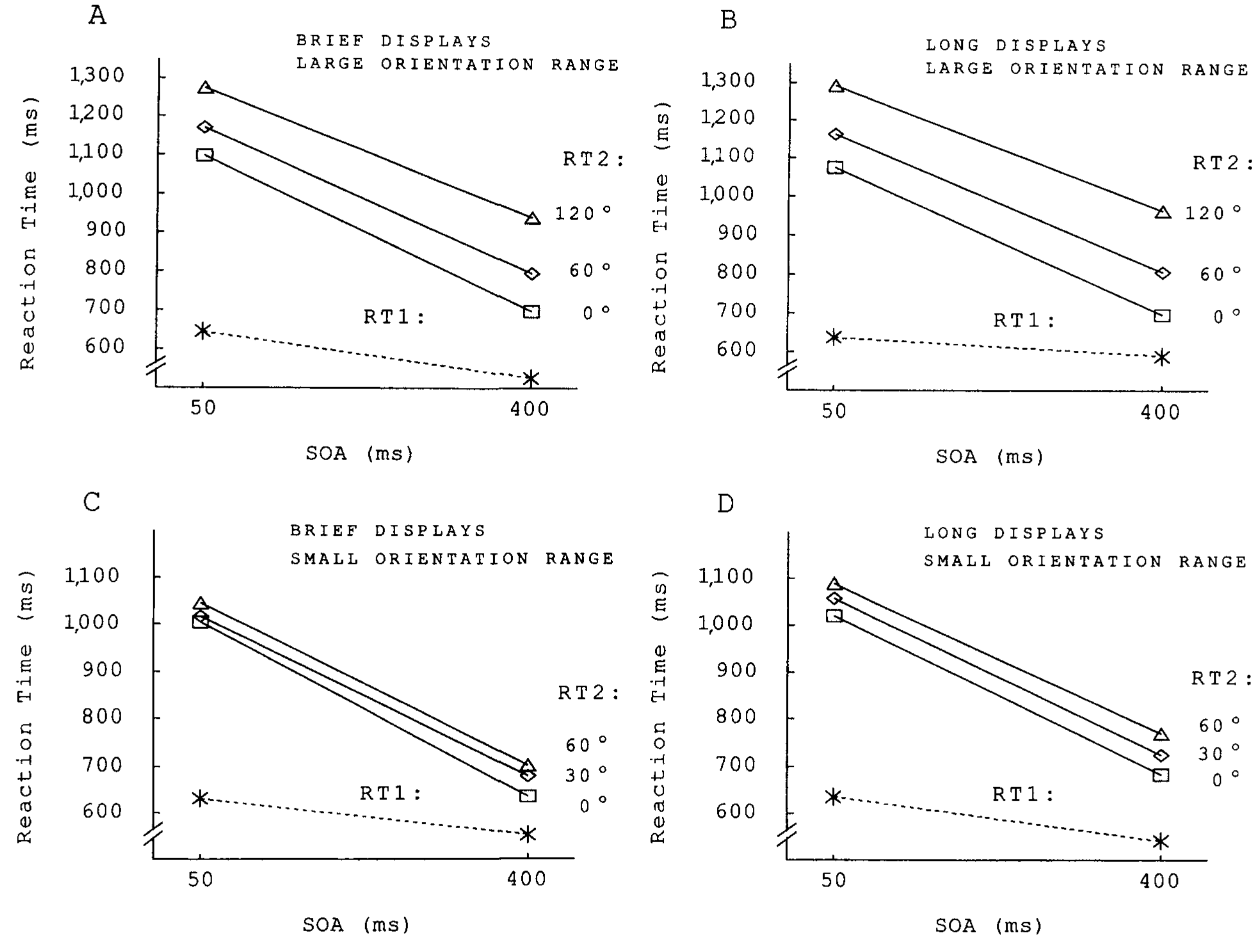

Figure 6. Experiment 4: Mean *RT*1 (tone task) as a function of stimulus onset asynchrony (SOA), and mean *RT*2 (mirror–normal task) as a function of SOA and stimulus orientation for correct responses. The data are plotted separately for groups differing in display duration and range of orientations.

Small orientation range: 0° versus 30° versus 60°. In this analysis, the underadditive interaction between orientation and SOA on *RT*2 was significant, $F(2, 108) = 3.93$, $p < .05$. Neither the main effect of stimulus duration nor its interactions with other factors were significant in this analysis ($p > .05$). There was a significant, 17-ms overadditive interaction between version and SOA on *RT*2, $F(1, 54) = 4.08$, $p < .05$; the effect of version was slightly greater at the short SOA.

Analysis of Task 2 error rates also revealed a small but significant overadditive interaction between version and SOA, $F(1, 54) = 12.2$, $p < .01$. Because these effects were not significant in Experiments 1 through 3, it appears that the unusually long SOA (800 ms) was particularly beneficial for mirror-image stimuli.

