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AN INTERACTIVE CONCEPTION OF THE PSYCHOLOGICAL REFRACTORY PERIOD EFFECT

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This dissertation is dedicated to a person
who was not able to attend my graduation

My father

He was always proud of me.

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ABSTRACT

Lien, Mei-Ching, Ph.D., Purdue University, May 2001. An Interactive Conception of the Psychological Refractory Period Effect. Major Professor: Robert W. Proctor.

An interactive conception of the psychological refractory period (PRP) effect is proposed on the basis of Hommel's (1998) two-process approach to account for compatibility effects in the PRP task. The interactive conception account assumes that response selection has two components. One component is stimulus-response (S-R) translation, which can occur automatically and simultaneously for both tasks. The other component is final response selection, which is the locus of the bottleneck and can process only one task at a time. The account suggests that between-task crosstalk and noncurrent-task response association have strong impacts on S-R translation when there is a contingency between the two tasks. Six PRP experiments were conducted: The first three experiments contained no contingency between the two tasks, but the last three did. Greenwald and Shulman's (1973) S-R compatible and ideomotor compatible tasks were used in Experiments 1-3, with both responses (R1 and R2 for Task 1 and Task 2, respectively) being required in Experiments 1-2 and only R2 in Experiment 3. The interactive conception predicts that the PRP effect should be obtained in Experiments 1 and 2 but not in Experiment 3 because the selection of R2 has to wait until the selection of R1 is completed. A PRP effect was evident in Experiments 1 and 2 but not Experiment 3. In Experiment 4, the dimensional overlap of the color between the first stimulus (S1) and the second one (S2) was manipulated and participants were instructed to respond to S2 only. A large PRP effect was obtained for the dimensional overlap condition and a small, but significant, PRP effect for the condition with no dimensional overlap. Experiments 5 and 6 examined the effect of S1-S2 correlation (high, low, and neutral), as well as spatial correspondence (R1-R2 correspondent and R1-R2 noncorrespondent) in Experiment 6, on the PRP effect. An overadditive interaction of S1-S2 correlation and SOA was obtained for both experiments. A comparison between Experiments 5 and 6 showed no difference in the PRP effect obtained with the three levels of S1-S2 correlation. However, the effect of correlation tended to be larger at the short SOA in Experiment 6, in which spatial correspondence of responses was manipulated, than in Experiment 5, in which it was not. Results of these experiments are in agreement with the interactive conception of the PRP effect, in which the contingency between two tasks affects S-R translation processing, which is distinct from the processing of final response selection.

INTRODUCTION

In everyday life, people carry out more than one concurrent activity, such as conversing with someone while walking and eating breakfast while reading. They believe that they are able to do different activities at the same time. Nevertheless, there is considerable evidence showing that people are unable to perform two tasks at once (e.g., Telford, 1931; Welford, 1952). The psychological refractory period (PRP) paradigm is the most common method used to study the dual-task interference. In it, participants are required to perform two tasks (T1 and T2) with a varied interval between the onsets of two stimuli (S1 and S2, respectively), which is called the stimulus onset asynchrony (SOA). The response time (RT) is measured for each task from the onset of the stimulus to the time when the response is made for that task (RT1 and RT2, respectively, for T1 and T2). A typical finding from such dual-task arrangements is that RT2 is delayed at the shortest SOA by several hundred milliseconds with respect to when T2 is performed alone. Considerable progress has been made toward a theoretical understanding of PRP effects with regard to whether the central processing of T1 is parallel or sequential with that of T2 (e.g., Allport, Antonis, & Reynolds, 1972; Keele, 1973; Meyer & Kieras, 1997a, 1997b; Pashler, 1994; Welford, 1952, 1959).

The most widely accepted account for the PRP effect is the response-selection bottleneck (RSB) model (Pashler, 1984, 1994; Pashler & Johnston, 1989, 1998). This model depicts the processing of T1 and T2 in the PRP paradigm as two noninteractive streams, with a fixed central bottleneck located at decision-related stages that can only process one task at a time (e.g., Welford, 1952). Stages prior or posterior to decision-related stages for two tasks are assumed to process stimuli concurrently (e.g., Davis, 1957). In other words, response-selection processing of one task must be completed before that of the other task can start, whereas the processing of stimulus identification or response execution of one task can be executed with that of the other task at the same time (see Schweickert & Boggs, 1984, for a detailed discussion of concurrent and sequential processes). The slowing of RT2 at short SOAs occurs because the response-selection processing for T2 cannot start until the response-selection processing in T1 has been completed (see Figure 1). According to the RSB model, any variables affecting the pre-bottleneck processing of T2 will have an underadditive interaction with SOA on RT2, whereas any variable affecting the response-selection processing of T2 will have an additive interaction with SOA on RT2. In other words, the variable affecting response-selection processing of T2 will be subject to the bottleneck and result in an effect on mean RT2 that is independent of SOA when T1 is processed before T2.

One manipulation whose effects are typically attributed to response selection is stimulus-response (S-R) compatibility (see Hommel & Prinz, 1997, and Proctor & Reeve, 1990, for reviews). The S-R compatibility effect, after the classic work by Fitts and Seeger (1953), refers to the finding that performance is more efficient when spatial locations of the stimulus and response correspond than when they do not. Not only can the S-R compatibility effect be found when the stimulus location is relevant to the task, but it also can be found when it is irrelevant. Typically, the response is faster when the stimulus location corresponds with the response location than when it does not, even when the stimulus location is irrelevant to the task. This result is called the Simon effect. In investigating the Simon effect of T2 on the PRP paradigm, McCann and Johnston (1992) and Lien and Proctor (2000) presented S2 to the left or right side of the screen, with the location being irrelevant to the task. The results in both studies showed an underadditive interaction of the Simon effect with SOA on RT2, with the Simon effect decreasing as SOA decreased. Such an outcome is inconsistent with the RSB model if the Simon effect is attributable to response selection.

Moreover, the RSB model does not explain explicitly how the decision-related translation processing of S2 to R2 affects decision-related translation processing of S1 to R1, except for the time course between the response selection for T1 and T2. Dzhafarov (1999) and Townsend and Thomas (1994) have suggested that selective influence can be considered in tasks with interdependent processes. Also, several studies have found considerable crosstalk effects between the two tasks in the PRP paradigm where the decision-related translation processing of T2 affects that of T1 and vice versa (see Lien & Proctor, 2001, for a review). Hommel (1998) proposed that the decision-related processing for T2 is not delayed until the response selection of T1 is completed, as the RSB model assumes. Instead, the S-R translation for both tasks can be activated and processed at the same time. He suggested that the response-selection processing should be treated as two distinct components, response activation and a decision about which response to make based on this activation, with the response activation proceeding either automatically or intentionally in parallel for T1 and T2 but the response decision being made in series. According to Hommel's two-process approach, the S-R translation of T2 can receive some degree of activation before R1 is selected, but the decision for R2 has to wait until the decision for R1 is made and completed. This hypothesis allows crosstalk effects between the two tasks to occur in the PRP paradigm, in which the decision-related translation processing of T2 affects that of T1 and vice versa. In addition, any variable affecting the activation of the S-R translation on T2, such as the compatibility of S-R mapping, should show an underadditive interaction with SOAs.

On the whole, the traditional RSB model that pictures the processing of T1 and T2 in the PRP paradigm as occurring in two parallel, noninteractive streams cannot easily accommodate the findings of the compatibility effect and the crosstalk correspondence effect in dual-task performance. Obviously, Hommel's (1998) two-process approach provides a promising start for developing a model that captures the compatibility phenomena in the PRP paradigm. However, there are a number of important points that have to be clarified in the two-process approach in order to provide a comprehensive theory of compatibility effects in dual-task performance. In this study, an interactive conception of the PRP effect is proposed that incorporates Hommel's (1998) two-process approach to account for compatibility effects in the PRP paradigm. Like the two-process approach, this interactive conception suggests that S-R translation of T1 and T2 can be executed at the same time, but the response decision based on the resulting activation for the two tasks has to be made serially. More explicitly, though, the interactive conception of the PRP effect suggests that the contingency relation between two tasks, either through dimensional overlap (similarity) or predictive correlation, is the key factor resulting in the crosstalk between the two tasks. Thus, this study will provide further insight of the nature of the dual-task interference by examining the contingency relation between two tasks in the performance of the tasks within the PRP paradigm.

