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Viewer Perspective Affects Central Bottleneck Requirements in Spatial Translation Tasks

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A psychological refractory period (PRP) approach and the locus of slack logic were applied to examine the novel question of whether spatial translation processes can begin before the central bottleneck when effector or noneffector stimuli are processed from an egocentric (viewer-centered) perspective. In single tasks, trials requiring spatial translations were considerably slower than trials without translations (Experiment 1). Dual tasks consisted of tone discriminations (Task 1) and spatial translations (Task 2) using PRP methods with different manipulations on perceptual and response demands. When a viewer-centered perspective was used, the effect of spatial translation was reduced at short compared with long stimulus onset asynchronies (SOAs) when the potential for code overlap between tasks was removed (Experiments 2, 3, and 4); this finding supports the view that translation processes can begin before the central bottleneck. When an allocentric (non-viewer-centered) perspective was used (Experiment 5), the slowing associated with spatial translation was additive with SOA, suggesting that the processes of spatial translation cannot begin before the bottleneck. These findings highlight the importance of viewer perspective on central bottleneck requirements. Findings are further discussed in relation to the dorsal–ventral model of action and perception.

Keywords: spatial representation, spatial translation, psychological refractory period, egocentric and allocentric viewer perspectives

Our understanding of the way the brain represents the world has implications on a broad range of issues related to perception and action. In the present study we used the psychological refractory period (PRP) approach and the locus of slack logic to investigate whether viewer perspective is a critical factor in determining central bottleneck requirements of spatial translation processes. The article begins with a description of the two primary viewer perspectives that are considered: egocentric and allocentric.

Egocentric Versus Allocentric Processing

A variety of neural maps or representations of space, generally classified as egocentric and allocentric, have been found in the primate brain. *Egocentric* refers to those representations that are coded relative to an observer's body, whereas *allocentric* representations are coded relative to other objects or referents in the environment (Neggers, Van der Lubbe, Ramsey, & Postma, 2006). A number of studies during the last decade have focused on differences in these two basic classes of representations, including their associated neural structures (Andersen, 1995; Galati et al., 2000) and associated cognitive processes (Bridgeman, Peery, & Anand, 1997). Functional neuroimaging studies have suggested that distinct neural networks are associated with egocentric and allocentric spatial judgments (Galati et al., 2000). However, these networks most likely interact (Bridgeman et al., 1997; Neggers, Schölvinck, van der Lubbe, & Postma, 2005). Understanding the psychological principles and processes associated with these different representations strongly impacts our understanding of actions. For example, a number of investigators have suggested that egocentric representations are associated with processing in the dorsal stream areas that are involved in goal-directed movements, whereas allocentric representations have been proposed to be associated more with ventral stream processing that depends on recognition and memory (Galati et al., 2000; Goodale & Milner, 1992; Neggers et al., 2006). Indeed, "objects, in ecological conditions, are typically viewed from a variety of egocentric (observer-based) perspectives, suggesting a close interaction between body- and object-based reference frames" (Galati et al., 2000, p. 156). In addition to elucidating the neural correlates of egocentric and allocentric representations, a full understanding of the way people perceive and interact with objects in the world requires investigations into possible differences in the cognitive processes that are involved when egocentric and allocentric viewer perspectives are used.

Research using transcranial magnetic stimulation (TMS) can be brought to bear on these issues. TMS induces an electrical current that can cause depolarization of cortical neurons underlying the location of the stimulation. Maeda, Kleiner-Fisman, and Pascual-Leone (2002) investigated whether action observation influences finger movements by applying TMS to motor representation areas

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and measuring the size of the motor evoked potentials at different muscles. Of critical importance to the present study, those investigators manipulated whether participants observed direct or translated views of hand stimuli. In that study, TMS stimulation resulted in greater muscle activation of the responding effectors (i.e., the involved finger muscles) when participants observed hands from a direct compared with translated view, presumably both from a viewer-centered (egocentric) perspective. This result suggests that the translated view might require additional processing as compared with a direct view. However, the nature of the differences in processing in the two situations is poorly understood. It is also unknown whether similar effects would occur using effector stimuli (such as hands) compared with noneffector stimuli (other objects), or whether viewer perspective (egocentric vs. allocentric) has an influence, our primary question.

One method to investigate whether the processing associated with a particular factor (e.g., that associated with spatial translations) can go on in parallel with other perceptual–cognitive processes is the PRP approach and the locus of slack logic. Below, we describe this approach. We follow this with a brief summary of the research that has examined spatial translations in mirror–normal and mental rotation judgments from a non-viewer-centered (allocentric) perspective, also using the PRP approach. A brief description of violations of single bottleneck models and the implications they may have on our proposal is then offered. Finally, we present a summary of our present hypotheses and a detailed account of our series of experiments. In brief, we investigate, for the first time, central bottleneck requirements of spatial translation processes using a viewer-centered (egocentric) perspective, to be directly contrasted with findings using spatial translations from a non-viewer-centered (allocentric) perspective.

PRP Approach and the Locus of Slack Logic

A typical PRP task involves the successive presentation of two stimuli (S_1 and S_2, respectively), each mapped to a response (R_1 and R_2, respectively) selected from among two or more alternatives. Accordingly, Task 1 consists of S_1–R_1, and Task 2 consists of S_2–R_2. Onset of the stimuli is separated by an experimentally manipulated temporal delay that usually takes on some short and longer values, referred to as the stimulus onset asynchrony (SOA). Typically, reaction time on Task 2 (or RT_2) is relatively long at short SOAs and decreases with increasing SOA. The slowing of RT_2 at short compared with long SOAs is referred to as the PRP effect.

A number of accounts for the PRP effect have been investigated, including strategic delays associated with processing (Logan & Gordon, 2001; Meyer & Kieras, 1997), capacity sharing (Navon & Miller, 2002; Tombu & Jolicœur, 2003), and structural bottlenecks (Pashler, 1994; Welford, 1952). For the present purposes, we elaborate on the single bottleneck account in order to introduce the locus of slack logic, which is a critical tool used in the present article. However, we consider exceptions to single bottleneck models and their implications in a later section.

According to the single bottleneck account, certain perceptual–cognitive operations or processes can be devoted to only one task at a time. Therefore, if two tasks demand those processes, at least some processing of one task must be delayed while the bottleneck is occupied carrying out the operations of the first task.

The single bottleneck view is based on the serial processing of three primary stages for each task involved. For each task, the stage of perceptual encoding occurs prior to response selection, which occurs prior to response execution, and these stages must occur serially. For simplicity, we refer to these stages as A, B, and C in Figure 1, to illustrate the locus of slack logic. According to a traditional single bottleneck account, the response selection stage requires access to the bottleneck, but the other stages (perceptual encoding and response execution) can occur in parallel with any other stage (Pashler, 1984; Pashler & Johnston, 1989). This model leads to specific predictions about the effects of factors that slow stages of processing of the second task (Task 2) in the PRP paradigm. Assume that a manipulation is performed on Task 2 that increases the amount of processing required at the bottleneck stage of processing of Task 2 (response selection). Assuming strict serial processing, that particular manipulation on Task 2 should increase the overall RT_2 by the same amount for short SOAs as for long SOAs. This results in additivity of the combined effects of SOA and the manipulated factor (see Figure 1). In contrast, if a manipulation is performed on Task 2 that affects perceptual stages of processing (and therefore prebottleneck stages), then there will be less impact on RT_2 at short SOAs compared with long SOAs. This is because the processing associated with the manipulated factor can go on in parallel with the bottleneck process of Task 1 (i.e., is absorbed by the slack). Thus, the effect of the manipulated factor should combine underadditively with decreasing SOA. The interpretation of this underadditivity is that the manipulated factor can begin before the bottleneck is fully available.

The model outlined above has received support from studies in which the manipulated factors reflect either response selection or perceptual stages of processing. One example of a factor that tends to depend on the bottleneck or stages of processing that follow the bottleneck is increases in the stimulus–response (S-R) mapping demands on Task 2 (McCann & Johnston, 1992; Pashler & Johnston, 1989; Van Selst & Jolicœur, 1994). In contrast, manipulations on the clarity of the stimulus of Task 2 have resulted in underadditivity of the combined effects of decreasing SOA and perceptual processing of the stimulus (Pashler & Johnston, 1989; Van Selst & Jolicœur, 1994). Specifically, the difference in RT_2 between trials with degraded compared with undegraded stimuli became smaller with decreasing SOA (i.e., as the overlap between Task 1 and Task 2 increased). Understanding what factors influence bottleneck versus prebottleneck processes is theoretically important in its own right. Our primary motivation in the present study was to use PRP methods and the locus of slack logic as tools to understand whether the particular viewer perspective used (egocentric or allocentric) is a critical determinant of whether spatial translation processes can begin before the bottleneck.