A comparable analysis of *RT*1 indicated that responses were significantly slower at the short SOA ($M = 633$ ms) than at the longer SOA ($M = 548$ ms), $F(1, 54) = 41.66$, $p < .001$. This effect, which might be due to perceptual interference, is more than twice as large as the effects of SOA on *RT*1 reported in Experiments 1 and 2, and the increased effect may be due to the larger range of SOAs used. As is true for all experiments reported in this article, the effect of SOA on *RT*1 did not depend on orientation, $F(2, 108) < 1$, so it appears that the interference is not due to the rotation process. The effect of SOA was slightly

Table 4
Mean Task 2 Error Rates for Experiment 4 as a Function of Orientation, Stimulus Onset Asynchrony (SOA), Display Duration, and Orientation Range

			Orientation			
Display	Range	SOA (ms)	0°	30°	60°	120°
Brief	Small	50	5.0	6.1	7.2	
		800	4.3	5.4	5.8	
Brief	Large	50	4.2	—	6.6	9.9
		800	4.2	—	5.2	8.1
Long	Small	50	4.7	5.0	6.0	
		800	3.3	4.0	5.9	
Long	Large	50	4.5	—	4.5	6.9
		800	2.7	—	5.3	8.2

greater for mirror- (91 ms) than for normal-image stimuli (80 ms), $F(1, 54) = 4.21$, $p < .05$. This effect was not observed for the other groups of participants and was not observed in the other experiments reported in this article, so there is some reason to doubt the effect is real. However, there is some evidence that it takes longer to perceive mirror images than normal images (Corballis, Zbrodoff, Shetzer, & Butler, 1978), so it is not completely surprising that *RT*1 would suffer more interference from mirror images. Once again, Task 1 errors were rare and therefore were not analyzed.

Large orientation range: 0° versus 60° versus 120°. The underadditive interaction between orientation and SOA on mean *RT*2 was again significant, $F(2, 108) = 15.11$, $p < .001$. Neither the main effect of stimulus duration nor its effect on the orientation by SOA interaction was significant for *RT*2 (both *F*s < 1). There was a significant interaction between orientation and version on *RT*2, $F(2, 108) = 4.08$, $p < .05$; the effect of orientation was slightly smaller for normal- than for mirror-image stimuli, as is often observed (e.g., Koriat & Norman, 1985; Van Selst & Jolicoeur, 1994). Finally, there was an interaction between orientation, version, SOA, and display duration on *RT*2 that barely reached significance, $F(2, 108) = 3.51$, $p < .05$. The interaction of orientation and SOA was actually slightly overadditive when normal stimuli were presented with long displays, as compared with the underadditivity observed when displays were brief or stimuli were mirror image.

The interaction between display duration, orientation, and SOA reached significance for Task 2 error rates, $F(2, 108) = 4.67$, $p < .05$. Numerically, the effect of orientation on error rates was larger at the SOA of 50 ms than at the SOA of 800 ms for the groups with brief displays, with the reverse ordering for the groups with response-terminated displays. The explanation for this interaction is not clear, but it may reflect an influence of display duration on a participant's strategies for processing rotated stimuli. Analyses of Task 2 error rates also revealed a small crossover interaction between display duration and version, $F(1, 54) = 7.85$, $p < .01$. It appears that mirror-image stimuli were responded to slightly less accurately than normal stimuli for the long display duration group, but there was a very small difference in the opposite direction for the brief display duration group.

Mean *RT*1 was again significantly slower at the short SOA ($M = 640$ ms) than at the longer SOA ($M = 558$ ms), $F(1, 54) = 53.49$, $p < .001$. The effect of SOA was greater for the brief display duration group (116 ms) than for the long display duration group (46 ms), $F(1, 54) = 10.01$, $p < .05$. If, as suggested earlier, *RT*1 is slower at the short SOA due to perceptual interference from S_2, it is not surprising that the interference should be greatest for brief displays, which must be processed promptly. Once again, Task 1 errors were rare and therefore could not be analyzed.

In summary, these results indicate that, at least for the current experimental design, orientation and SOA are not perfectly additive: We observed consistent trends toward underadditivity that reached significance in both analyses. The interactions were quite small, however, even for stimuli rotated 120°, where the effect of orientation was 257 ms at the long SOA. Computations to be described in the General Discussion section show that the observed underadditivities are far too small to be consistent with models in which mental rotation proceeds as usual while the bottleneck mechanism operates on S_1. Nevertheless, this experiment yielded larger underadditivities than those observed in Experiments 1 through 3, and it is worth considering what procedural changes might account for this difference.

The effect of display duration did not reach significance, consistent with results of the control condition described in conjunction with Experiment 1. However, it should be noted that the interactions between orientation and SOA were consistently smaller (by 10 ms on average) for the long display duration groups. So, it is possible that the use of brief display durations leads to slightly greater amounts of underadditivity, but that the current experiment was not sufficiently powerful to detect the effect.

The range of orientations also did not seem to affect the amount of underadditivity between orientation and SOA. To test for small but statistically reliable effects of range on underadditivity, we conducted an additional analysis on the 0° and 60° conditions from both the small and large orientation groups (i.e., excluding data from either 30° or 120°). The factors in this analysis were Orientation Range, Display Duration, SOA, Version, and Orientation (0° vs. 60°). This analysis indicated that the interaction between orientation and SOA was not significantly different for the different orientation range groups, $F(1, 108) < 1$. The present results, therefore, provide no support for the claim that the use of a small range of orientations increases the amount of underadditivity.

A further difference between the methodology of Experiments 1 through 3 and the present experiment is the range of SOAs. Although the duration of the longest SOA used in Experiments 1 through 3 was only 400 ms, the longest SOA in the present experiment was 800 ms. It seems possible, then, that the slightly larger underadditivities observed in Experiment 4 are due to the use of a longer SOA. To test this hypothesis we ran another 80 participants in a control experiment identical in all ways to the current experiment except that the longest SOA was only 400 ms. The amount of observed underadditivity (21 ms) was slightly smaller than that observed in Experiment 4 (31 ms), but the difference did not reach significance ($p > .20$).