Stimulus-Response Compatibility Effects

In the last 50 years, numerous researchers have devoted their efforts to examining the effects of relevant and irrelevant stimulus information on the response selection (see Hommel & Prinz, 1997; Proctor & Reeve, 1990, for reviews). In recent years, a dual-route hypothesis of the compatibility effect has become increasingly popular. This model assumes that the translation of stimulus codes to response codes is processed through two parallel routes, a slow route involving intentional S-R translation and a fast route based on automatic response activation. The concept of dual-route process provides a valuable tool in explaining that S-R compatibility tends to obtain a maximum when stimulus and response sets spatially correspond to one another (e.g., Fitts & Seeger, 1953; Garvey & Mitnick, 1955). It also provides an explanation of why the performance is efficient when a single mapping rule (either direct or mirrored) can be applied for each S-R element in whole stimulus and response sets (e.g., Duncan, 1977a, 1977b; Fitts & Deininger, 1954), or when the pairs of stimulus and response elements agree with strong population stereotypes (e.g., Alluisi & Warm, 1990). Kornblum, Hasbroucq, and Osman (1990) explicitly implemented the dual-route concept in their dimensional overlap model, which has served as a significant impetus for subsequent research into compatibility effects.

The dimensional overlap model depicts that when an S-R ensemble has a high degree of overlap (similarity) between the relevant stimulus dimension and the response dimension, the presentation of a stimulus will trigger two response functions of the type discussed previously for the dual-route approach (Kornblum, 1994; Kornblum et al., 1990; Kornblum & Lee, 1995). One is automatic activation of the congruent response, and the other is identification of the assigned response by way of intentional S-R translation. If the stimulus has an irrelevant dimension that overlaps with the response dimension, this irrelevant information will also produce automatic activation of the corresponding response but will not be identified through intentional translation. If a response that is automatically activated by either a relevant or irrelevant stimulus dimension is the one assigned to the relevant stimulus dimension by the task instructions, it can be executed as soon as identification is completed, and RT will be facilitated. In contrast, if the automatically activated response is not the correct one, it must be inhibited before the correct response can be programmed and executed, thus slowing RT.

Dimensional overlap will also influence the speed of the intentional response-identification process. Response identification will be fastest with a congruent S-R mapping because an identity rule can be applied (e.g., respond at the corresponding location). For an incongruent mapping, response identification will be slowest if the stimuli are randomly assigned to responses because identification of the correct response must proceed by a time consuming search through specific S-R associations. The time for response identification will be reduced substantially when there is a systematic relation between stimuli and responses that allows application of either direct or mirrored mapping rule (e.g., respond at same or mirror opposite location).

Kornblum et al. (1990) also developed a task taxonomy of S-R compatibility on the basis of the dimensional overlap model. Initially, they proposed a four-category taxonomy based on dimensional overlap between (a) the relevant stimulus information and the response and (b) the irrelevant stimulus information and the response. Kornblum

(1992) and Kornblum and Lee (1995) expanded the dimensional overlap model to include (c) the relevant and irrelevant stimulus dimensions. In the model, overlap between two stimulus dimensions is presumed to produce conflict in the stimulus identification stage of processing when the dimensions are not consistent (e.g., a right pointing arrow to which participants were instructed to respond was presented in the left side of the computer screen). This overlap of the two stimulus dimensions will thus affect the time for stimulus identification, prior to the initiation of response selection. The inclusion of this additional kind of overlap resulted in a taxonomy that classifies tasks into eight categories (see Table 1).

Kornblum and his colleagues tested the dimensional overlap model using the task taxonomy to classify tasks in terms of their dimensional overlap properties in a series of studies (Kornblum, 1992; Kornblum & Lee, 1995; Kornblum, Stevens, Whipple, & Requin, 1999; Zhang & Kornblum, 1998). Many of their findings are generally consistent with the model. For example, Zhang and Kornblum used congruent and incongruent S-R mappings in their Experiment 1 and asked participants to respond to one of two types of words (color word or digit word) that was presented in the middle of the two irrelevant words. The irrelevant words were either from the same word type or different word type. Two response sets, color naming and digit naming, were combined with the two stimulus sets to form four different S-R ensembles (Types 2, 3, 4, and 8). Type 8 ensembles, as described by Kornblum and his colleagues, have dimensional overlap among the relevant stimulus dimension, the irrelevant stimulus dimension, and the response dimension. The other three ensembles each possess only one of the three types of dimensional overlap. Zhang and Kornblum developed an interactive activation network based on the dimensional overlap model that was able to fit the data for all four ensembles, treating the Types 2, 3, and 4 ensembles as interactive components of the Type 8 ensembles.

Several correspondence phenomena can be derived using the taxonomy to specify dimensional overlap, but there is a problem associated with the taxonomy. Although the dimensional overlap model assumes that perceptual, conceptual, and structural similarity have the same effect on processing (Kornblum & Lee, 1995), the taxonomy is based solely on conceptual similarity. Studies have shown that the Stroop color-naming task and the spatial Stroop task, in which there is conceptual overlap between the relevant stimulus dimension, the irrelevant stimulus dimension, and the response dimension (Type 8 ensembles), yield Stroop effects of different magnitudes as a function of whether the color word is defined as relevant or irrelevant. Typically, little or no Stroop effect is obtained when the color word, rather than the color, is named (MacLeod, 1991). Similarly, Lu and Proctor (2001) found that, with keypress responses, the effect of irrelevant arrow direction on responding to a relevant location word was larger than that of an irrelevant location word on responding to relevant arrow direction. Such asymmetric effects, where different magnitudes of S-R compatibility effects occur when the task relevance between two stimulus information dimensions is exchanged, are not predicted by the model when dimensional overlap is defined from the taxonomy, which was developed solely on basis of conceptual similarity. According to the taxonomy, the effect of irrelevant stimulus information should be the same for keypress and verbal response versions. That is because the concept to which the responses refer is conceptually similar in spatial codes (e.g., a left or right keypress versus “left” or “right” verbal response). However, asymmetric effects are obtained for the two different response modalities when the task relevance between two stimulus dimensions is exchanged.

Regardless of the problem associated with the taxonomy, the fundamental dual-route architecture of Kornblum et al.'s (1990) dimensional overlap model has been embraced by many authors in the S-R compatibility field (see Hommel & Prinz, 1997; Lu & Proctor, 1995, for reviews). Most current explanations of S-R compatibility effects have incorporated automatic response activation and intentional S-R translation as two response-selection routes. When a stimulus occurs, it may automatically activate its corresponding response, even if that response is not the one assigned to it for the task, but the activation tends to decay when the stimulus dimension that produces it is defined as irrelevant. Consequently, the correspondence effect produced by the irrelevant information will tend to decrease as responding is delayed. Intentional translation is presumed to occur on the basis of the mapping defined by task instructions. When the relation between stimuli and responses is systematic, translation can occur by application of a rule, rather than by means of the specific S-R association. There is evidence that the code or modality for stimuli and responses and the relative timing of the activations produced automatically and intentionally have strong impacts on the magnitude of the S-R compatibility effect. In sum, the studies of S-R compatibility in single tasks present a relatively coherent picture in which response selection is a consequence of response activation from a number of sources and is affected by variables such as timing and S-R modalities. The number and nature of these interactions likely are even more complex when two different tasks must be performed in close temporal proximity, as in the PRP paradigm.

Psychological Refractory Period Effects

As described in the Introduction, the most influential account for the PRP effect is Pashler's RSB model. Although various sources of evidence in the PRP studies strongly suggest that two tasks cannot be performed in parallel, the RSB model declared that only certain critical stages for both tasks cannot operate simultaneously (Pashler, 1984, 1989). Pashler took the suggestion that the PRP effect is a result of single-channel processing from Welford (1952, 1959) and argued that the stage of response selection, rather than of perception or motor execution, involves a bottleneck. In other words, there is a central bottleneck, where the stimuli are processed in a sequential manner, located at decision-related stages. In contrast, the processing prior or posterior to decision-related stages occurs in parallel for two tasks. The relationship between the processes of two tasks in a PRP paradigm proposed by the RSB model is illustrated in Figure 1. The model assumes that the slowing of RT2 at short SOAs in a PRP task occurs because the processing of response selection for T2 cannot start until the response selection for T1 has finished. That causes "slack" (Schweickert, 1978, 1980), or a delay, between the completion of perceptual processing of S2 and the beginning of the response-selection processing of T2. In contrast, when SOA increases, response selection for T1 may have been completed before response selection for T2 commences, and thus response selection for T2 can occur immediately upon the completion of the perceptual processing of S2 with less delay.