Previous Studies on Spatial Translations Using an Allocentric Viewer Perspective

To our knowledge, the PRP approach has not been used to investigate possible differences in spatial translation processes using a viewer-centered (egocentric) perspective compared with a non-viewer-centered (allocentric) perspective. Nor have PRP studies been conducted using effector stimuli. Perhaps the most closely related investigation has involved mirror–normal judgments of letters and digits, as seen in Ruthruff, Miller, and Lachmann

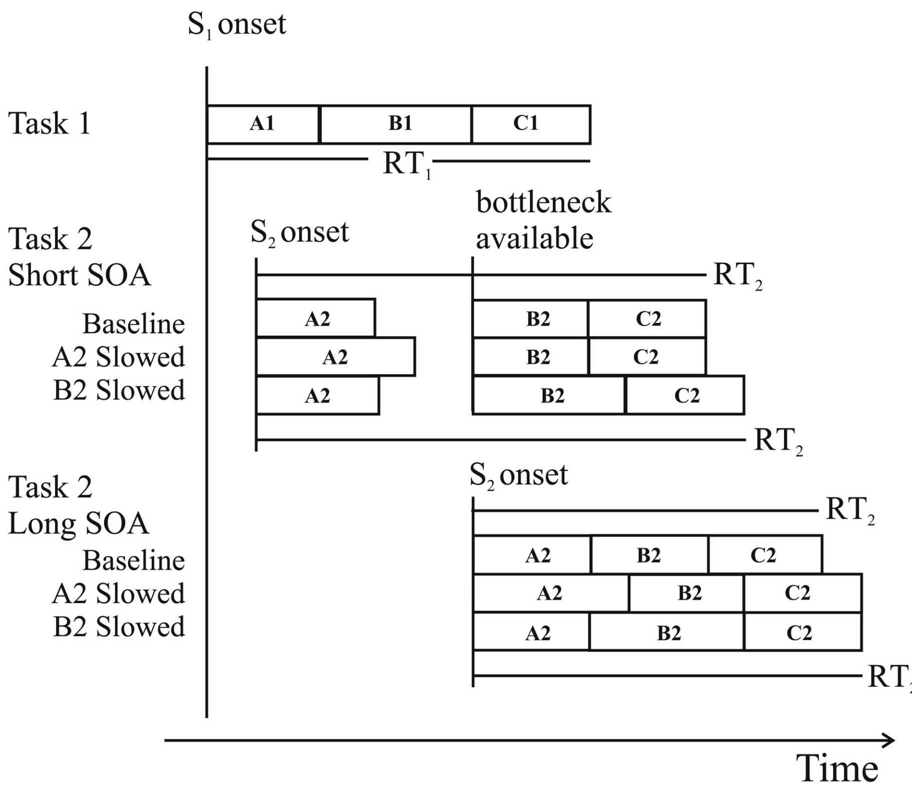

Figure 1. Schematic illustration of the locus of slack logic. Each box represents a stage of processing that occurs in serial. For Task 1 and Task 2, respectively, A1 and A2 are perceptual stages, B1 and B2 are central bottleneck stages, and C1 and C2 are response execution stages. Slowing B2 delays the response for Task 2 (RT_2) at both short and long stimulus onset asynchronies (SOAs) compared with baseline. Slowing A2 delays RT_2 at long SOAs but not at short SOAs compared with baseline. This is because at short SOAs the slowing of A2 is absorbed into the cognitive slack that occurs before B2 can begin. The lesser impact on RT_2 at short compared with long SOAs is referred to as underadditivity. In contrast, when the slowing affects a stage at or after the central bottleneck, the effect on RT_2 is similar across SOAs (referred to as additivity). S_1 = Stimulus 1; S_2 = Stimulus 2.

(1995) and Van Selst and Jolicœur (1994). Both of those studies consistently reported additivity of the combined effects of SOA and mirror–normal judgments of alphanumeric characters presented as Task 2 following tone discriminations as Task 1. For the most part, additivity was also reported for the combined effects of SOA and the degree of rotation of the stimuli, although there were a couple of exceptions in which this interaction just reached significance (i.e., suggestive of some underadditivity). However, Ruthruff et al. made a convincing argument that the degree of underadditivity shown in those cases (coupled with a very low reliability in the context of the additive findings reported in most other experiments) provides little evidence to suggest that mental rotation can occur prior to the bottleneck.

We believe that the types of manipulations that have been tested (mirror–normal and mental rotation, as described above) tend not to require a viewer-centered perspective. Rather, participants view the digits or letters and translate them mentally in terms of the coordinate space of those stimuli (and not the coordinate space of participants' body representations). Thus, previous research strongly suggests that when a non-viewer-centered (allocentric) perspective is used, spatial translation processes tend not to begin before the bottleneck. In view of the different neural systems involved in egocentric and allocentric processing, the bottleneck requirements might also be different. Given that only one system (allocentric) has been investigated so far, the question remains whether spatial translations using a viewer-centered (egocentric) perspective are more likely to begin before the bottleneck.

Possible Exceptions to a Strict Bottleneck Model

Possible violations of bottleneck models, some of which are consistent with strategic effects, might impact interpretations of the present study. For example, one prediction that must hold in order for a strict bottleneck account to be supported is that RT_1 should remain stable across SOA. Exceptions to this prediction constitute violations of single bottleneck models. One such example is consistent with capacity sharing between tasks (Navon & Miller, 2002). Another strategy is response grouping between Tasks 1 and 2 (Borger, 1963; Knight & Kantowitz, 1976; Pashler, 1994). With respect to SOA, response grouping results in the opposite effect on RT_1 as does capacity sharing. Specifically, a decrease in RT_1 (i.e., faster responses to Task 1) with increasing

SOA is consistent with capacity sharing, whereas an increase in RT_1 with increasing SOA is consistent with response grouping.

Consistent with many other studies in the literature, in the present PRP experiments tone discriminations were used for Task 1. Some methods (e.g., Experiment 2 of the present study) involve the possibility that shared codes are used for the response of Task 1 (code for a left vs. right finger response) and the perception of Task 2 (perceptual code of a left or right hand) (i.e., a code occupation account; Müsseler & Hommel, 1997; Prinz, 1990). It is therefore possible that another type of strategic delay occurs to avoid potential confusion between codes.[1] Highly compatible S-R relations might also constitute an exception to bottleneck effects, as has been discussed at some length by Karlin and Kestenbaum (1968), Van Selst and Jolicœur (1997), and Sommer, Leuthold, and Schubert (2001). These considerations were incorporated into the present set of studies, as will now be briefly summarized.

Predictions and Outline of the Present Experiments

The present experiments employed a PRP approach using a viewer-centered (egocentric) framework to investigate spatial translation processes associated with discriminating and judging effector and noneffector stimuli. Our primary purpose was to investigate whether spatial translation processes can begin before the bottleneck in this situation.

Our initial task involved presentation of a realistic depiction of a human hand in either a direct or a translated framework using a viewer-centered (egocentric) perspective. On each trial, a left or right hand stimulus was presented either as though protruding from the participant's own body (direct) or as though attached to someone else's body, with that person facing the participant (translated). Our rationale was that the translated trials would take longer than the direct trials, and it was this spatial translation process that was of primary interest. For simplicity, we refer to the different trial types as a direct framework (DF) or a translated framework (TF), respectively, to differentiate them from the two types of viewer perspective (egocentric or allocentric). Intuitively, and as we confirm in Experiment 1, left–right judgments made in TF trials take longer than left–right judgments in DF trials. The pertinent question is whether the translation processes involved in TF compared with DF trials can begin before the central bottleneck or whether those processes must wait for the availability of the central bottleneck in order to begin, as we argue is the case for the spatial translation processes associated with mirror–normal judgments on stimuli viewed from an allocentric perspective. Experiment 2 addresses this issue using a PRP approach with a tone task as Task 1 and left–right judgments of hands (Experiment 2a) or arms (Experiment 2b) as Task 2, thereby also providing direct comparisons under two different perceptual contexts. In Experiment 2 participants used two fingers of each hand for responding; in Experiment 3 the same basic procedure as in Experiment 2 was used, except that we removed the potential for code overlap by substituting a vocal response for the two-finger (left–right) response used in Task 1. In addition, we incorporated a more subtle manipulation on Task 2 S-R mapping into Experiment 3 to examine its possible effects on bottleneck requirements. As we will show, the removal of code overlap reveals that the spatial translation processes can begin before the bottleneck when a viewer-centered (egocentric) perspective is used.