In conclusion, we observed small but statistically reliable underadditivities between orientation and SOA. The amount of underadditivity was not significantly affected by display duration, the range of stimulus orientations, or the range of SOAs, so there is no obvious explanation for the discrepancy between the additivities obtained in Experiments 1 through 3 and the underadditivity obtained in the present experiment or the even larger underadditivities obtained by Van Selst and Jolicoeur (1994). On the basis of the evidence collected so far, then, we must conclude that orientation and SOA can be either additive or slightly underadditive, depending on as yet unidentified aspects of the experimental procedure. Therefore, we consider next the theoretical implications of these results. With regard to our original questions, we shall argue that both additivity and slight underadditivity support the same general conclusion: that mental rotation cannot be effectively carried out while the bottleneck mechanism is occupied with Task 1.

General Discussion

Using a mirror–normal judgment as the second task in a PRP paradigm, we found the effects of SOA and second-task stimulus orientation to be additive or nearly so, even when participants were especially encouraged to carry out Task 2 mental rotation during Task 1 processing (Experiment 3). This result contradicts bottleneck models in which mental rotation can proceed without interference while the bottleneck mechanism is busy with Task 1 operations, because such models predict large underadditive interactions of orientation and SOA. The approximate additivity supports models in which little or no mental rotation can be carried out during the time the bottleneck is occupied with another task. Thus, the results suggest that mental rotation requires access to a single-channel bottleneck mechanism.

Because bottleneck models predict additivity of SOA with any experimental factor affecting a process at or after the bottleneck, the present results are also consistent with models in which the bottleneck mechanism is required for some process prior to mental rotation (e.g., determining the orientation of the stimulus) rather than for the rotation itself. According to this view, mental rotation could, in principle, be performed while the bottleneck mechanism is occupied with Task 1, but it never gets the chance because some earlier process must wait for access to the bottleneck mechanism. This seems unlikely, however, because mental rotation appears to be much more demanding than the processes that precede it (Cooper & Shepard, 1973). Furthermore, the account is difficult to reconcile with the results of Band and Miller (1994), who found psychophysiological evidence that mental rotation interferes with the selection of a response, preparation of a response hand, or both. Given that response processes seem to require the bottleneck (e.g., Pashler, 1994a), such interference supports the conclusion that the rotation process ties up the bottleneck mechanism.

Predictions of Bottleneck Models With Stochastic Stage Durations

In the introduction we showed that models allowing mental rotation to proceed while the bottleneck is busy with Task 1 predict large amounts of underadditivity when the stage durations are assumed to be constant. The constancy assumption is not likely to be satisfied, however, so it makes sense to see whether predictions change drastically when stage durations vary randomly from trial to trial. To do this, we carried out four additional sets of computations based on Equation 3. One set of computations examined the change in orientation effect (0° vs. 180°) across SOAs under conditions comparable to those studied in Experiments 1 *through* 3. Additionally, to see how much underadditivity is predicted for smaller orientations, we conducted three sets of computations in which the orientation effect was measured by comparing $RT2$s to upright stimuli against $RT2$s to stimuli at each of the different nonupright orientations used in Experiment 4 (30°, 60°, and 120°). In each set of computations, the goal was to see how much the effect of orientation should change across SOAs, on average, assuming a stochastic model in which mental rotation does not require the bottleneck mechanism. If stochastic models, like the deterministic model discussed in the introduction, predict much larger underadditivities than were observed, then these models can also be rejected.

Unfortunately, there are an infinite number of stochastic models, differing with respect to their assumptions about the probability distributions of the quantities entering into Equation 3, so it was necessary to restrict the range of models by making some assumptions. One major assumption was that the three stochastic durations B, MR_1, and MR_2 had gamma distributions, because this distribution is a reasonably general model for stochastic latency mechanisms (Luce, 1986; McGill, 1963) and because it produces roughly the amount of skew observed in the data. We carried out additional computations assuming normally distributed random variables and found virtually identical results, so we suspect that the exact form of the probability distribution is not particularly important.

Within each set of computations, we tried 150 different combinations of parameter values for the gamma distributions of B, MR_1, and MR_2. These combinations were obtained by factorially combining five equally spaced means for B, six equally spaced means for MR_1, and five equally spaced durations of rotation (corresponding to $MR_2 - MR_1$). In all cases, the means were constrained to be roughly consistent with the means and variances of RTs observed in the various experimental conditions. The mean of B, for instance, was assumed to be 400 to 500 ms. This seems appropriate, because mean $RT1$ was about 600 ms, and the postbottleneck portion of this corresponds to response execution, which seems to take approximately 100 to 200 ms (Luce, 1986, pp. 59–62). Similarly, we constrained the mean value of MR_1 to be 100 to 350 ms. This range was suggested by the fact that mean $RT2$ was about 850 ms for upright stimuli, and the postbottleneck processes following mental rotation in this task (i.e., the mirror–normal judgment, response selection, and response execution) account, on average, for at least 500 ms but at most 750 ms of this time.[6] Finally, the mean value of MR_2 was determined by adding an average rotation duration for a given orientation to the mean of MR_1. Values of 30 to 58, 60 to 120, 200 to 300, and 300 to 500 ms were used for the average rotation durations of 30°, 60°, 120° and 180° stimuli, respectively, because these were the typical values observed in Experi-

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[6] These values were derived under the assumption that the mirror–normal judgment requires the bottleneck mechanism and thus does not contribute to MR_1. If we assume instead that this judgment does not require the bottleneck mechanism, then the range of means for MR_1 should be increased by 100–200 ms. Additional computations using this latter assumption yielded essentially the same results.

ments 1 through 4. The values of SOA_1 and SOA_2, meanwhile, were set to the constants, determined by the experimenter, that were used in each simulated experiment.