Schweickert (1978) derived predictions for the effects on RT of selectively influencing processes in tasks involving both sequential and concurrent processes.

Pashler considered predictions on the basis of the locus-of-slack logic for the RSB model in particular, and provided compelling evidence supporting the central bottleneck hypothesis (see 1994, 1998, for reviews). Four major predictions drawn from the RSB model involve effects of independent variables that influence the duration of either pre-bottleneck, post-bottleneck, or bottleneck processing for T1 and T2. The first of the four predictions is that if there is a bottleneck in response selection, then increasing the duration of that stage or a prior stage (e.g., perceptual) in T1 should increase RT2. Second, increasing the duration of post-bottleneck processing (e.g., response execution) in T1 will not increase RT2 because the response execution for T1 normally proceeds without interfering with the processing of T2.

The third prediction involves effects of independent variables that influence the duration of pre-bottleneck processing in T2. Increasing the perceptual processing of S2 by a certain amount of time may not slow RT2 at the short SOAs correspondingly. This is because the delay of response selection in T2 at short SOAs allows the extra perceptual processing time for S2 to be absorbed into the slack. Thus, there is a small effect on RT2. However, at long SOAs increasing the perceptual processing time in T2 will delay all the processing after it, without being absorbed into the slack. Therefore, the variables affecting the pre-bottleneck stage of T2, such as stimulus intensity and display size, will produce an underadditive interaction with SOA in which the effect decreases as SOA decreases. The final prediction from the RSB model is that any variables affecting primarily the response selection stage of T2 should have a constant effect on RT2 that is independent from SOA. In other words, manipulation of a variable affecting the response-selection stage of T2 will be subject to the bottleneck. Thus, increasing the processing time of response selection in T2 will increase RT2 correspondingly, without being absorbed into the slack. Therefore, variables affecting response-selection stage on T2 will have an additive effect with SOA.

According to the RSB model, the response-selection stage cannot operate simultaneously for the two tasks in a PRP paradigm, resulting in the delays of processing for T2 at the short SOAs. This hypothesis yields apparently straightforward predictions for the PRP effect. Evidence in support of the hypothesis comes from several literatures. Pashler and Johnston (1989) confirmed the predicted underadditive interaction with SOA of a perceptual variable on S2. In their Experiment 1, participants were asked to classify a tone as high or low pitch for T1 by making a keypress response with one hand; for T2 a single visual letter (A, B, or C) was identified by a keypress of the other hand. The visual intensity (or contrast) of the letters for T2, either white (high intensity) or gray (low intensity) against a dark background, was manipulated. The effect of S2 intensity was significantly larger at long SOAs than at short SOAs. This underadditive pattern of results is consistent with the RSB model, according to which the additional time to process a low intensity S2 could be absorbed into the slack at short SOAs. Underadditive interactions also have been obtained for other perceptual variables such as display size (De Jong, 1993; Pashler, 1984).

In addition to the intensity of S2, Pashler and Johnston (1989) also included a response-selection variable, repetition of S2, in their experiment. They obtained evidence consistent with the prediction of an additive effect of a response-selection variable with SOA: Repetition of S2 from the previous trial did not interact significantly with SOA. Pashler (1989) obtained additional evidence in support of the predicted additive effect with a different manipulation of response-selection difficulty. In his Experiments 3 and 4, T2 was to identify the highest digit in the display by making one of four keypress responses (difficult task) or vocal naming responses (easy task). The keypress and vocal responses both showed a substantial PRP effect. In addition, RT2 in the manual response condition was 150 ms constantly slower than the RT2 in the vocal naming condition across all SOAs.

In sum, the core idea of the RSB model is that there is a fixed structural bottleneck located at the response-selection stage. This hypothesis is able to account for the PRP effect because distinctive predictions can be drawn based on the processing stage on which variables have their effects.

Compatibility Manipulations in the PRP Effect

Ideomotor Compatibility

Greenwald and Shulman (1973) reported that the dual-task interference was eliminated when specific S-R sets, which they called ideomotor compatible tasks, were used for both tasks. They distinguished ideomotor compatibility from S-R compatibility and related S-R compatibility to the situation where the “natural or highly learned associations are involved” (p. 70) and ideomotor compatibility to the situation where the “stimulus resembles sensory feedback from the response” (p. 70). The roles of S-R compatibility and ideomotor compatibility in the PRP effect were examined in their experiment by manipulating the relations between stimuli and responses for both tasks. In Experiment 1, Greenwald and Shulman presented a pair of stimuli with 0-, 100-, 200-, 300-, 500- or 1,000-ms SOA presentation. For T1, a left or right movement of a switch was always made to visual stimuli, which could be either a word “left” or “right” or a left or right pointing arrow. For T2, a spoken letter name “A” or “B” or digit name “one” or “two” was always made to an auditory stimulus A or B. Four S-R combinations of T1 and T2 were used in the experiment. The conditions of movement responses to arrow directions and vocal responses “A” and “B” to auditory stimuli A and B were referred to as ideomotor compatible (IM) tasks, whereas the conditions of movement responses to words “left” and “right” and vocal responses “one” and “two” to auditory stimuli A and B were referred to as S-R compatible (SR) tasks (see Figure 2). The four S-R combinations (SR-SR, SR-IM, IM-SR, and IM-IM) were varied as a between-subject variable.

In their Experiment 1, Greenwald and Shulman (1973) obtained a PRP effect of 89 ms on RT2 in the IM-IM group, as well as over 100 ms of the effect in the other three groups. Assuming that participants might trade off processing capacity between T1 and T2, Greenwald and Shulman (1973) took the average of RT1 and RT2, rather than the RT2 alone, and examined it as a function of SOA. The results showed that a nonsignificant PRP effect of 18 ms was observed in the IM-IM group, whereas a significant PRP effect was observed for the other three groups. Greenwald and Shulman concluded that the dual-task interference was eliminated when both tasks were ideomotor compatible but obtained when one or both tasks were replaced by S-R compatible tasks.

The elimination of the PRP effect in Greenwald and Shulman’s (1973) study, according to them, suggested that the translation of the perceptual representation of the stimulus code to a response code, which usually is required prior to motor action, was not needed when ideomotor compatible tasks were used. In other words, there was no S-R translation in the processing of the ideomotor compatible task because the stimulus was identical to the response code. Because of bypassing the response-selection bottleneck, thus, the RSB model would predict no dual-task interference when an ideomotor compatible task is combined with a non-ideomotor compatible task in which the S-R translation is necessary. In other words, the PRP effect should be eliminated when one or both tasks in the PRP paradigm are ideomotor compatible tasks. Kantowitz and Knight (1976) challenged this hypothesis and demonstrated that interference could occur between an ideomotor compatible speech-shadowing task (e.g., saying the two-digit number that was just heard) and a non-ideomotor compatible manual tapping task, where the tapping rate was determined by a pacing signal and was maintained at a constant rate. The presence of the tapping task in their Experiment 1 interfered with the rate of ideomotor compatible speech compared to a non-tapping control condition. If the ideomotor compatible task requires no S-R translation, then the processing of the task itself should not be delayed by the non-ideomotor compatible task or disrupt the processing of response-selection for the non-ideomotor compatible task. No PRP effects should be found. However, this was not the case.

To test whether the ideomotor compatible speech interfered with tapping in a similar way, Klapp, Porter-Graham, and Hoifjeld (1991) conducted a similar experimental design to that of Kantowitz and Knight (1976) but that differed in the pacing method for the tapping task. Instead of using signal-paced tapping, they used self-paced tapping, where tapping was paced by the participant rather than by a stimulus. This method allowed the possibility of interference of digit naming with the tapping rate, which could not be observed if tapping was kept at a constant rate as in Kantowitz and Knight's study. Klapp et al.'s (1991) experiment showed not only the interference of tapping with the rate of digit naming but also of digit naming with the rate of tapping. That mutual interference in a dual-task paradigm occurred even when one of the tasks was ideomotor compatible presents an additional difficulty for both ideomotor theory and RSB model.