In Experiment 4 we examine whether the findings obtained in Experiment 3 might have been due to the use of effector stimuli, rather than reflecting a critical role of viewer perspective. Contrary to this possibility, findings demonstrate that it is the viewer perspective and not the type of stimulus that seems to be critical in determining whether translations can begin prebottleneck. In Experiment 5 we manipulate spatial translation using a non-viewer-centered (allocentric) perspective through the use of explicit instructions (Experiment 5a) or by presenting objects in a spatially translated manner with respect to an allocentric frame of reference (Experiment 5b). The purpose of these final experiments was to reinforce conclusions drawn from previous research using a non-viewer-centered perspective, to contrast them directly with findings using a viewer-centered perspective. As will be shown, findings of both experiments confirm our hypothesis that spatial translation processes are unlikely to begin before the bottleneck when a non-viewer-centered (allocentric) perspective is used. Moreover, novel to the present study, spatial translation processes are likely to begin before the bottleneck when a viewer-centered (egocentric) perspective is used. Thus, the viewer perspective is critical in determining when the spatial translation processes begin. The details of these experiments are now discussed.

Experiment 1: Baseline Measures Using a Viewer-Centered Perspective

Method

Participants. Twenty students (12 female, 8 male), with a mean age of 20.5 years, were recruited to participate and received partial credit in Psychology 100. All participants were right-handed according to both self-report and an abbreviated handedness inventory (mean handedness score = .81 on a scale ranging from –1.00 = *strongly left-handed* to 1.00 = *strongly right-handed*; Oldfield, 1971).

Stimulus materials. Stimuli were pictures of left and right hands presented separately in biologically realistic postures as though holding objects, but without the actual objects presented. The stimuli were constructed by taking photos of a person's hand while wearing a white glove to hide any discriminating features, with the hand holding a common object (either a cup, pencil, computer mouse, stapler, or compact disk). Using five postures ($\times$ 2 hands $\times$ 2 spatial frameworks) ensured that the stimulus set (n = 20) would be too large for participants to hold in short-term memory (Miller, 1956). To ensure that the left and right hand postures were as identical as possible, we measured the joint angles at the elbow and shoulder of the model's body while the two arms were held in postures that were symmetrical with respect to the model's body axis. We then took photo images of the hand and arm of each side separately. The model's face was not shown in the pictures presented to participants, there was no information about gaze included in any pictures, and all pictures were presented in the center of the computer screen (covering an area of approximately 10 $\times$ 10 cm) to avoid any left–right biases in position (therefore, this was not a spatial compatibility task). For stimuli to be presented in a direct framework that did not require

[1] We thank Guido Band for pointing out this possibility.

translation, photos were taken by placing the camera just behind the model, who sat 60 cm away from the camera with a viewing angle of approximately 30° with the horizontal. For stimuli to be presented in the translated framework (requiring spatial translation), photos were taken by placing the camera just in front of the model, at the same distance and viewing angle as in the direct framework. Using computer graphics, we then removed the hand-held object from each picture so that only the arm (up to the shoulder) and hand posture remained.

The stimulus set comprised 2 hands (left, right) × 2 levels of spatial translation (DF, TF) × 5 stimulus hand postures (derived from the different objects), making a total of 20 distinct stimuli. For clarity, please note that DF and TF refer to the level of spatial translation and not to the distinction between egocentric and allocentric (Experiments 1–4 all used an egocentric perspective). For experiments that used hands only, we removed the upper part of the arm from each picture, leaving only the hand and wrist. Examples of the stimuli appear in Figure 2A (for experiments using hands only) and Figure 2B (using whole arms). There were no interesting differences across the five postures used, and we therefore averaged across the postures for all analyses contained herein.

Data collection apparatus. In-house built response keyboards consisted of four buttons each, with an upper left button and an upper right button spaced 117 mm apart, and a lower left button and a lower right button spaced 65 mm apart. The upper and lower rows of buttons were separated by 60 mm. The response buttons were 15 × 15 mm square. This response apparatus was constructed so that the buttons would be spatially compatible with a left–right or a high–low location display (given the two leftmost buttons as well as the two rightmost buttons were aligned on a diagonal and therefore could be mapped using left–right or high–low spatial locations). The purpose was to maintain, as much as possible, spatial compatibility between the relevant stimulus attributes (high–low and left–right) and the spatial locations of the responses (although this was more a form of conceptual compatibility than spatial compatibility because spatial location was not the relevant attribute; e.g., Proctor & Reeve, 1990). Stimuli and instructions were displayed on a computer screen of a standard desktop computer that was interfaced with the response boards to collect the

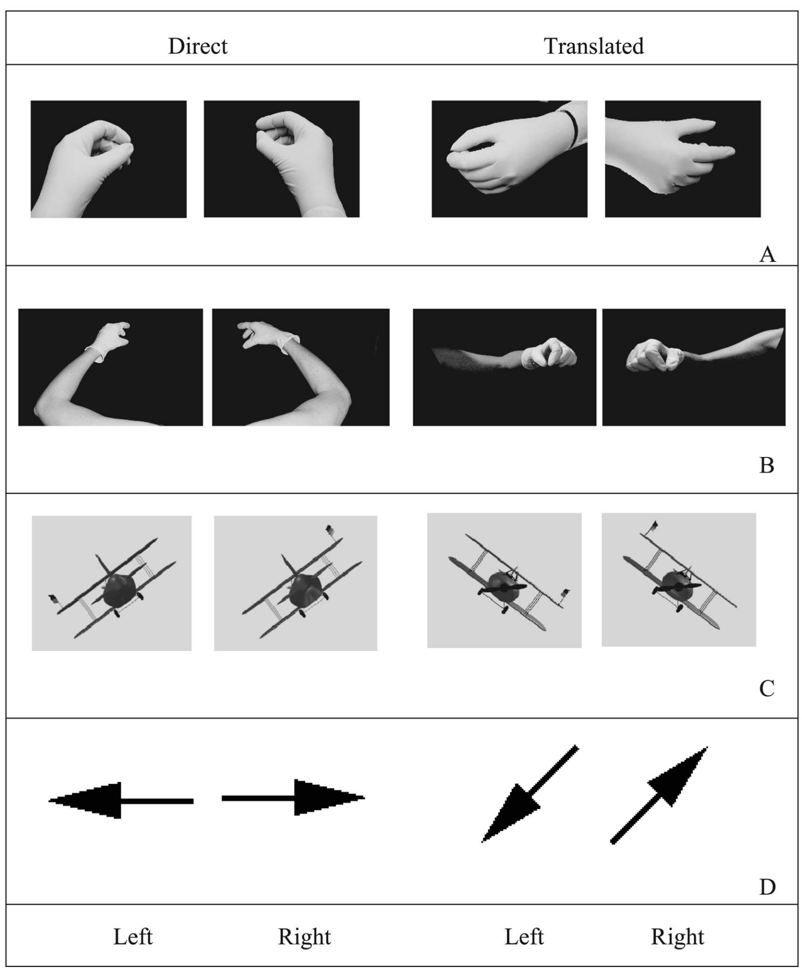

Figure 2. Some examples of stimuli used in experiments involving hands (A), arms (B), biplanes (C), and arrows (D). In each case, the two levels of spatial translation (direct and translated) are illustrated with an example of a “left” stimulus and a “right” stimulus.

data using turbo Pascal routines and millisecond accuracy time cards. On each trial, the hand stimulus was displayed until a response was made or for 2,000 ms, whichever came first. A 1.5-s delay occurred prior to stimulus presentation for the next trial.

Design. A 3 × 2 × 2 within-subject design was employed using the following factors: response mode (left within-hand, right within-hand, between-hand) × stimulus hand (left, right) × spatial framework (direct, translated). There were 16 trials of each of 20 unique stimuli, totaling 320 trials for each response mode. The three response modes were counterbalanced in different blocks across participants. A total of 960 trials were administered per participant in testing sessions that lasted approximately 90 min.

Procedures. Depending on response mode, two buttons were used for responding. For left within-hand responses, the two leftmost buttons on the response board were used, with the left middle finger on the leftmost button and the left index finger on the other button. For right within-hand responses, the two rightmost buttons on the response board were used, with the right index finger positioned on the left of the two buttons and the right middle finger on the other button. For the between-hand responses, only the lower row of response buttons was used, with the left index finger positioned on the leftmost button and the right index finger positioned on the rightmost button. Participants were instructed to press the left button if the hand viewed on the computer screen was a left hand and to press the right button if the hand on the screen was a right hand. They were instructed to do so as quickly and accurately as possible.