Having chosen the desired mean for a given parameter as described earlier, the two parameters of the gamma distribution for that parameter were adjusted to give the desired mean and a standard deviation proportional to the mean.[7] For example, the *SD* of *B* was fixed at 0.27 times the mean of *B*, because this was the observed ratio of the mean to the *SD* for *RT*1 across experiments. Similarly, the *SD*s of MR_1 and MR_2 were fixed at 0.30 and 0.34 times their means, because these were the observed ratios of the means of the *SD*s of *RT*2 for upright and rotated stimuli, respectively.

In total, we computed the average interactions predicted by 600 stochastic models (i.e., the expected value of the *I* of Equation 3), and these interactions are shown in Figure 7, separately for different orientations: (a) 30°, (b) 60°, (c) 120°, and (d) 180°. The vertical axis represents the size of the underadditive interaction between orientation and SOA, and the horizontal axis represents the effect of SOA for upright stimuli. The predictions are given by the open diamonds; the data, by filled rectangles. In almost all cases, the predicted interaction effects are about as large as the effect of SOA for upright stimuli or the effect of orientation at the longer SOA, whichever is smaller. This is quite consistent with the conclusion from the analysis using constant stage durations, presented in the introduction: The size of the underadditive interaction should be equal to the effect of SOA for upright stimuli when $MR_2 \geq B - SOA_1$, or equal to the effect of orientation at the longer SOA when $MR_2 < B - SOA_1$.

Most important, it is quite clear that in almost every case the predictions are very different from the observed data points. The differences are most apparent when the orientation effect is large, because in these cases the predicted underadditivity is also quite large, whereas the observed underadditivity is not. Because of the very poor correspondence between predicted and observed values, we can also reject stochastic versions of models in which mental rotation proceeds, without interference, during Task 1 response selection.

Models With Interference

So far, we have argued against models in which mental rotation proceeds without interference during Task 1 bottleneck processing, because such models predict substantial underadditivity of orientation and SOA. One could attempt to preserve the idea that mental rotation proceeded while the bottleneck mechanism was busy with Task 1, however, by allowing interference between simultaneous mental rotation and Task 1 bottleneck processes. If the amount of interference were very large, then little mental rotation would be accomplished during this period, resulting in very small underadditive interactions. In fact, the addition of interference allows such models to predict arbitrarily small interactions, including zero, so we cannot hope to rule them out on the basis of the magnitude of the underadditive interactions. One defect of such models, however, is that they seem to predict that *RT*1 should be markedly slowed at short SOAs, and it was not. Further, the slight slowing of *RT*1 that was observed was just as large for upright stimuli as for upside-down stimuli, indicating that mental rotation itself did not cause *RT*1 slowing. To explain this, interference models must assume that Task 1 operations slowed mental rotation but not vice versa. Furthermore, to explain the near-additivity observed in the present experiments, the assumed interference would have to be very large, such that only a small amount of mental rotation could be accomplished during Task 1 bottleneck processing. We note that such models do not allow mental rotation to proceed effectively without the bottleneck, just like models in which mental rotation requires access to the bottleneck mechanism.

In addition, although such models are able to correctly predict the small change in the overall orientation effect across SOAs, they do not seem consistent with the observed changes in the individual orientation effects, measured by comparing *RT*2s to upright stimuli against *RT*2s to stimuli at each nonupright orientation. As shown in the Appendix, models allowing some mental rotation to occur without the bottleneck mechanism predict that the size of the interaction between SOA and orientation (measured using orientations of 0° and *A*°) should begin approaching a maximum when *A* is equal to 60° and should be essentially constant for any orientation *A* greater than about 90°. Essentially, this prediction arises because the change in a relatively large orientation effect across SOAs is primarily determined by the time Task 2 must wait for the bottleneck mechanism, and this waiting time should not depend on stimulus orientation. Figure 8 shows the actual size of the interaction effects in Experiments 1 through 4 (including any control experiments) as a function of stimulus orientation, where positive numbers indicate underadditivity and negative numbers indicate overadditivity. Rather than leveling off for angles greater than 60° to 90°, as predicted, the amount of underadditivity appears to continue to increase with increasing orientation well beyond 90°; in fact the interaction size seems to increase more or less linearly out to 180°. Thus, it seems unlikely that the observed underadditivity can be attributed to the hypothesis that mental rotation proceeds, with interference, while the bottleneck mechanism is busy with Task 1.

What Causes the Small Underadditivity?

We have concluded that mental rotation does not operate until the bottleneck mechanism is finished with Task 1, primarily because the interaction of orientation and SOA is far too small to conclude the reverse (i.e., that mental rotation is carried out while the bottleneck is busy with Task 1). Nonetheless, there are persistent hints of a small under-

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[7] We assumed that the ratio of RT to *SD* is constant, as is often observed in RTs (e.g., Chocholle, 1940; Myerson, Widaman, & Hale, 1990). Another possible assumption is that the ratio of RT to variance is constant. We performed the same computations using this alternative assumption and obtained very similar results.