If the definition and classification of ideomotor compatibility proposed by Greenwald (1970a, 1970b, 1972) is correct, the contradiction between the results in Greenwald and Shulman's (1973) study and the other results described above may due to the nature of the tasks that were combined in the dual-task condition. When one of two tasks involved speech shadowing (saying what was just heard), the studies in which interference occurred involved continuous tasks (Kantowitz & Knight, 1976; Klapp et al., 1991), whereas the studies showing no interference involved discrete tasks (Greenwald, 1972; Greenwald & Shulman, 1973). Klapp et al. (1991) extended the notion of ideomotor compatibility to explain this discrepancy. They proposed that integration of two actions into one combined behavior is more likely for continuous responses and less likely for discrete responses that have no inherent temporal relation for each other.

Moreover, the studies of Greenwald and Shulman (1973) and Smith (1967) seem to show that the dual-task interference can be reduced when both tasks are S-R compatible but with the elimination of interference only when they are ideomotor compatible. The PRP effect was 35 ms for the two spatial visual-manual tasks in Smith's S-R compatibility study, whereas it was only 5 ms for the visual-manual and auditory-vocal tasks in Greenwald and Shulman's (1973) ideomotor experiment. However, the elimination of the PRP effect might not be due entirely to the type of tasks, either S-R compatible or ideomotor compatible, used in the experiment. Another possible explanation for this discrepancy is that the elimination of dual-task interference in Greenwald and Shulman’s study may be due to the fact that stimuli were presented in different modalities (visual and auditory) and responses were executed through different modes (manual and verbal). In all task combinations used in their study, stimulus and response modalities differed for the two tasks: T1 was always visual-manual response and T2 was auditory–vocal response. These two tasks were differentiated on a spatial versus language basis. The dual-task interference appeared when the auditory stimuli “A” and “B” were responded to with the vocal responses “one” and “two” but reduced when they were responded to with the vocal responses “A” and “B”. The reduction of dual-task interference was observed only when the within-task was of maximum compatibility as well as being low compatibility on linguistic and spatial grounds between-task, such as a vocal response “A” or “B” to a stimulus “A” or “B”, and a left or right movement to a left or right pointing arrow.

Clearly, the predictions drawn from the RSB model are on the basis of the processing timing for each task. The results from Smith’s (1967) and Greenwald and Shulman’s (1973) studies, however, suggest that not only the bottleneck determines which stages can be processed in serial or in parallel. Changing the nature or modalities of tasks will also affect the processing and influence the magnitude of the PRP effect. If no S-R translation is needed for the processing of an ideomotor compatible task, as Greenwald and Shulman suggested, then the existence of the PRP effect in the conditions where only one task is ideomotor compatible challenges the RSB model. It seems clear that the bottleneck is not the sole cause of the PRP effect. The properties of stimulus and response sets in the dual-task context will modulate the magnitude of the interference.

The question of how the ideomotor tasks in a PRP paradigm are processed and affect the response-selection bottleneck still remains. Further research seems to be required to systematically manipulate the nature and modalities of tasks to examine the effect on the PRP task.

Underadditive Interaction of S-R Mapping with SOA

The major prediction of the RSB model is that a response-selection variable of T2 should have an additive effect with SOA. However, this prediction is not supported by several studies in which T2 mapping, which is presumed to affect the response-selection, was manipulated in the PRP paradigm. For example, McCann and Johnston (1992) manipulated S-R mapping rules, either consistent or arbitrary, to alter the response-selection processing for T2, using randomly intermixed SOAs of 50, 150, 300, and 800 ms. In Experiment 1, T2 involved mapping six stimuli onto six responses: Three sizes of triangles and three sizes of circles were mapped onto the index, middle, and ring fingers of each hand, with one stimulus type mapped consistently and the other arbitrarily. For the consistent mapping, the sizes of stimuli corresponded to the positions of responding fingers. For the arbitrary mapping, the sizes of stimuli were randomly mapped to the positions of responding fingers. As predicted by the RSB model, the effect of mapping did not interact significantly with that of SOA. However, there was a nonsignificant tendency toward underadditivity, with the mapping effect being 72 ms at the 800-ms SOA and only 55 ms at the 50-ms SOA. Van Selst, Ruthruff, and Johnston (1999) found a similar nonsignifcant tendency toward underadditivity with their manipulation of ordered versus arbitrary mapping of four numerals and four letters to four response keys, both in sessions 1-3 (mapping effects of 232 ms at the longest SOA and 180 ms at the shortest) and sessions 27-36 (mappings effects of 25 ms at the longest SOA and 12.5 ms at the shortest).

McCann and Johnston's (1992) Experiment 2 also had two levels of mapping difficulty. In the "easy" condition, participants were to make a right response to an arrow pointing in the right direction or a left response to an arrow pointing in the left direction. In the "difficult" condition, participants were to respond left or right to the letter M or T. Letter and arrow stimuli were randomly intermixed; their locations were manipulated as irrelevant information and were either on the right or left side of the computer screen. Compared to the letter stimuli, the arrow stimuli have natural associations with the concept of right and left and should be more easily translated into left and right response codes. Responses were in fact slower for the letter task than for the arrow task, and this response-selection difficulty effect was additive with SOA, an outcome consistent with the RSB model.

Although McCann and Johnston (1992) obtained differences in RT between the easy and difficult mappings in their two experiments, neither of the compatibility variables they used can be classified as standard compatibility manipulations. In their Experiment 1, participants had to determine the hand for the R2 based on the shape that was presented and the specific finger to press on the basis of stimulus size, with the mapping of size to fingers being orderly for one hand (small to large sizes mapped left to right) and not for the other. This is a complex task in which it is unclear exactly how participants would go about performing response selection. The same argument holds for Van Selst et al.'s (1999) compatibility manipulation in which two sets of stimuli were mapped to responses, one in an ordered manner and one in an arbitrary manner. In

McCann and Johnston's Experiment 2, highly compatible arrow stimuli were intermixed with letter stimuli that had no dimensional overlap with the responses. Mixing different compatibility levels of mappings as in Experiment 2, as well as in their Experiment 1, is known to alter response-selection systematically relative to blocks of pure mappings and to reduce the benefit of compatible mappings (e.g., Ehrenstein & Proctor, 1998).

From the standpoint of the S-R compatibility literature, a more appropriate manipulation for evaluating whether T2 compatibility has additive or interactive effects with SOA is to have a direct, compatible mapping of spatial information for one condition and an incompatible mapping of that information for the other condition. Moreover, the compatible and incompatible mappings should not be mixed but should be varied between participants or between blocks of trials within participants. Lien and Proctor (2000) conducted two experiments similar to McCann and Johnston's (1992) Experiment 2 but that used only the arrow stimuli for T2 and had half of the participants perform with a compatible mapping and half with an incompatible mapping of the arrow directions to the responses. In both experiments, left and right keypress responses with a single hand were made to the arrows for T2. T1 was a manual response with the other hand to a high or low pitch tone in Experiment 2 and to the centered letter M or T in Experiment 3. Both experiments showed an overadditive interaction of compatibility and SOA, with the mapping effect being much larger at the 50-ms SOA (149 and 348 ms in Experiments 2 and 3, respectively) than at the 800-ms SOA (67 and 223 ms, respectively).

Two of the studies mentioned above also examined the effects of irrelevant location information on performance (i.e., the Simon effect). In McCann and Johnston's

(1992) Experiment 2, the letter and arrow stimuli for T2 could occur in a left or right location. The Simon effect, which has been assumed to affect response selection, showed an underadditive interaction of location correspondence with SOA across the letter and arrow stimuli (which were compatibly mapped to responses). In other words, the advantage of responding to T2 when the S2 and R2 locations corresponded than when they did not was eliminated at short SOAs. Lien and Proctor (2000) obtained a similar underadditive pattern of the normal Simon effect and SOA for the compatible arrow mapping, both when letter stimuli were intermixed as in McCann and Johnston's study and when they were not. One possible explanation for this underadditive interaction is that the response corresponding to S2 location is automatically activated when S2 occurs and then decays. In either study, the RSB model has difficulty to provide explanations for the underadditive interactions of compatibility of T2 with SOAs.