Results

Correct RTs were the dependent variable of interest. An error was defined as an incorrect response or no response. The total proportion of errors was less than 1% for all conditions, and there were approximately twice the number of errors in the two within-hand response modes (approximately 0.46%) compared with the between-hand response mode (approximately 0.27%), $F(2, 38) = 5.92$, $p = .006$. Errors for left- versus right-hand stimuli were not reliably different, $F(1, 19) < 1.00$, although the difference between translated (error $M = 0.61\%$) and direct (error $M = 0.19\%$) trials was highly significant, $F(1, 19) = 26.84$, $p < .001$.[2]

Anticipatory responses were considered to be those with an RT below 100 ms. In total, there were approximately 1.8% of trials with anticipations, and these were not differentiated on the basis of any within-subject variable. The grand mean RT for all remaining correct responses was 974 ms. There was a main effect of response mode, with the between-hand response mode producing faster RTs ($M = 835$ ms) than either the left ($M = 1{,}035$ ms) or the right within-hand mode ($M = 1{,}052$ ms), $F(2, 38) = 5.98$, $p = .006$. Post hoc tests verified that RTs for both within-hand response modes were slower than the between-hand mode, both $Fs(1, 19) > 8.60$, both $ps < .008$, replicating Kornblum (1965). However, the two within-hand modes did not differ reliably from one another, indicating that the speed of responding was not generally faster for the dominant hand ($F < 1.00$).

Of primary importance, and as predicted, TF trials were significantly slower than DF trials, $F(1, 19) = 37.92$, $p < .001$. It is interesting to note that this highly significant difference in spatial framework did not interact with response mode ($F < 1.00$). Figure 3

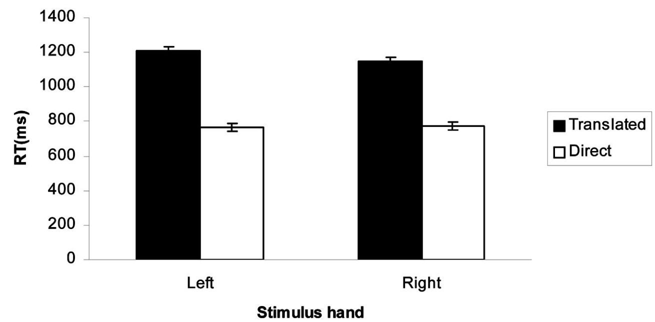

Figure 3. Interaction of spatial translation and stimulus hand for data of Experiment 1 collapsed across all response modes. Error bars represent standard errors across subjects. RT = response time.

depicts the interaction of spatial translation and stimulus hand for data collapsed across all response modes.

Discussion

The expected effects—slower RTs and more errors for trials in which a spatial translation was required compared with direct trials—were clear cut and highly reliable for all three modes of responding. Moreover, although the between-hand response mode was fastest overall, the response mode did not interact with the magnitude of the effect of spatial translation. As will become obvious in later experiments, it seems important that only one task was involved in this experiment (i.e., there was no dual-task requirement). With the dual-task (PRP) experiments used in later experiments, it becomes clear that when two hands are used for responding to separate tasks, discrimination and classification of stimuli might begin to interact with processes involved in selecting the effectors for responding.

With the baseline differences between direct and translated stimuli using a viewer-centered perspective firmly established, we were able to further probe the nature of the cognitive processing associated with these effects using the PRP approach.

Experiment 2: Manipulating Stimulus Cues

Our primary interest in all PRP experiments herein was in whether spatial translation processes could begin before the bottleneck, particularly with the use of a viewer-centered (egocentric) perspective. A secondary purpose of Experiment 2 was to identify whether this effect depends on the perceptual richness of the stimuli used. In practice, people never really see disembodied hands (as shown in Figure 2A). Stimuli that are perceptually richer, such as whole arms, might therefore facilitate left–right judgments owing to the increase in biologically realistic cues available. This hypothesis was tested using a PRP approach with hands (Experiment 2a) or arms (Experiment 2b) as stimuli, in a between-subjects design.

Method

Participants. Experiment 2a was conducted on 20 right-handed participants (8 male, 12 female), with a mean age of 20.4

[2] Throughout this article, p values have been adjusted using Greenhouse–Geisser corrections where appropriate.

years. Their mean score on the handedness inventory was .72 (Oldfield, 1971). Experiment 2b was conducted on a different group of 20 naive participants (12 male, 8 female), with a mean age of 22 years. They were also all right-handed, with an average handedness score of .74. In both experiments, participants were partially reimbursed for their time in the amount of $10.

Procedure and design. Stimulus materials for the hand task (Task 2) of Experiment 2a were identical to those used in Experiment 1. For Task 1, tone stimuli were characterized as being either high (1000 Hz, 50-ms duration) or low (300 Hz, 50-ms duration). The tones were amplified so that participants could hear them relatively comfortably. Experiment 2b was identical except for the use of arm stimuli rather than hands for Task 2 (see Figure 2).

Participants were instructed to respond to the tone task first and then to the hand/arm task. Instructions emphasized that both tasks were important and neither had priority over the other except that they should be responded to in their presented order. For Task 2, participants were instructed to discriminate and classify whether the hand was a left hand or a right hand and to press the appropriate button to indicate their responses; the same instructions were given in Experiment 2b, even though the stimuli consisted of whole arms rather than hands. Note that the precise location of the hand or arm on the computer display was approximately the same (centered) on each trial, although the hand appeared in different postures; thus, participants could not selectively avoid processing the arm when it was also present as part of the stimulus. The index and middle fingers of the left hand were used for responding to Task 1 (with high–low compatible mapping to the high–low tones), and the index finger and middle finger of the right hand were used, respectively, to respond to stimuli that depicted a left hand/arm or a right hand/arm.

Each trial began with presentation of a central fixation cross that lasted 800 ms. The screen was blanked for 300 ms, and the tone for Task 1 was then presented. Following onset of the tone stimulus on each trial, an SOA delay of 50, 150, 400, or 1,000 ms was presented. The hand/arm stimulus then appeared until a response was made to that stimulus or until 2,000 ms had transpired, whichever came first. Feedback in the form of *correct* or *incorrect* was displayed on each trial for 500 ms in 14-point font just below the stimulus location. Incorrect trials were logged for Task 1 and Task 2 as any response faster than 150 ms or no response (including responses $> 2{,}000$ ms). A 1,500-ms intertrial interval (measured from the end of the response interval for Task 2) occurred prior to presentation of the tone stimulus for the next trial.

The 20 hand/arm stimuli were crossed with two tone types and four SOAs, producing 160 distinct trials for each block. Prior to testing of four experimental blocks using a PRP paradigm (to total 640 experimental trials per participant), a practice block of each single task condition was tested (40 trials for each block). The response mode used for each of the single tasks was always the same as that used in the PRP combined task situation that followed. A practice block for the PRP task (32 randomly chosen trials) was run just preceding the experimental blocks. Although data were recorded for the single-task practice trials, they are not reported in this article, given there were no interesting findings of significance that would add to the content. Thus, the findings outlined below focus on four complete blocks of the PRP tasks only. Methods for all PRP experiments contained herein are identical to these unless otherwise stated. For RT_2 and RT_1, separate mixed-effects analyses of variance were applied to the data in Experiments 2a and 2b combined, using the between-subjects factor of effector (hand, arm) and the within-subject factors of SOA and level of spatial translation (DF, TF).

Results

RT_2. Of primary importance were the interactions of SOA and level of spatial translation, and whether those factors interacted with stimulus type (hand or arm). The three-way interaction of Effector × SOA × Spatial Translation was not significant, $F(3, 114) = 1.997$, $p = .127$, nor was the two-way interaction of SOA × Spatial Translation, $F(3, 114) = 1.286$, $p = .283$. Table 1 contains the means for the three-way interaction of SOA × Spatial Translation × Effector (compare columns 2a and 2b). One can see by examination of the mean RT_2 values that the difference in magnitude between TF and DF trials ranges from 197 ms to 248

Table 1
Proportion of Task 2 Trials in Error, Mean RT_1 (ms), and Mean RT_2 (ms) for the Interaction of SOA × Spatial Translation for Dual-Task Experiments Using Effector Stimuli

	Experiment			
Trial type	2a	2b	3a	3b
SOA 50				
TF				
Error	.17	.15	.12	.11
RT_1	787	772	747	842
RT_2	1,425	1,180	1,127	1,130
DF				
Error	.12	.11	.07	.05
RT_1	780	738	731	790
RT_2	1,228	1,068	991	1,013
SOA 150				
TF				
Error	.15	.14	.13	.12
RT_1	784	764	774	810
RT_2	1,334	1,084	1,057	1,046
DF				
Error	.10	.10	.05	.05
RT_1	744	740	759	796
RT_2	1,086	965	899	913
SOA 400				
TF				
Error	.14	.12	.12	.14
RT_1	730	711	768	822
RT_2	1,124	861	889	923
DF				
Error	.08	.08	.06	.05
RT_1	711	711	754	812
RT_2	886	753	729	753
SOA 1,000				
TF				
Error	.13	.12	.11	.16
RT_1	730	758	752	896
RT_2	962	725	773	780
DF				
Error	.09	.08	.04	.06
RT_1	750	751	726	896
RT_2	755	590	557	601

Note. RT = reaction time; SOA = stimulus onset asynchrony; TF = translated framework; DF = direct framework.

ms for the hand stimuli of Experiment 2a. The comparable values for the arm stimuli of Experiment 2b range from 108 ms to 135 ms. Clearly, these differences are approximately additive with SOA in both cases, and there is no obvious evidence of a departure from additivity (see Figure 4). As can easily be seen from the mean values at each SOA shown in Table 1, mean RT_2 decreased with increasing SOA, revealing a highly robust PRP effect, $F(3, 114) = 315.08$, $p < .001$. There was no hint of a difference in this main effect of SOA for the two effectors ($F < 1.00$).