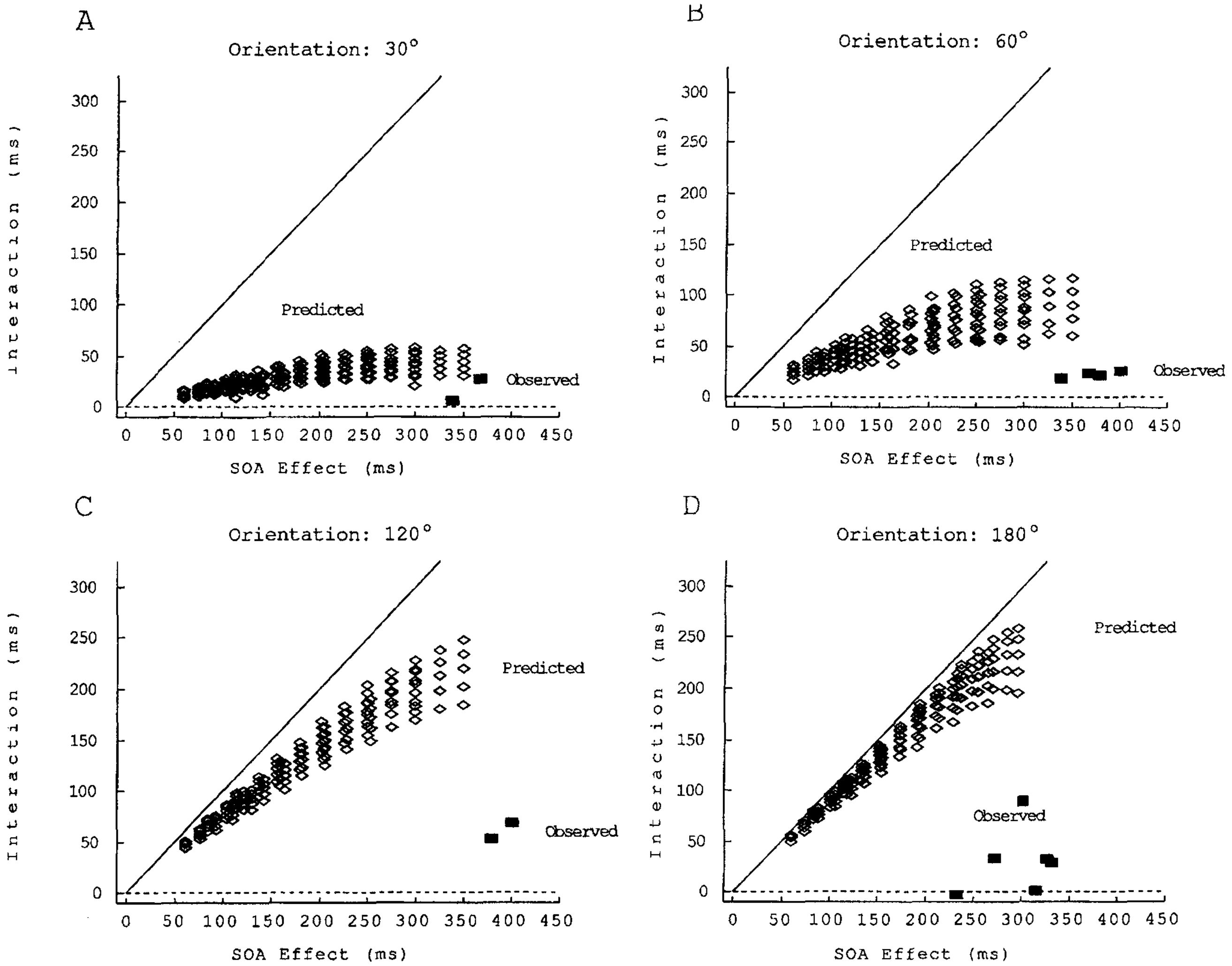

Figure 7. Interaction sizes predicted by stochastic models in which mental rotation can proceed, without interference, during Task 1 response selection (open diamonds) and observed interaction sizes (filled rectangles), plotted as a function of the effect of stimulus onset asynchrony (SOA) for upright stimuli. Data and predictions are plotted separately for different orientations: (A) 30°, (B) 60°, (C) 120°, and (D) 180°. Interaction sizes were calculated as the change in the effect of the indicated orientation (relative to 0°) from largest to smallest SOA.

additive interaction between orientation and SOA, both in our own data (especially Experiment 4) and in those of Van Selst and Jolicoeur (1994). What is the explanation of this small underadditivity?

Despite the arguments against models in which mental rotation can proceed without help from the bottleneck, one might still attempt to reconcile these models with the small observed underadditivities by appealing to the possibility of probability mixtures. For instance, it is possible that some participants can perform mental rotation without assistance from the bottleneck mechanism, whereas the majority cannot (Van Selst & Jolicoeur, 1994). However, our data show no evidence of the intersubject differences predicted by this explanation. Alternatively, one could argue that all participants can perform mental rotation while the bottleneck mechanism is occupied with another task, but they do so only on occasional trials (Van Selst & Jolicoeur, 1994). This explanation is not very appealing, however. If participants can sometimes perform mental rotation without the bottleneck, why do they not do so on almost all trials, at least when provided with plenty of encouragement (Experiment 3)?