T1-T2 Crosstalk Effects

The major assumption of Pashler's (1984) RSB model, in terms of the timing of each processing component being activated, is that the response selection of T2 cannot go on in parallel with other processes that also require the bottleneck, such as the response selection of T1. However, data reported by Way and Gottsdanker (1968), although not collected for this purpose, showed that participants could process S2 to some extent while processing S1 at the short SOA, thus affecting the magnitude of RT1. To demonstrate that the variation in the PRP effect was due to the degree of difference between the two tasks, Way and Gottsdanker used a pair of two-direction choice tasks where participants were required to move a lever either toward or away from themselves with the left hand for T1 and the right hand for T2, according to which half of the upper surface of the lever was illuminated. The intervals between the presentation of the two signals were either 100 ms or 900 ms. Both responses required a compatible mapping of the stimulus to the associated response. In one display-control arrangement, the axes for the two tasks were parallel. In the other arrangement, the display-control axes for the two tasks were made perpendicular by rotating the second display-control axis 90° to reduce the spatial relatedness between the two tasks. Therefore, the response directions for T1 and T2 could be either the same (e.g., away for T1 and T2, or toward for T1 and T2) or opposite (e.g., away for T1 and toward for T2, or toward for T1 and away for T2) in parallel arrangement, and were unrelated (e.g., away for T1 and left for T2) in perpendicular arrangement. Their results showed that the PRP effect was not entirely eliminated in any of the conditions. Yet, the effect was largest when the response directions of the two tasks were opposite, intermediate when they were unrelated, and smallest when they were the same. Way and Gottsdanker concluded that the PRP effect is dependent on the response spatial relation between the two tasks rather than on the relatedness between the two tasks.

Another interesting finding in Way and Gottsdanker's (1968) experiment was that RT1 at the short interstimulus interval was noticeably longer for the opposite direction condition than for the same direction condition. Moreover, RT1 for the unrelated condition was very similar to that for the same direction condition. This suggests that the nature of T2 may affect RT1 under some situations. This disconcerting finding, from the RSB model perspective, is that the RT1 may increase if the direction of R1 movement has to be made in the opposite direction to that of R2. This implies that the information of S2 is processed to some extent to influence the ongoing course of T1 processing. Way and Gottsdanker argued that under some circumstances, at least, the response selection of T2 can proceed without waiting for the central processing of T1 to be completed. Therefore, RT1 may be affected by the information of S2 or selection of R2, which causes some problems for the RSB model that depicts the processing of two tasks in the PRP paradigm as non-interactive processing streams for which the decision-related stages of T2 cannot start until the corresponding stages in T1 are completed.

Hommel (1998) also presented evidence from a series of dual-task experiments that is inconsistent with the assumption of the RSB model that the response selection of T2 is not processed before the response selection of T1 is completed. Counter to this implication of the model, Hommel reported crosstask correspondence effects indicating a considerable interaction in the processing of the two tasks. In his Experiment 3, a red or green rectangle appeared on the center of the screen as S1. After an SOA of 50, 150, or 650 ms, S1 was replaced by the same color of a stimulus letter “H” or “S” which served as S2. Participants were asked to respond to the color of the rectangle by pressing a left or right key (R1) and to the letter identity by saying “red” or “green” (R2), depending on which letter was assigned to the “red” response and which to the “green” response. There was a correspondence relation between manual and vocal responses when the letter stimulus indicated the same color as that in the rectangular stimulus, whereas a noncorrespondence relation existed when the letter stimulus indicated the opposite color of that in the rectangular stimulus. As most PRP studies found, Hommel’s results showed approximately a 250-ms delay of RT2 at short SOA for the vocal task. The striking finding, however, is that the correspondence effect between R1 and R2 was larger not only for T2 but also for T1 at short SOAs and decreased for both tasks as SOA increased. The findings of R2-S1 and R2-R1 correspondence effect leads Hommel to conclude that the S-R translation for T2 is activated while S-R translation for T1 is activated.

Examination of crosstalk correspondence effects in Lien and Proctor's (2000) PRP study (see also Lien, Schweickert, & Proctor, 2001) indicated quite clearly that there was a considerable interaction of the spatial information sources from the two tasks that affected both RT1 and RT2 (see Table 2 for all possible information sources). In Experiments 2 and 3, T2 involved an arrow direction task (left or right direction in which the arrow pointed to), with T1 being identification of tone pitch in Experiment 2 and of a visual letter on the center of the screen in Experiment 3. The effect of irrelevant S2 location on RT2, the Simon effect, was also manipulated by presenting the arrow on either the left or right side of the screen. Manual keypresses were required for both tasks. Four SOAs, 50, 150, 300, and 800 ms, were used to vary the degree of processing overlap between the two tasks.

Of concern in Lien and Proctor's (2000) experiments were multiple crosstalk spatial correspondence effects, those of R2-R1 and S2-R1 on RT1, and of R1-R2 and S2-R2 on RT2. Results showed that RT2 was faster when the location of R1 corresponded with that of R2, particularly at short SOAs. In fact, at short SOAs the effect of R1-R2 correspondence on RT2 was even stronger than the Simon effect on RT2 produced by S2 location. Of particular interest are the spatial correspondence effects of R2-R1 on RT1. R2 location showed a positive correspondence effect on RT1 in which RT1 was faster when the location of R2 corresponded with that of R1. If the response selection of T2 does not start until the selection of R1 is completed, as depicted by the RSB model, the results in Lien and Proctor's study are inconsistent with the RSB model.

Logan and Schulkind (2000), on the other hand, examined the correspondence effects of the semantic category relation for two tasks in the PRP paradigm, rather than the R1-R2 location relation. In their Experiment 1, letter-digit category discrimination tasks were used for both T1 and T2 with S1 being presented above the fixation point and S2 below the fixation point. Manual left- or right-keypress response was made with the index and middle fingers of the left hand for one task and the index and middle fingers of the right hand for another task. Results showed overall category-match effects of 133 ms for RT1 and 217 ms for RT2. Responses were faster for both T1 and T2 when S1 and S2 were in the same category (both letters or both digits) than when they were in the different category (one digit and one letter). The category-match effects on RT1 found in this experiment suggest that the semantic category for T2 can be retrieved and activated prior to response selection for T1.

In sum, the finding of R1-R2 correspondence effects on RT1 in both Hommel's (1998) and Lien and Proctor's (2000) studies, and of S1-S2 category-match effects on RT1 in Logan and Schulkind's (2000) experiment, indicates that the response selection of T2 can occur in parallel with that for T1 to some extent when the two tasks overlap at short SOA.

Hommel's Two-Process Approach

According to the RSB model, the central processing of R2 is delayed during the response selection of T1 at short SOAs and should have no effect on RT1. However, the results in Way and Gottsdanker's (1968), Hommel's (1998), and Lien and Proctor's

(2000) studies imply that the decision-related processing of T2 is activated to some extent while still dealing with the response-selection of T1. Hommel argued that the S-R translation of T2 was not delayed until the response selection of T1 was completed, as the RSB model states. Instead, the S-R translations for both tasks could occur concurrently. Therefore, the correspondence relation between R1 and R2 affected not only RT2 but also RT1 at short SOAs. However, the response-selection processing of T1 might have been completed before the presentation of S2 at long SOAs. Thus, the correspondence effect decreased as SOA increased.

To reconcile the correspondence effect in dual-task performance without giving up the response-selection bottleneck view, Hommel (1998) proposed that S-R translation and final response selection are two distinct stages in the processing (see Figure 3). He argued that the process of S-R translation proceeds either automatically or intentionally and in parallel for T1 and T2, with the final response selection being made sequentially. In other words, the bottleneck is located after the S-R translation stage. Such a view of automatic activation of S-R translation has been supported by several studies (e.g., Marble & Proctor, 2000; Tagliabue, Zorzi, Umiltà, & Bassignani, 2000). For example, Proctor and Lu (1999) showed that after participants practiced for several hundred trials with an incompatible spatial mapping in a two-choice task, the Simon effect when color was relevant and location irrelevant on subsequent transfer trials was reversed such that responses were slower when the irrelevant stimulus location corresponded with the response than when it did not. The proposal that S-R translation occurs automatically before the bottleneck of final response selection in the performance of the PRP task is in contrast to the view, predominant in the RSB model, that response selection involves only intentional S-R translation.