The magnitude of the difference between levels of spatial translation was significantly larger for the hand stimuli compared with the arm stimuli, $F(1, 38) = 8.778$, $p = .005$. A difference in magnitude was also apparent on the main effect of stimulus type, which suggests that some general effect of increased perceptual information results in an easier discrimination or classification for arms compared with hands, $F(1, 38) = 4.663$, $p = .037$, although this does not significantly influence the effect of SOA (i.e., the PRP effect).

These results support the hypothesis that the processes involved in spatial translation do not start before the bottleneck and require the bottleneck stage of processing, according to the standard logic of single bottleneck models (at least in this situation). These results also support the hypothesis that the increase in perceptual cues available when one views arms compared with hands does not alone influence the PRP effect, nor does it affect when the spatial translation processes can begin. Nonetheless, processing overall is faster with arm stimuli compared with hand stimuli.

RT_1 and errors. Effects on RT_1 revealed no interesting or meaningful patterns (all $p > .05$). Although the means were not completely stable across SOA, there were no obvious violations of bottleneck models. In addition, errors on Task 1 were so few that they were not worth reporting. Thus, we do not further discuss errors for Task 1.

Proportion of trials in error for Task 2 responses are reported in Table 1 for each combination of SOA × Spatial Translation (DF, TF) and for the two effectors (compare columns 2a and 2b). Errors are defined as responses that were incorrect, missing, or slower than 2,000 ms (which would be recorded as no response). As can be seen in Table 1, for error there was a highly significant effect of SOA that revealed a pattern of increasing error with decreasing SOA, $F(3, 114) = 8.30$, $p < .001$. This pattern is in the opposite direction as would be expected with a speed–accuracy trade-off for Task 2. Finally, there was a significant effect of spatial translation that was consistent with findings on RT_2 in that error was larger for the TF compared with DF trials, $F(1, 38) = 23.11$, $p < .001$.

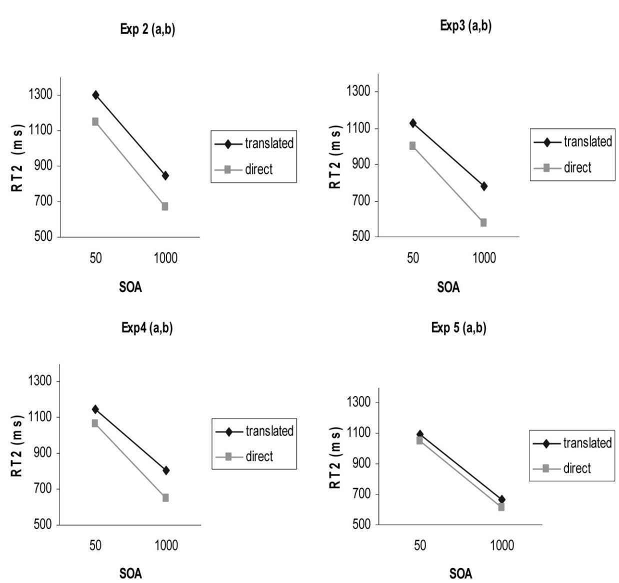

Figure 4. Patterns of additivity versus underadditivity shown for all psychological refractory period experiments, with the subexperiments averaged together in each case. Only the shortest and longest stimulus onset asynchronies (SOAs) are shown for each experiment so that direct comparisons can easily be made. Experiments 2 and 5 show strict additivity in the effect of interest. Experiments 3 and 4 reveal underadditivity. RT2 = response time for Task 2.

Discussion

When effector stimuli depicting biologically realistic hands or arms (Task 2) were preceded in a PRP task by tones (Task 1), a robust PRP effect was found on RT_2. These findings support a large corpus of literature on the PRP effect (described in the introduction). According to the locus of slack logic, additivity in the combined effect of SOA and level of spatial translation indicates that the spatial translation processes do not begin before the bottleneck and therefore require the bottleneck stage. There were no obvious violations of the single bottleneck model according to the results on RT_1. The faster responses on Task 2 using arm compared with hand stimuli, despite no differences in the effect of SOA for the two different stimuli, support the hypothesis that the increase in perceptual cues available when viewing arms compared with hands does not specifically influence the PRP effect or the locus of the factor of interest (spatial translation), at least not in this situation.

Experiment 3: Manipulating Response-Mapping Requirements

In the PRP task of Experiments 2a and 2b, two fingers of the left hand were used for responding on Task 1, and two fingers of the right hand were used for responding on Task 2. Given the potential of shared codes between the response of Task 1 and the perception of Task 2 (i.e., left–right in both cases), it is possible that participants strategically delayed processing for Task 2 to avoid code confusion between tasks. By this hypothesis, the additivity in Experiment 2 might have been due to strategic delays in responding, and a removal of code occupation might reveal the underadditivity. Moreover, if S-R mapping plays no further role in this effect, then the same degree of underadditivity should occur (with code occupation removed) even if subtle differences exist in the S-R mapping demands of Task 2. To test this, we substituted a vocal response for the left-hand responses of Task 1 to eliminate left–right coding in Task 1. In Experiment 3a, one finger of each hand was assigned to responses of Task 2 (between-hand mode) to produce a direct S-R mapping that maximizes ideomotor compatibility (Greenwald, 1970; Prinz, 1997). Experiment 3b also used a vocal response for Task 1 (thereby also eliminating the potential for code occupation) but with a right within-hand response (i.e., two fingers of the right hand) for Task 2, to maintain some demands on S-R mapping that were not present in Experiment 3a. If a lack of code occupation is the primary determining factor that produces underadditivity (in the combined effect of SOA and spatial translation), then the pattern of results for both versions of Experiment 3 (3a and 3b) should reveal underadditivity, in direct contrast to effects in Experiment 2. A further interaction with response mode (i.e., a three-way interaction of SOA × Spatial Translation × Response Mode) might suggest that subtle demands on S-R mapping can affect bottleneck requirements even if code occupation (between Task 1 response codes and Task 2 perceptual codes) is removed.

Method

In each experiment, 20 naive participants were recruited. In Experiment 3a, 7 were male and 13 were female, the mean age was 22 years, and all were right-handed (handedness inventory, $M = .79$; Oldfield, 1971). In Experiment 3b, 9 participants were male and 11 were female, the mean age was 24 years, and all were right-handed (handedness inventory, $M = .83$). Participants were partially reimbursed for their time in the amount of $10.

The same stimuli were used as in Experiment 2a except that the responses were changed as indicated above. A voice-activated response key was used to record verbal response latencies to the tone task. Participants were instructed to respond by saying "high" or "low" for high- and low-pitch tones, respectively. Given that the voice key measured RT only, an auditory tape was used to record the identity of the responses, and accuracy results were collated later. For the results reported below, we refer to the between-subjects factor as response mode, given that the only manipulated difference between Experiments 3a and 3b was in the response mode of Task 2.

Results

RT_2. Of primary importance was the highly significant underadditivity found in the combined effect of SOA × Spatial Translation, $F(3, 114) = 6.79$, $p < .001$. Moreover, this effect was approximately the same for the two response modes tested, as shown by a nonsignificant three-way interaction, $F(3, 114) < 1.00$.[3] As shown in Table 1, the magnitude of underadditivity from the longest to the shortest SOA was 80 ms in Experiment 3a and 62 ms in Experiment 3b. These effects clearly differ from the additive effects found in Experiments 2a and 2b (see Table 1 and Figure 4). Note, however, that even though underadditivity was found in both Experiments 3a and 3b, RT_2 differences between the two levels of spatial translation did not completely disappear at the shortest SOA. Thus, although these effects suggest that the spatial translation processes can begin before the bottleneck (according to the locus of slack logic), the central bottleneck is still used for a good portion of that processing. Alternatively, there might not have been enough slack present to absorb all of the effects of spatial translation (e.g., Ruthruff, Van Selst, Johnston, & Remington, 2006).[4]

As expected, the main effect of SOA was highly significant, as was the main effect of spatial translation, respectively, $F(3, 114) = 250.77$, $p < .001$, and $F(1, 38) = 85.50$, $p < .001$. There was no hint of an interaction across the two response modes in either of these effects (both Fs < 1.00).