In view of the difficulty of explaining the small underadditivity using the idea that mental rotation operates while the bottleneck is occupied with Task 1, it seems worthwhile to consider the possibility that processes other than mental rotation might be responsible for a small orientation by SOA interaction. For example, Cooper and Shepard (1973) suggested a model in which two processes—determination of letter identity and determination of letter orientation—

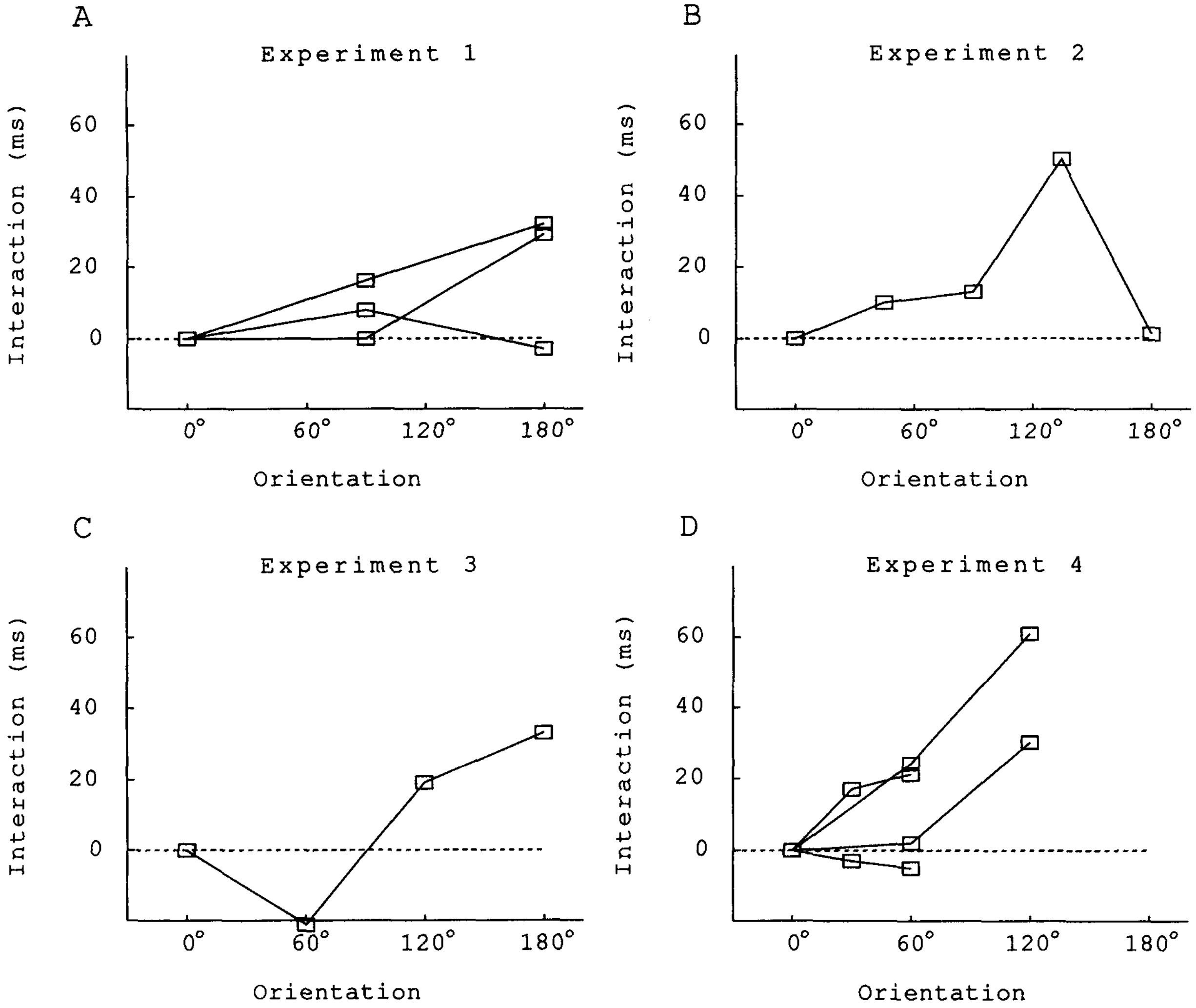

Figure 8. Interaction between orientation and stimulus onset asynchrony (SOA) as a function of orientation for Experiments 1–4. (At all orientations, the interaction was measured with respect to the effect of SOA at 0°.)

must precede the onset of rotation. If either of these processes is sensitive to orientation (see Corballis et al., 1978, for evidence that both are) and can also be carried out without assistance from the bottleneck mechanism, then either could be responsible for the underadditivity. Van Selst and Jolicoeur (1994) tested the hypothesis that letter identification is responsible by measuring the amount of underadditivity between orientation and SOA when Task 2 was to determine whether a visually presented character was a letter or a digit—a task that presumably does not require mental rotation. They found a small underadditive trend (6.1 ms) but noted that it did not reach significance and argued that it was not nearly large enough to account for the interactions observed in their original experiments. However, it seems unlikely that the letter–digit judgment requires the same degree of perceptual processing as does the mirror–normal task. For instance, in the letter–digit judgment, participants might not fully determine stimulus identity, and they might not need to determine stimulus orientation at all.

Another possibility is that participants, when presented with highly familiar stimuli, discover processing "shortcuts" and thus do not perform mental rotation on every trial. If these short-cut processes can operate without aid from the bottleneck mechanism, then underadditivity could result.

A further possibility is that mental rotation simply proceeds slightly faster at short SOAs, which could result in small underadditivities of the sort we observed. Note that at short SOAs participants have extra time for perceptual processing, while mental rotation waits for Task 1 to release the bottleneck mechanism. Such extra perceptual processing could produce a more stable mental image, which might in turn be rotated more rapidly.