The crosstalk effects found in Hommel's (1998) study, as well as others, suggest that the response activation can go on automatically and in parallel between two tasks. Hommel has argued that a distinction between response activation and final response selection is necessary, and that S2 can activate R2 before response selection for T1 is completed. His two-process account of response selection suggests that only the final response selection involves a bottleneck, either structural or strategic, and that evidence of such a bottleneck will be restricted to variables that affect this aspect of response selection and not those that affect response activation. Thus, this hypothesis predicts that the Simon effect on T2, where the S2 location is automatically activated and decays rapidly if it is irrelevant to the task, would be underadditive with the effect of SOA, as was found in studies of McCann and Johnston (1992) and of Lien and Proctor (2000). According to Hommel's approach, the decision-related processing of T2 can receive some degree of activation before the R1 is selected. It allows crosstalk between the two tasks, and the processing of T2 shows backward correspondence effects on RT1 at short SOAs.

Hommel's (1998) two-process hypothesis is generally consistent with crosstalk effects and the underadditive interaction of compatibility and SOA. However, even with the hypothesis of two distinct response-selection processes, the two-process approach would not be able to predict when the crosstalk takes place and how the various patterns of interaction of T2 mapping with SOA obtained if there is no deeper examination of the nature of within and between S-R sets. As Hommel states, "solving this problem requires information about the source of activation, hence the stimulus" (p. 1383). Therefore, examining the nature and properties of stimuli, as well as the responses within and between the tasks in the PRP paradigm, is important in providing a comprehensive understanding of dual-task performance.

Summary

Most current explanations of S-R compatibility effects incorporate two response-selection routes, automatic response activation and intentional S-R translation. When a stimulus occurs, it may automatically activate its corresponding response by way of natural associations or population stereotypes, even if that response is not the one assigned to it by the task instruction. This automatic activation appears to decay when the stimulus dimension that produces it is defined as irrelevant to the task, with the consequence that the correspondence effect produced by the irrelevant information will tend to decrease as responding is delayed. Intentional translation is presumed to occur on the basis of short-term associations of stimuli to responses defined by the task. When the relation between stimuli and responses is systematic, translation can occur by application of a rule, rather than by means of the specific S-R association. There is evidence that the code or modality for stimuli and responses and the relative timing of the activations produced automatically and intentionally have strong impacts on the magnitude of the S-R compatibility effect.

On the other hand, most PRP models consider response selection as a single processing component with the emphasis of whether the response-selection stage for both tasks is processed concurrently or sequentially. The RSB model assumes that two tasks in the PRP paradigm can be processed concurrently with the exception that response-selection processing is sequential. It predicts that a response-selection variable on T2 should show an additive effect with SOA and should have no influence on the response-selection processing for T1 since it does not occur after the completion of R1 selection. However, several studies that involved compatibility manipulations assumed to have their effects primarily on response selection have not obtained the additivity but an underadditive interaction with SOAs (e.g., Lien & Proctor, 2000; McCann and Johnston, 1992; Schumacher et al., 1999). In addition, a few findings showed that the response-selection of T2 can occur to some extent simultaneously with that of T1 and affect RT1 (e.g., Hommel, 1998; Way & Gottsdanker, 1968). These studies have been taken as strong evidence against the RSB model that considerable interaction can occur between the decision-related processing of two tasks.

In an attempt to account for the crosstalk effect and the underadditive interaction of mapping and SOA, Hommel's (1998) two-process approach assumes that S-R translation can be activated automatically and be distinct from the final response-decision processing. Such a model depicts that the S-R translation of T2 in the PRP paradigm can occur concurrently with that of T1 and that final response selection of T2 has to wait until response selection of T1 is finished. Therefore, it predicts that the mapping manipulation of T2, which primarily affects S-R translation, will have an underadditive interaction with SOA, as most studies have found. In addition, it allows the crosstalk in the translation processing of two tasks on the performance of the PRP task.

In general, S-R compatibility and PRP effects have been observed individually with various stimulus and response manipulations. There are relatively few studies that have examined compatibility effects in the PRP paradigm. One possible reason for the relative lack of studies on this topic may due to PRP researchers believing that the processing of two tasks in a rapid succession is related only in terms of the timing of each processing component. There are some important reasons, however, to question the generality of the compatibility effects in the PRP task. First, the PRP studies conducted by Hommel (1998) and Lien and Proctor (2000) revealed extensive interactions among the stimulus sets and response sets that have a strong impact on the performance of each task. Particularly, this effect of crosstalk or interaction on performance tends to increase when the temporal overlap between the two tasks is great. Such crosstalk among stimulus and response sets at short SOAs may affect the magnitude of compatibility effects in the PRP paradigm. Second, the S-R compatibility literature suggests that the processing of the compatibility manipulation may involve automatic response activation in addition to the intentional S-R translation. Treating the response-selection stage as a single processing component, as most PRP models do, is not appropriate for studying the compatibility effect in the PRP task. The two-process approach proposed by Hommel (1998) is an attempt to accommodate these assumptions. Although the two-process approach has been conceived on both theoretical and empirical grounds, it needs to be refined to be able to generate testable predictions for tasks of different nature. Tasks used in the PRP paradigm may differ in their demands and may produce different effects under different experimental conditions. Therefore, the primary goal of this study is to provide a detailed examination of how the crosstalk between two tasks affects the compatibility effect in the PRP task by systematically considering the nature of compatibility within and between tasks.

AN INTERACTIVE CONCEPTION OF THE PRP EFFECT

The Scope of the Conception

An interactive conception of the PRP effect is built on the basis of Hommel's (1998) two-processing approach, which assumes that response-selection processing should be treated as two distinct components: S-R translation and final response selection. The interactive conception of the PRP effect considers that S-R translation for both tasks can occur concurrently, that is, the processing of S-R translation for both tasks can begin simultaneously and end randomly. This assumption allows the processing of the current task to be influenced by the processing of the other task, both in the direction of T1 to T2 and of T2 to T1. Similar to Hommel's two-process approach, the interactive conception of the PRP effect assumes that the final response selection for two tasks can only be processed sequentially, that is, one final response selection immediately following another, with no overlap in processing. However, a more specific and unique assumption made by the proposed interactive conception is that the translation of stimulus codes to response codes for both tasks in the PRP paradigm is performed interactively in a single, unitary system. Although the stimulus information for both tasks can be activated simultaneously and can interact with each other, only certain information from the noncurrent task, not as general as that implied by Hommel's approach, will have a direct impact on processing of the current task.

Two major assumptions can be made from this interactive conception of the PRP effect. First, the information of each stimulus, both relevant and irrelevant, in the dual-task context provides an individual opportunity for its own response to be activated. Second, the information concerning the identity and selection of the response for the noncurrent task influences the current task, but only to the extent that an informative contingency exists between the two tasks. The response activation of the noncurrent task competes with the response activation of the current task. Separate decisions for each task are processed, with competition occurring among the activation of S-R translation from different sources of the two tasks. Particularly, only specific forms of information, and not all forms for the two tasks, are involved in the competition. This second assumption includes some crucial revisions that distinguish it from the Pashler's (1984) RSB model and Hommel's (1998) two-process approach.

Processing Mechanism

The processing of compatible tasks in the PRP paradigm is affected by two mechanisms in parallel: *Between-task crosstalk* and *noncurrent-task response association*. Between-task crosstalk refers to the fact that information of one task in the PRP paradigm can influence the other task from the processing of stimulus identification through the selection and initiation of responses. The second mechanism, the noncurrent-task response association, concerns the possible influence of the noncurrent-task response association on the processing of the current task. This bias has not been explored and studied in most PRP models. The interactive conception of the PRP effect incorporates the noncurrent-task response association mechanism to allow the noncurrent task to provide contingency information to the decision processing of the current task. The information can be used to bias response activation, either speeding or slowing the RT for the current task.