RT_1. The main effect of SOA approached significance, revealing increasing RT_1 with increasing SOA, on average, for both experiments combined, $F(3, 114) = 3.24$, $p = .06$. As can be seen in Table 1, this marginal evidence of response grouping was primarily due to the slowing at an SOA of 1,000 in Experiment 3b, which resulted in a highly significant interaction of SOA × Response Mode, $F(3, 114) = 7.28$, $p < .001$. Thus, the effect did not generalize to the two experiments, and we suspect that the finding is spurious. However, the highly significant effect of slowing on RT_1 (of approximately 26 ms on average) with respect to the Task 2 manipulation on spatial translation is consistent with some form of cross-talk between tasks, $F(1, 38) = 13.65$, $p = .001$. The interaction of Spatial Translation × Response Mode on RT_1 was not significant, $F(1, 38) < 1.00$.

Task 2 error. Although the main effect on SOA did not reach statistical significance, the interaction of SOA × Response Mode was highly significant, respectively, $F(3, 114) = 1.37$, $p = .26$, and $F(3, 114) = 6.75$, $p = .001$. As can be seen by the means in Table 1, on average, the error rate increased slightly with increasing SOA in Experiment 3b only. In addition, there were significantly more errors in spatially translated compared with direct trials across both experiments combined, $F(1, 38) = 30.98$, $p = .001$. This latter effect did not interact with response mode ($F < 1.00$). Together with results on RT_2, this latter effect reveals a slight speed–accuracy trade-off for Experiment 3b (but not 3a). However, the absence of a speed–accuracy trade-off in Experiment 3a (and an additional experiment using arms as stimuli; see footnote 3) suggests that this alone cannot account for the highly significant underadditivity of the combined effects of SOA and spatial translation on RT_2 found across both Experiments 3a and 3b.

Discussion

Of primary importance, the effects on Task 2 revealed a highly significant interaction of SOA × Spatial Translation for both experiments, consistent with underadditivity. This finding suggests that the processes associated with a spatial translation on TF compared with DF trials can begin before the bottleneck. This effect contrasts with the strict additivity found in Experiment 2. Note, however, that the difference in RT_2 for the TF compared with DF trials did not converge completely at the shortest SOA. Thus, although the translation processes can begin before the bottleneck according to the locus of slack logic, it is clear that the bottleneck was still required for a large portion of those processes (or there was not enough slack to completely absorb the effects of spatial translation).

In sum, the findings of Experiments 2 and 3 combined provide support for the account that the additivity found in Experiment 2 could have been the result of strategic delays to avoid possible confusion due to shared codes between the responses of Task 1 and the perception of Task 2. Thus, the findings across Experiments 2 and 3 are consistent with the hypothesis that spatial translations are

[3] We conducted an additional experiment using the same response mode as in Experiment 3a but with arm rather than hand stimuli (as in Experiment 2b). Underadditivity was again found in the combined effects of SOA and spatial translation to the $p < .001$ level, and the effects of all other factors were virtually identical to those found in Experiment 3a.

[4] We thank Jeff Miller for pointing this out.

likely to begin before the bottleneck when a viewer-centered perspective is used; however, a strategic delay in responding to Task 2 might occur to avoid code confusion when there is potential sharing between response codes of Task 1 and perceptual codes of Task 2.

Experiment 4: Using Noneffector Stimuli

Given that the use of a viewer-centered perspective was novel in the context of PRP studies, it was unclear whether the present findings based on effector stimuli (Experiment 3) would generalize to noneffector stimuli. Clearly, it is important to determine whether the observed underadditivity (in the combined effects of SOA and spatial translation) occurs only with effector stimuli. It might be the case, for example, that when one perceives effector stimuli, egocentric representations (presumably containing the body's effectors) become automatically activated, thereby facilitating the processes of spatial translation when egocentric representations are involved. Consistent with this possibility, we noted that approximately one third of participants in Experiment 3 made twisting or rotating body movements (some subtle but some quite overt) when performing the task, as though using their own body coordinates to assist in making the left–right judgments. Our question was whether the evidence of a prebottleneck commencement in spatial translation processes would still occur if noneffector stimuli were used. Answering this question is crucial in dissociating whether the observed underadditivity is due to observer viewpoint or to the use of effector stimuli.

Consider a task in which the stimuli are biplane objects (as shown in Figure 2C). Notice that each biplane has a flag on either its left or its right side (substituting for a left or a right hand). The judgment of left and right would be relatively straightforward to make if the biplane were presented so that the participant observes from the perspective of behind the plane. In this case, the participant (viewer) would not have to translate any spatial representations to mentally align representations of his or her own body with his or her representation of the biplane's orientation in space. We can compare this orientation with one in which the participant observes the biplane as though it is flying toward him or her (i.e., akin to another person facing the participant in the case of the translated hand stimuli). In this case, a spatial translation is required in order to determine whether the flag of the biplane is on its left or right side. Of primary interest was whether underadditivity would occur in the combined effects of SOA and spatial translation even with the use of noneffector stimuli.

Method

Methods were identical to those of Experiments 3a and 3b except for the substitution of biplane stimuli for effector stimuli. Biplanes were constructed to be the same size and viewed from the same orientations (as much as possible) as the 20 unique effector stimuli used in previous experiments. Because biplanes are normally oriented in 3-D space (as are effectors), we were able to construct five different flight orientations (to substitute for the five different postures used for the effector stimuli) using computer graphics. Moreover, the biplane stimuli could be presented with the flag on the left or right and viewed in a direct manner (DF) or a manner requiring a spatial translation (TF). The same number of trials (and unique trial types) were presented as in the previous PRP experiments of this study, and all other methods were identical except that for Task 2, participants were instructed to press the button on the left if the flag was on the left side of the biplane, and the button on the right if the flag was on the right side of the biplane. We also added one procedure to the method, which was to interview participants afterward about how they performed the task. Specifically, we asked whether they used any specific forms of imaging or representations to assist in making the left–right judgments.

Results

RT_2. Of primary importance, highly significant underadditivity was found in the combined effects of SOA and spatial translation, as in Experiment 3, $F(3, 114) = 16.15$, $p < .001$;[5] this did not interact with response mode of Task 2 (the between-subjects variable; $F < 1.00$). The means for RT_1, RT_2, and error for each level of spatial translation and SOA (for Task 2) can be seen in Table 2. The main effect of spatial translation was highly significant, with longer RT_2s for translated (990 ms) compared with direct (878 ms) trials on average, $F(1, 38) = 49.70$, $p < .001$. Also as expected, the main effect of SOA was highly significant, $F(3, 114) = 219.61$, $p < .001$. This also did not further interact with response mode ($F < 1.00$).

RT_1. From the pattern of RT_1s shown in Table 2, it is clear that RT_1 was faster for DF compared with TF trials, on average, although the magnitude of this difference was small overall, $F(1, 38) = 7.49$, $p = .009$. As in Experiment 3, this effect is consistent with some form of cross-talk between tasks, given that the Task 2 manipulation of interest influenced RT_1 in a similar manner as for RT_2. There were no other meaningful or significant effects on RT_1.

Error. There were so few errors for Task 1 that they are not worth reporting further. For Task 2, there were no significant effects on error.

Discussion

Findings for experiments using biplanes were very similar to those using hands in Experiment 3. Specifically, highly significant underadditivity was found in the combined effects of SOA and spatial translation when there was a lack of code sharing between responses of Task 1 and perception of Task 2, with presumed use of a viewer-centered (egocentric) perspective. These findings suggest that under these conditions, the processes associated with spatial translations of Task 2 are likely to begin before the bottleneck even when the stimuli of Task 2 are noneffector objects.[6]

It is important to mention that although we did not instruct participants in Experiments 4a and 4b to represent the task as though they were sitting in the biplane, there is strong evidence to

[5] However, Experiment 4b does not show the expected decrease in the effect of spatial translation at the shortest SOA, for reasons we are uncertain of.

[6] As pointed out by an anonymous reviewer, we cannot rule out the possibility that discriminating the back of the biplane might be easier than discriminating the front. However, no participants indicated this when interviewed; moreover, the similarity in findings across Experiments 3 and 4 suggests to us that parsimony rings true in this case.