It is, at this point, impossible to be sure what causes the small underadditive interaction of orientation and SOA. One difficulty is that it is not yet clear what experimental manipulations cause the underadditivity to come and go (see Experiment 4). Nonetheless, given the small size of the underadditivity, the pattern of underadditivity across orientations, and the availability of plausible alternative explanations, there seems at present very little reason to suspect that any mental rotation is carried out while the bottleneck mechanism is occupied with Task 1. Moreover, even if some mental rotation can be accomplished during this time, the amount must be very small, given the small interaction between orientation and SOA. Thus, at the very least the data provide firm support for the more general conclusion that stimuli cannot be effectively rotated while the bottleneck mechanism is occupied with another task.

Mechanisms Responsible for Mental Rotation

The present conclusion that mental rotation cannot be performed simultaneously with mental operations that require the bottleneck mechanism, such as response selection, may seem surprising given electrophysiological and neuropsychological evidence that these operations engage distinct brain structures (e.g., Peronnet & Farah, 1989; Requin et al., 1988; Stuss et al., 1983). One explanation of this apparent contradiction is that mental rotation and response selection both depend on a common structure (i.e., a physiological embodiment of the bottleneck), even though each also relies on its own unique area. If the common structure cannot deal with two different tasks at the same time, then a processing bottleneck of the sort seen here would occur. At the same time, the unique areas would yield evidence of different evoked potential responses and would provide opportunities for dissociations in patients with brain lesions, as has been observed. A further possibility is that the processes of response selection and mental rotation truly are carried out in different regions of the brain, but a central enabling mechanism allows only one of these operations to proceed at any one moment in time, perhaps in an effort to reduce crosstalk. Further work will be needed to identify the precise explanation of this discrepancy.

The notion that mental rotation requires bottleneck mechanisms also seems incompatible with the results of Corballis (1986), who found that the rate of mental rotation was not affected by a concurrent memory load. However, it is not clear what operations, if any, were required to maintain items in short-term memory over brief intervals in Corballis' task. It is quite possible that the requirement to maintain a memory load does not tax central mechanisms but simply interferes with preparation of the stimulus–response mapping (Logan, 1978; Pashler, 1994a). If so, then there would be no reason to expect the memory load to slow mental rotation, even if—as suggested here—mental rotation does require access to the bottleneck mechanism.

In summary, the present data indicate that a letter stimulus cannot be rotated effectively while central mechanisms are occupied with another task. These results therefore suggest that the bottleneck mechanism identified in previous *PRP* studies is required for mental rotation as well as response selection (e.g., Pashler, 1984; Pashler & Johnston, 1989), the retrieval of information from long-term memory (Carrier & Pashler, in press), and difficult perceptual discriminations (McCann & Johnston, 1992). In conjunction with previous findings, this evidence points to the existence of a single-channel mechanism that is responsible for a wide range of higher cognitive operations.

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Appendix

Form of Predicted Stimulus Onset Asynchrony (SOA) by Orientation Interaction

The purpose of this appendix is to show that models in which mental rotation can proceed—although possibly very slowly—while the bottleneck mechanism is busy with Task 1 predict a particular form of orientation by SOA interaction, which is in fact different from the form of interaction that has been observed in the present experiments. Specifically, the prediction is that the size of the interaction obtained using orientations 0° and $A°$ should increase as A increases, but only up to a certain orientation value, beyond which the size of the interaction should remain essentially constant for all orientations.

The models considered here, which are a generalization of those considered in the introduction, may be formalized with the following assumptions:

1. At the onset of S_2, prerotational perceptual analysis (i.e., formation of a rotatable image) begins. If prerotational perceptual analysis of S_2 finishes before the bottleneck mechanism is finished with Task 1 (i.e., before the end of the "slack" period), mental rotation begins anyway. Mental rotation may be carried out at the same rate as it would with the bottleneck or more slowly (e.g., due to interference).

2. When the bottleneck mechanism becomes available for processing S_2, it simply picks up the partially rotated image at its current angle, to which it was rotated during the slack period, and finishes the rotation process. Thus, any remaining mental rotation (i.e., rotation not completed during the slack period) is finished at the usual, fast rate.

3. After mental rotation of S_2 is finished and the bottleneck mechanism is available, decision-making and response execution processes occur.

According to models of this form, $RT2_{SOA,A}$—the reaction time at a given SOA and angle of orientation, A—is the sum of three components:

$$RT2_{SOA,A} = \max(B - SOA, P) + [MR_A - \min(MR_A, S_{SOA})] + C. \tag{A1}$$

The first component, $\max(B - SOA, P)$, represents the time between the onset of S_2 and the moment when the bottleneck mechanism begins working on Task 2 mental rotation. Because the bottleneck mechanism cannot begin working on mental rotation

(*Appendix continues on next page*)

until (a) it has finished with Task 1 and (b) prerotational analysis of S_2 has enabled mental rotation to begin, this component is whichever is longer: (a) the amount of time before Task 2 can gain access to the bottleneck mechanism, $B -$ SOA or (b) the time required to prepare for mental rotation, P.