Most importantly, the possibility of interaction between two tasks in the PRP paradigm via between-task crosstalk or noncurrent-task response association is only relevant to the analysis of performance if the two tasks include an information contingency among the stimuli and responses. The contingency relation between two tasks is that any information concerning the processing of one task can occur in the other task or that the information in the two tasks is correlated (see Townsend & Thomas, 1994, for a detailed discussion). In other words, the two mechanisms of the interactive conception of the PRP effect contribute to performance only under conditions in which the necessary contingencies between two tasks are present. When there is no contingency-based information included in the experimental design, the mechanisms of between-task crosstalk and noncurrent-task response association will not be activated. In this case, the processing for T1 and T2 can be treated as two parallel streams, but with the modification of assuming the two response-selection components distinction. That is, the S-R translation for both tasks can be processed concurrently, but the final response selection for the two tasks must be processed sequentially.

The task contingency-based interaction is determined largely by three variables: (1) the dimensional overlap between the two tasks, (2) the strength of predictive relations between S1 and S2, and (3) the time elapsing between the availability of information from each task. The influence of natural or familiar associations between the two tasks in a PRP paradigm, between either stimuli, responses, or stimuli and responses, is usually attributed to the automatic processing that is acquired from population stereotypes or through long experience with the materials. For example, when T1 involves a manual left or right keypress in the direction to which a visual arrow points, there is contingency-based interaction when T2 requires a vocal "left" or "right" response to the verbal stimulus "left" or "right". The natural association or dimensional overlap of elements between the two tasks in the PRP paradigm usually facilitates performance when the elements of stimuli or responses of the tasks correspond (i.e., "left" information in T1 and "left" information in T2) and inhibits performance when they do not (i.e., "left" in T1 and "right" in T2).

The second factor influencing the task contingency-based effect is the strength of predictive relations between S1 and S2. In a typical PRP task design, the onset of S1 precedes the presentation of S2, and S1 can be treated as a cue for S2. Therefore, the facilitation or inhibition observed on the selection of R2 will increase with cue validity, which can be changed by varying the relative frequency with which specific elements of T1 are paired with one of the correct responses in T2. In other words, such association between T1 and R2 will speed or slow RT2, depending on whether it agrees or conflicts with the relevant S2 information on a given trial. For example, when the visual word "above" is more likely to be followed by the auditory word "right" than by the auditory word "left", responding will be faciliated in the former case and inhibited in the latter case because of participants' expectations.

The correlative or predictive information from S1 to S2 can be used to bias the response activation for selection of R2, thus affecting RT2. A similar assumption was made in Miller's (1987, 1991) single-task studies. Miller (1987) pointed out that coactivation from the simultaneously or closely presented stimuli, both relevant and irrelevant, could occur during speeded responses. To examine effects of an irrelevant stimulus (a flanker) that was not a target assigned to either response, Miller used neutral flanking letters that were not in the target letter set but manipulated the correlation between flanker and target (e.g., on 88% of the trials in which the flanker was “X”, the target was “A”, whereas on 12% of the trials in which the flanker was “X”, the target was “B”). RTs were strongly affected by the correlation between flanker and target, even though there was no similarity between them and the flankers were not potential targets. Miller concluded that the flanker could produce activation of the response corresponding to the letter to which it was associated, even though the flanker was not in the target set. In addition to the predictive information from S1 to S2, a similar cueing effect on RT2 can be found when there is correlative or predictive information between R1 and R2. On the whole, the contingency in the PRP paradigm is not necessarily defined as dimensional overlap between the two tasks but also can be task-defined association.

The third factor affecting the contingency in the PRP task is the time elapsing between the availability of information from each task. The time at which information from T1 and T2 sources becomes available is important because it limits the opportunity for one source to influence and be influenced by the other. In the PRP paradigm, the time-course of opportunity for influence is manipulated by varying the delay between the onset of S1 and the onset of S2, in other words, the SOA. There is some evidence showing that the correspondence effect in the PRP paradigm is larger at the short SOAs (e.g., Hommel, 1998; Lien & Proctor, 2000). The facilitation and inhibition of the contingency-based interaction on the two tasks can occur only when the noncurrent-task response association information is available before a response decision is made for the current task. Thus, the between-task crosstalk and noncurrent-task response association is more likely to occur when the temporal overlap of the processing between two tasks is large.

The interactive conception of the PRP effect is considered as an alternative to the traditional RSB model and as a complement to Hommel's (1998) two-process approach. It relaxes some of the traditional RSB model's assumptions while retaining the locus of response-selection bottleneck and the notion of separate decisions. It also refines the predictions of the two-process approach, while retaining the hypothesis that the processing of S-R translation for two tasks is in parallel and that of final response selection for two tasks is sequential. The interactive conception allows information extracted from multiple sources to be involved in activating a response for each task, but this integration occurs only when there is contingency information between the two tasks. The two mechanisms, *between-task crosstalk* and *noncurrent-task response association*, that have been incorporated into the interactive conception of the PRP effect not only differentiate it from the RSB model but also allow it to make unique predictions that Hommel's two-process approach does not.

Overview

In most PRP models, the response-selection stage is considered to be a single S-R translation processing stage and the locus of the bottleneck. Yet, there is ample evidence from the compatibility studies showing that there are two processing components involved in response selection: automatic response activation and response selection based on that activation. The interactive conception of the PRP effect incorporates the dual-route hypothesis of response selection and assumes that the S-R translation of T2, both automatic and intentional, can occur concurrently with the decision-related processing of T1. However, the final response selection of T2 has to wait until the final response decision of T1 is made.

According to the interactive conception, performance in the PRP task is affected by the between-task crosstalk and noncurrent-task response association mechanisms when certain types of contingency are present between two tasks. The studies of correspondence effects for the irrelevant stimulus information in single-task performance, in which the experimental design is similar to the PRP paradigm where no R1 is required, have revealed two types of contingency. One type of contingency occurs when there is dimensional overlap among stimuli and responses. Another type of contingency appears when there is a correlation between the two tasks, regardless of whether there is dimensional overlap among stimuli and responses. Therefore, either with or without R1 requirement, the interactive conception of the PRP effect predicts that performance of T2 in the PRP task will be facilitated or interfered with when there is dimensional overlap among stimuli or responses, or when there is a predictive relation between two tasks. Moreover, both types of contingency are affected by the time at which stimulus or response information sources from T1 and T2 become available, in other words, the SOAs. The longer the SOA between the onsets of two stimuli, the less the impact of between-task crosstalk and noncurrent-task response association on the processing of two tasks.

When the contingency is absent, the interactive conception will predict in a similar way as Pashler's (1984) RSB model does, but with the two response-selection components notion that S-R translation is processed in parallel and final response selection is processed sequentially for both tasks. Thus, when there is not a contingency relation between two tasks in the PRP paradigm, they can be treated as two noninteractive processing streams. The interactive conception of the PRP effect predicts that any variable affecting S-R translation of T2 should show an underadditive interaction with SOA, whereas variables affecting only the final response selection of T2 will have an additive effect with SOA.

EXPERIMENTS 1A and 1B

The purpose of Experiment 1 was to examine whether the interactive conception of the PRP effects can be treated as a simple two-process model, with the notion that the bottleneck is located in the final response selection, when there is no contingency between the two tasks. Similar to Hommel's (1998) two-process approach, the interactive conception assumes that the response activation of T2 can occur automatically and in parallel with that of T1 and that the final response selection for both tasks has to be processed sequentially. Although T2 can receive some degree of activation before R1 is selected, according to the interactive conception, the S-R translation of T2 will not affect the processing of T1 when there is no contingency relation. In addition, the interactive conception suggests that the PRP effect will not be eliminated even when both tasks are highly compatible because of the bottleneck of the final response selection.