Table 2
Proportion of Task 2 Trials in Error, Mean RT_1 (ms), and Mean RT_2 (ms) for the Interaction of SOA × Spatial Translation for Dual-Task Experiments Using Noneffector Stimuli

	Experiment			
Trial type	4a	4b	5a	5b
SOA 50				
TF				
Error	.06	.06	.06	.06
RT_1	770	724	776	776
RT_2	1,167	1,137	1,156	1,025
DF				
Error	.04	.05	.05	.05
RT_1	743	719	753	779
RT_2	1,074	1,059	1,094	1,006
SOA 150				
TF				
Error	.06	.05	.06	.06
RT_1	755	746	793	690
RT_2	1,099	1,040	1,077	927
DF				
Error	.04	.06	.05	.06
RT_1	737	719	751	701
RT_2	981	975	1,031	905
SOA 400				
TF				
Error	.06	.05	.06	.07
RT_1	740	714	773	717
RT_2	957	891	893	758
DF				
Error	.06	.06	.05	.06
RT_1	740	717	745	725
RT_2	825	793	837	733
SOA 1,000				
TF				
Error	.08	.06	.07	.07
RT_1	758	735	784	689
RT_2	858	770	774	556
DF				
Error	.08	.07	.07	.06
RT_1	748	729	772	699
RT_2	683	634	702	526

Note. RT = reaction time; SOA = stimulus onset asynchrony; TF = translated framework; DF = direct framework.

suggest that this was generally what participants did. First, a majority of participants (approximately two thirds) reported having used some form of a viewer-centered (egocentric) perspective, as though they imagined themselves from the perspective of sitting in, or flying, the plane. As in Experiment 3, a significant proportion of participants (about 30%) produced small body movements when doing the task, as though slightly rotating the head or body to assist in discriminating left and right stimuli. Thus, we were fairly certain that participants did, as instructed, adopt a viewer-centered perspective. However, if some did not, it seems our claims would only be strengthened, given that the present findings would be quite conservative. Our final experiments aimed to demonstrate that when one makes discriminations that involve spatial translations but without a viewer-centered perspective, additivity is likely to occur in the interaction of SOA × Spatial Translation.

Experiment 5: Using a Non-Viewer-Centered (Allocentric) Perspective

Findings of Experiments 3 and 4 are consistent with the proposal that a highly significant underadditivity in the combined effects of SOA and spatial translation is likely to occur when a viewer-centered perspective is used and there is little potential for code sharing between tasks. In the case of an allocentric perspective, the observer's body representation is presumably not used in the spatial translation processes. Rather, the available representations are of the object and the environment surrounding the object. Our suggestion is that when one adopts an allocentric perspective, the alignment of representations (both extracorporeal) that underlies the spatial translation processes cannot begin prior to the central bottleneck (a more thorough elaboration of this idea is saved for the General Discussion). This delay in spatial translation processing might be due to the mental difficulty, attention, or memory demands associated with manipulating allocentric representations, but that issue is beyond the scope of this article. Our claim is that the previously published PRP studies that used translations of stimuli in space employed tasks that are unlikely to use a viewer-centered framework. Examples include PRP studies on the mental rotation of letters or digits, which have consistently demonstrated additivity of the combined effects of SOA and mirror–normal judgments in tasks using alphanumeric characters (Ruthruff et al., 1995; Van Selst & Jolicœur, 1994). Even the degree of rotation (i.e., referred to as mental rotation) in those studies tended to be additive with SOA on most experiments, albeit with two possible exceptions (as noted in the introduction). Thus, in our view, those previous studies did not use a viewer-centered perspective. Rather, the alphanumeric stimuli were rotated in terms of the coordinate space of the stimuli (i.e., the viewer perspective was allocentric). The final two experiments were conducted to cement our claims by examining other task situations in which left–right discriminations are required but without the use of a viewer-centered perspective.

Viewer perspective was manipulated either by specific instructions to participants (5a) or by the use of stimuli presented in a spatially translated manner with respect to the coordinate space of the stimuli and not the participant (5b). Predictions for both experiments were that strict additivity should occur (in the combined effects of SOA and spatial translation), suggesting that the processes associated with spatial translation are not likely to begin prior to the central bottleneck when a non-viewer-centered (allocentric) perspective is used. These experiments are described and discussed in as brief a manner as possible, given that they are included only to demonstrate a direct contrast with findings of Experiments 3 and 4 of the present article. Owing to the very different methods and different numbers of participants in each, we present the results of these experiments separately.

Method, Results, and Discussion of Experiment 5a

Experiment 5a was identical in all respects to Experiment 4a except that the participants were a new group and the instructions were different. Specifically, if looking at the back of the biplane, participants were instructed to press the left button for a flag on the left and the right button for a flag on the right (compatible mapping). If looking at the front of the biplane, they were to press the response button located opposite the side of the flag (incompatible mapping). The purpose of this manipulation on instructions was to encourage processing based on a non-viewer-centered (allocentric) perspective so that participants would observe from "outside of the biplane." The same S-R mappings were used as in Experiment 4a. Note, however, that we left open the possibility that adopting a viewer-centered framework might be somewhat unavoidable for at least some participants. To check for this, we interviewed participants afterward to query their strategies and methods of representation so that we could then have the opportunity to rerun analyses without data from participants who claimed to have used a viewer-centered perspective. The following results are based on the data from 25 participants, all of whom claimed they followed our instructions and adopted a non-viewer-centered perspective (i.e., as though viewing from outside of the plane).[7]

RT_2. Of primary importance, the interaction of SOA × Spatial Translation was not statistically significant, $F(3, 72) = 1.83$, $p = .16$. As can be seen in Table 2, although overall the mean difference between TF and DF trials was slightly smaller at the shortest SOA compared with the longest SOA, the overall magnitude of this decrease was only 10 ms, and the pattern across SOA was not monotonic. These findings contrast with the pattern of underadditivity (and the associated level of statistical significance) reported in our previous experiments that used a viewer-centered perspective. As predicted, the main effect of SOA was highly significant, as was the main effect of spatial translation, respectively, $F(3, 72) = 119.54$, $p < .001$, and $F(1, 24) = 22.56$, $p < .001$.

RT_1. The main effect of spatial translation was highly significant, consistent with some form of cross-talk between tasks, $F(1, 24) = 27.36$, $p < .001$. However, the effect of SOA on RT_1 showed no regular effect, $F(3, 72) < 1.00$. The means for the interaction of SOA × Spatial Translation can be seen in Table 2.

Together, these results are consistent with additivity in the combined effects of SOA × Spatial Translation on RT_2, supporting the hypothesis that prebottleneck processing of Task 2 is far less likely to occur with use of a non-viewer-centered perspective compared with use of a viewer-centered perspective. In the General Discussion, we discuss the implications and interpretations of the patterns of results across experiments.

Method, Results, and Discussion of Experiment 5b

The purpose of Experiment 5b was to examine performance of a task that is similar to mental rotation but using symbolic directional stimuli, to demonstrate that strict additivity occurs when one uses a non-viewer-centered perspective. Arrows were used as stimuli (rather than alphanumeric symbols, as in past studies on mental rotation) because we considered arrows to be mapped to directions in a manner that might be even more ideomotor compatible than, for example, biplanes or hands. Thus, if the effect of primary interest is strictly additive when arrow stimuli (and a non-viewer-centered perspective) are used, then one could not raise the possible argument that additivity is more likely to occur with alphanumeric (i.e., somewhat unnatural and nondirectional) stimuli.[8] Arrows were presented in either a horizontal or diagonal orientation, pointing either partially to the right or partially to the left, with some rotation from the horizontal. Of note, left–right judgments of the arrows do not require or encourage a viewer-centered framework. Thus, the task qualifies as one involving primarily an allocentric rather than egocentric viewer perspective. In this experiment, we refer to the two stimulus orientations as direct (horizontal arrows) and translated (diagonal arrows); to maintain consistency with other experiments we again refer to this factor as the level of spatial translation and use the abbreviations DF (direct) and TF (translated).

Thirty-four new, naive participants with demographics approximately identical to those in the previous experiments were tested.[9] The stimuli for Task 1 were the same as in previous experiments. Examples of the stimuli used in Task 2 are shown in Figure 2D. As can be seen in the figure, arrows along the horizontal were not translated, and arrows along the diagonals were translated along their own coordinate plane (with respect to the horizontal axis). The arrows appeared in approximately the same screen size as the hands, arms, and biplanes used in the earlier experiments (extending approximately 10 cm, with the midpoint of the stimulus approximately centered on the computer screen). Each of six arrow stimuli was crossed with the four SOAs to make 24 unique trial types. Because there was twice the number of diagonal arrows compared with horizontal, we doubled the number of horizontal stimuli (to make 32 possibilities in total) to avoid problems related to different probabilities for the two levels of task difficulty. The 32 SOA–stimulus pairs were crossed with the two levels of tone pitch for Task 1 to make a total of 64 trials. This number was doubled for each block of trials, and four blocks were tested for each participant to total 512 trials. It might be important to mention that the number of unique stimuli was actually smaller in these experiments than in previous ones using hands and arms. One might argue that evidence of underadditivity in the effect of interest would be more likely the fewer stimuli used, given the smaller load on memory. Thus, we strongly stacked the cards in favor of obtaining underadditivity in Experiment 5b, given the use of left–right directional stimuli and owing to there being few unique stimulus types.