The second component, $MR_A - \min(MR_A, S_{SOA})$, is the time during which the bottleneck mechanism carries out mental rotation, which we will call the "postbottleneck rotation time." This is the time required for the bottleneck to fully rotate the stimulus from angle A to upright, MR_A, minus any time that has been saved by virtue of the fact that some mental rotation occurred during the slack period, $\min(MR_A, S_{SOA})$. The variable S_{SOA} represents the amount of rotation time that could be saved if mental rotation is carried out during the entire slack period. However, if mental rotation can be finished without using the entire slack period (e.g., for small departures from the upright) the actual savings will simply be the total rotation time, MR_A. Thus, the actual savings on any trial is $\min(MR_A, S_{SOA})$.

Finally, the third component, C, is the time needed for response selection—for which the bottleneck is assumed to be required—plus any additional response-related processes (e.g., response execution).

All of the parameters of Equation 5 are assumed to vary randomly from trial to trial, except for SOA and A, which are under the experimenter's control. We make a number of simplifying assumptions about how these parameters depend on experimental conditions:

1. B is independent of orientation. This assumption is supported by the lack of an orientation effect on RT1. B may be allowed to depend on SOA without changing the predicted interaction shown below.
2. P is independent of orientation.[A1] As with B, this parameter may be allowed to depend on SOA without changing the predicted interaction.
3. MR_A is independent of SOA. That is, the time to rotate stimulus letters with the aid of the bottleneck does not depend on the waiting time to gain access to the bottleneck. This assumption is actually at the heart of all bottleneck models, which by their very nature assume that Task 2 processing delays stem only from time spent waiting to get access to the bottleneck, not changes in processing speed once the bottleneck is available.
4. S_{SOA} does not depend on orientation. This assumption says that the same amount of time is saved, regardless of stimulus orientation, if rotation takes place during the entire slack period. For example, if rotation during the slack period would save 50 ms of postbottleneck rotation time for a 120° stimulus, then it would also save 50 ms for a 180° stimulus. This assumption would be satisfied, for example, if the rate of rotation without the bottleneck were a constant fraction of the rate of rotation with the bottleneck. Potential savings depends on SOA, of course, because SOA influences the length of the slack period. It also depends on the rate of rotation during the slack period.
5. C is independent of SOA and orientation. Actually, C may be allowed to depend on both SOA and orientation without changing the form of the predicted interaction, as long as SOA and orientation have additive effects on it.

Using the model represented by Equation 5, we will now compute the average predicted SOA by orientation interaction computed using SOAs of 50 and 800 ms and angles of 0° and A°. The predicted expected value of the interaction at angle A, I_A, is

$$E[I_A] = E[RT2_{800,A}] - E[RT2_{800,O}] - E[RT2_{50,A}] + E[RT2_{50,O}], \qquad \text{(A2)}$$

where positive interactions indicate underadditivity and negative interactions indicate overadditivity. Substituting values from Equation 5 into this definition and simplifying yields the following:

$$E[I(A)] = -E[\min(MR_A, S_{800})] + E[\min(MR_O, S_{800})] + E[\min(MR_A, S_{50})] - E[\min(MR_O, S_{50})]. \qquad \text{(A3)}$$

It is reasonable to assume that $S_{800} = 0$; at such a long SOA, mental rotation will virtually never have the opportunity to operate while Task 1 engages the bottleneck. With the additional restriction that $MR_0 = 0$ by definition, this interaction further reduces to

$$E[I(A)] = E[\min(MR_A, S_{50})]. \qquad \text{(A4)}$$

When A is large enough that MR_A is always greater than S_{50}, it will be the case that $E[I(A)] = E[S_{50}]$, which is independent of A. Thus large orientations produce the maximum interaction; as A is reduced, MR_A will sometimes be less than S_{50}, reducing the overall expected value of the interaction. The minimum interaction is obtained when A is arbitrarily small, because for very small angles MR_A is always quite small.

Now the average underadditivity observed in the present experiments for nearly upside-down stimuli was approximately 30 ms, and the largest was 61 ms, observed in Experiment 4. Using 61 ms as a conservatively large estimate for $E[S_{50}]$, it follows that $E[I(A)]$ should approach a maximum when $E[MR_A]$ is much larger than 61 ms, because large values of MR_A will exert little influence on $E[I(A)]$. The average rotation time for 60° stimuli is about 90 ms, which already is considerably greater than our conservatively large estimate of $E[S_{50}]$, so it seems plausible that MR_{60} would usually be greater than S_{50}. As a result, when A is 60° or greater, orientation should have only a small influence on $E[I(A)]$. The average rotation time for 90° stimuli, meanwhile, is about 138 ms, which is more than twice as large as the estimate of S_{50}. With such an extreme difference in means, it is reasonable to expect that MR_{90} should almost always be greater than S_{50} even if these quantities are quite variable. Accordingly, $E[I(A)]$ should be essentially constant when A is greater than about 90°. In summary, the size of the interaction between orientation and SOA, $E[I(A)]$, should initially increase as A increases, but should begin leveling off by 60° and should be essentially constant for orientations greater than 90°. As shown in Figure 8, this predicted pattern was clearly not obtained in the present experiments.

[A1] Contrary to this assumption, the evidence actually suggests that the duration of prerotational perceptual analysis does depend slightly on orientation (e.g., Corballis et al., 1978). Although violations of this assumption can by themselves produce underadditivity, the violations appear to be small, and would therefore perturb only slightly the predictions of the model considered here. Furthermore, it is of interest to see whether the observed patterns of orientation by SOA interaction can be explained in terms of a model in which the underadditivity is due solely to the operation of mental rotation without the bottleneck mechanism. Naturally, such models can predict any pattern of interaction whatever by incorporating additional, extraneous sources of interaction.

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