Task 1 was a vocal response to the tone task (as in Experiments 3 and 4). For Task 2, participants were instructed to press the response button on the left (using the index finger of the left hand) if the centrally presented arrow pointed to the left to some degree, and to press the response button on the right (with the index finger of the right hand) if the centrally presented arrow pointed to the

[7] In total, 34 participants were tested, of whom 9 indicated in our posttest interview that they had used some form of viewer-centered perspective. Thus, we eliminated their data from analysis. Note, however, that $n = 25$ is a larger sample than that used in the previous experiments that revealed underadditivity.

[8] However, this argument is tricky because spatial translations performed on alphanumeric stimuli most likely use a non-viewer-centered perspective. Our intention here is to show that when an allocentric perspective is used, additivity is likely to occur (even without the use of alphanumeric stimuli), thereby isolating the factor of viewer perspective.

[9] Originally, we tested 20 participants and obtained an interaction of SOA × Spatial Translation approaching significance ($p = .10$) but without any obvious pattern of underadditivity in the means. One could argue that a lack of power prohibited this marginal effect from becoming statistically significant (i.e., underadditive). Contrary to this possibility, data from the additional participants strengthened the evidence of additivity (refer to footnote 7 for additional evidence related to statistical power).

right to some degree relative to the fixation stimulus. Owing to the use of a non-viewer-centered perspective, the results were predicted to reveal strict additivity. This finding would cement our hypothesis that additivity is most likely to occur with a non-viewer-centered perspective.

Of critical importance, there was absolutely no hint of a significant interaction of SOA × Spatial Translation on RT_2, $F(3, 99) < 1.0$, $p = .87$. The means for RT_1, RT_2, and error rate for each condition can be seen in Table 2. The main effect of SOA and the main effect of spatial translation on RT_2 were both highly significant as expected, respectively, $F(3, 99) = 236.56$, $p < .001$, and $F(1, 33) = 12.49$, $p = .001$. The only significant effect on RT_1 was a barely significant main effect of SOA, $F(3, 96) = 6.1$, $p = .016$. As can be seen from the means in Table 2, the magnitude of this effect was very small and the pattern not monotonic (moreover, the slightly longer RT_1s for DF compared with TF trials, although not significant, lead us to think that any instability in RT_1 is spurious). There were no significant effects on error. Figure 4 depicts the mean RT_2s for both levels of spatial translation at the shortest and longest SOAs, with means averaged for Experiments 5a and 5b, to illustrate the additivity (i.e., parallel lines).

One might argue that the magnitude of the difference in RT_2 between the translated and direct trials in Experiment 5b was overall smaller than in the other experiments. This is true, but the magnitude of the difference between trials for the two levels of spatial translation was also larger in the experiments using hands or arms as stimuli (2a and 2b), where evidence of strict additivity was also found. Thus, findings of additivity are not confined to those tasks in which the overall effect of spatial translation is large to begin with. Nor does the additivity depend on the stimulus type, given that it occurred both with hands/arms and with arrows as stimuli. Notably, however, we attribute the additivity in Experiment 2 to strategic effects (to avoid code sharing between tasks), whereas we attribute additivity in Experiment 5 to the use of a non-viewer-centered perspective. Interpretations across our series of experiments are now discussed.

General Discussion

The present study examined whether the processes of spatial translation required in making left–right stimulus discriminations and judgments are likely to begin before the central bottleneck when a viewer-centered perspective is used. Novel to this study is the finding that viewer perspective is an important determinant in that the use of a viewer-centered perspective increases the likelihood that the processes associated with spatial translation can begin before the bottleneck. To our understanding, previous research using the locus of slack logic did not examine the processes of spatial translations using a viewer-centered perspective. Thus, findings from previous research on mirror–normal and degree of rotation translations (as described in the introduction) are consistent with our findings from Experiment 5; additivity of the combined effects of SOA and level of spatial translation tends to occur when a non-viewer-centered perspective is used. The increased likelihood of underadditivity with a viewer-centered perspective is novel to the present study.

Some of the effects we observed on RT_1 (Experiments 3 and 4) are suggestive of some form of cross-talk between tasks. These effects actually strengthen our claim that some parallel processing is likely to occur between tasks, and this might be more pronounced when a viewer-centered perspective is used (compared with when a non-viewer-centered perspective is used).

We view the additivity of the combined effects of SOA and level of spatial translation on RT_2 found in Experiment 2 as consistent with strategic delays in the processing of Task 2, perhaps as a means to avoid potential confusion between codes associated with responses of Task 1 and perceptual processing of Task 2. Notably, when the potential for code sharing was removed in Experiments 3 and 4, highly significant underadditivity was found using experimental methods that were otherwise nearly identical to those of Experiment 2a (except for the stimulus type used in Experiment 4). Together, these effects are consistent with the idea that strategic delays can occur as a result of code occupation, but the later postponement of spatial translation processes with a non-viewer-centered perspective (compared with a viewer-centered perspective) implicates different requirements on bottleneck processes.

Our own theoretical view is that it is evolutionarily beneficial for humans' action systems to quickly interface with their representations of the outside world; we think that this interface involves the process of aligning different representations. Accordingly, the brain's representations of (potential) actions (i.e., egocentric representations) and its representations of objects in the world must come into alignment often and efficiently. It would be an advantage, therefore, if this type of alignment can go on in parallel (at least in part) with the response selection of other actions; otherwise it is difficult to conceive of smooth and efficient interactions with objects in the world. We believe that our proposed account is consistent with Goodale and Milner's (1992) account of the dorsal visual stream of processing. Specifically, Goodale and Milner suggested that the dorsal visual pathway is activated somewhat automatically in the processing of objects related to actions (and they also linked an egocentric framework to the dorsal stream). Consistent with their account, we propose that a viewer-centered (egocentric) perspective is a necessary condition for activation of that pathway. Our findings and interpretations of others' findings suggest that when spatial translations are made on stimuli that are perceived from a non-viewer-centered (allocentric) perspective, those judgments depend wholly on bottleneck processes and therefore cannot begin before the bottleneck. This seems consistent with Goodale and Milner's proposal that the ventral visual pathway is involved in recognition memory, which takes more time than online (virtually automatic) processing associated with actions. Its demands on memory, for example, might be why the bottleneck is necessary.

It is important to emphasize that the underadditivity found in our conditions using a viewer-centered perspective was not complete; that is, the difference in RT_2 for translated compared with direct trials did not converge completely at the shortest SOA. This indicates that the bottleneck is still necessary for spatial translations, even though such processes are likely to begin before the bottleneck when a viewer-centered perspective is used. Alternatively, there may not have been enough slack to absorb the entire effect; however, this possibility cannot be determined on the basis of our data. It seems reasonable to assume that the processing associated with an alignment of one's own body representation and other (extracorporeal) representations would require some portion of the bottleneck stage, given the importance in monitoring one's actions as they occur (which most likely involves at least some serial processing). This also leaves open the possibility that a number of subprocesses constitute what we are referring collectively to as *spatial translation*. In the case of a viewer-centered perspective, some subprocesses might occur before the bottleneck (and be absorbed by the slack), whereas others might depend on the bottleneck. Testing this theory would require careful manipulations on the putative subprocesses involved. We also leave open the possibility that findings on a task like ours might reflect a mixture of trials using different viewer perspectives, particularly in the case of our biplane experiments, in which it is possible to do the task using either perspective. Nonetheless, our findings indicate that manipulations targeted at using an egocentric perspective (e.g., Experiments 3 and 4) lead to a higher likelihood that spatial translations will begin earlier (i.e., before the bottleneck) than manipulations targeted at using an allocentric framework (e.g., Experiment 5). Our findings might also help clarify the results obtained in an earlier study that measured event-related potentials while participants determined whether line drawings depicted rotated left or right hands (Thayer, Johnson, Corballis, & Hamm, 2001). Those investigators reported that the mental rotation most likely involves perceptual as well as response selection processes, but they did not measure stages of processing to confirm this with certainty.

In conclusion, the present findings shed new light on the question asked previously about whether mental rotation requires central bottleneck processes (Ruthruff et al., 1995; Van Selst & Jolicœur, 1994). Consistent with conclusions from those previous studies, the present findings indicate that mental rotation using a non-viewer-centered (allocentric) perspective is not likely to begin before the bottleneck. Novel to our study are the findings based on a viewer-centered (egocentric) perspective, which appears to increase the likelihood that spatial translation can begin before the bottleneck. In sum, these findings contribute to our theoretical understanding of the perceptual–cognitive processes involved in spatial judgments produced in different viewer perspectives, thereby offering a broad range of implications on our understanding of the way the brain represents space. We conclude that viewer perspective might be a critical factor in determining how the processing associated with spatial translations occurs in the brain.

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