To determine whether the processing of two tasks in the PRP paradigm can be treated as two noninteractive processing streams, as specified by the interactive conception, it is necessary to eliminate the contingency relation in the tasks. One way to exclude the contingency relation from the experimental design is to use stimuli and responses that have no dimensional overlap or correlational relation. The dual tasks used in Greenwald and Shulman's (1973) Experiment 1, visual-manual for T1 and verbal-vocal for T2, satify this restriction. In their experiments, T1 was a left/right joystick movement to the visual word LEFT/RIGHT (the SR condition) or the visual left-/right-pointing arrow (the IM condition), and T2 was a vocal response of A/B (the IM condition) or one/two (the SR condition) to the auditory stimuli A/B. Four groups of participants were assigned to one of the SR-SR, SR-IM, IM-SR, and IM-IM combinations. The SOAs were 0, 100, 200, 300, 500, and 1,000 ms in their Experiment 1 and 0, 100, 200, and 1,000 ms in Experiment 2. Greenwald and Shulman found virtually no PRP effect when the two tasks were highly ideomotor compatible (the IM-IM group). They suggested that the IM-IM tasks produced little PRP effect because they did not require the normal process of mapping arbitrary stimuli onto responses. They argued that in IM-IM condition, the stimuli generated a mental code that was already in the correct format to select the response. Therefore, no response-selection processing was necessary for this S-R mapping.

However, it is not clear from Greenwald and Shulman's (1973) interpretation how dual-task processing differs for each task combination and why the elimination of the PRP effect occurred only for the IM-IM condition and not for the conditions with one IM task. In Experiment 1A, I used a similar experimental design as that of Greenwald and Shulman's Experiment 1, but it differed in the instructions that were given to participants. In Greenwald and Shulman's Experiment 1, participants were told that S1 always would appear before S2 even in the simultaneous condition (the 0-ms SOA). However, in their Experiment 2, participants were told that two stimuli on each trial would be presented simultaneously most of the time. The results showed that the PRP effect was eliminated in Experiment 2 but not in Experiment 1. Greenwald and Shulman attributed the PRP effect obtained in Experiment 1 to the instruction they used. Thus, to avoid the possibility of PRP effects obtained artificially due to the instruction, the present experiment used the simultaneously instruction. The experimental design was similar to that of Greenwald and Shulman's Experiment 1, but the instruction in Greenwald and Shulman's Experiment 2 was adopted. Participants were told that most often the two stimuli on each trial were presented simultaneously, with no indication of which stimulus preceded the other. In addition, they were encouraged to respond to each task quickly, as well as accurately, without grouping the responses for the two tasks. Experiment 1B was similar to Experiment 1A and only differed in that keypress responses, instead of joystick movements, were used for T1. Comparison across Experiments 1A and 1B were conducted to provide further information on whether different PRP effects would be obtained for keypress and joystick movement responses. It was predicted that no difference would be evident on the basis of unbiased-contingency relations between T1 and T2 for both conditions because the joystick movements in Experiment 1A and the keypresses in Experiment 1B were spatial-manual responses.

In both experiments, RT2 was examined as a function of SOA for each task combination. If the ideomotor compatibility effect obtained in Greenwald and Shulman's (1973) study could be replicated, then the PRP effect should not be found for the IM-IM group but for the other three groups. Moreover, if their assumption that IM tasks bypass response selection is correct, the traditional RSB model would predict that no PRP effects should be obtained when one of the two tasks is IM compatible task because no delay of RT2 caused by the response-selection bottleneck. In contrast, the interactive conception predicts that the PRP effect should be evident for all four groups. That is because the final response decision for both tasks, the locus of the bottleneck, has to be made regardless of which tasks are used in the PRP paradigm. Moreover, the current interactive conception of the PRP effect can be treated as a simple, noninteractive two-process model under unbiased-contingency relations. In other words, the processing of two tasks can be considered as noninteractive but with the bottleneck in the final response-selection stage. Therefore, the interactive conception attributes the PRP effect obtained in the two tasks with unbiased-contingency relations to the final response-selection bottleneck.

Method of Experiment 1A

Participants

Forty undergraduate students enrolled in Introductory Psychology at Purdue University participated in partial fulfillment of course requirements. Their mean age was 20 years, with a range of 17 to 23 years. Ten participants were assigned randomly to each of the four dual-task combinations. All participants were required to have normal or corrected-to-normal vision.

Apparatus and stimuli

Stimulus presentation, timing, and data collection were controlled using IBM-compatible microcomputers driven by Micro Experimental Laboratory Version 2.0 (MEL 2.0) software (Schneider, 1995). T1 was either a visual word LEFT or RIGHT (the SR condition) or a visual left- or right-pointing arrow (the IM condition) presented on the center of the screen. Responses for T1 were made to the direction of visual stimuli by moving a joystick to the left or right with the dominant hand. T2 was an auditory stimulus A or B that was created by the MEL 2.0 program and was presented through a Labtec LVA8550 headset that had an attached microphone. The auditory stimuli were equated for rise times, amplitudes, and durations. Responses for T2 were made by saying "A" to A or "B" to B (the IM condition) or "one" to A and "two" to B (the SR condition) into the microphone, which was connected to the voice key of a MEL 2.0 standard serial response box.

The arrows were 1.4 cm in width and 0.8 cm in height. At a viewing distance of 55 cm, each arrow subtended a visual angle of 1.46° × 0.83°. The words LEFT and RIGHT were 1.8 cm and 2.3 cm in width, respectively, and 0.8 cm in height, and were presented in the same locations as the arrows. The words subtended a visual angle of approximately 1.87° x 0.83° for the word LEFT and 2.39° x 0.83° for the word RIGHT. All visual stimuli were presented in white on a black background monitor.

Design and procedure

The group of task combinations (SR-SR, SR-IM, IM-SR, and IM-IM) was a between-subjects variable. Each participant received 18 regular blocks of 20 trials each, and one practice block of 24 trials. The SOAs, which were constant within blocks, were varied over the 6 values of 0, 100, 200, 300, 500, and 1,000 ms, with onset of T1 always preceding onset of T2 except when the two tasks were simultaneous. Within each of 3 subsets of 6 blocks of trials, the six SOA conditions each appeared once, in a random order. Within each block, each of the four possible stimulus combinations appeared with equal probability (25% of the trials in each block), in a random order. For the visual words, the four stimulus combinations were LEFT with A, LEFT with B, RIGHT with A, and RIGHT with B. For the visual arrow, the combinations were a left-pointing arrow with A, a left-pointing arrow with B, a right-pointing arrow with A, and a right-pointing arrow with B.

The first trial in each block was initiated by the experimenter, who pressed the space bar of the keyboard, when a prompt instruction appeared on the screen. One-thousand ms after the experimenter pressed the space bar, the visual word or arrow (S1) was displayed on the center of the screen until the participant made the response, and then it disappeared. The auditory stimulus (S2) followed S1 after one of six SOAs and lasted for 1,000 ms. In T1, participants were instructed to hold the joystick by using their dominant hand. For the SR-SR and SR-IM groups, participants were asked to move the joystick to the left in response to the word LEFT and to the right in response to the word RIGHT. For the IM-IM and IM-SR groups, participants were asked to move the joystick to the left in response to a left-pointing arrow and to the right in response to a right-pointing arrow. In T2, participants were told to respond to the auditory letter A or B by saying “A” or “B”, respectively, for the IM-IM and SR-IM groups. For the SR-SR and IM-SR groups, participants were told to say “one” to the auditory letter A and “two” to the auditory letter B. The identity of each spoken response was entered into the computer by the experimenter, who pressed either the “1”, “2”, or “0” key on the computer keyboard for “A”, “B”, or “no response”, respectively, for the IM-IM and SR-IM groups, and for “one”, “two”, or “no response”, respectively, for the SR-SR and IM-SR groups. Feedback for incorrect responses, “Incorrect T1/T2 response”, was presented in the center of the screen for 1,000 ms. The following trial was presented 1,000 ms after the offset of the feedback message.

Participants were instructed that most often the two stimuli on each trial would be presented simultaneously and were not given any expectation about which stimulus appeared first. They were asked to respond to each stimulus as quickly and accurately as possible. Only correct trials with both RT1 and RT2 greater than 100 ms and less than 2,000 ms were included in the RT data. The proportion of errors for each task was determined without regard to whether the response for the other task was correct.

Results of Experiment 1A

The mean RT1 and RT2, as well as the average of RT1 and RT2, are shown in Figure 4, and proportion of errors (PEs) for each task (PE1 and PE2 for T1 and T2, respectively) is shown in Table 3. Each measure was analyzed as a function of T1 condition (SR and IM), T2 condition (SR and IM), and SOA (0, 100, 200, 300, 500, and 1,000 ms).

Task 1 RT and PE

The main effects of T1 condition and T2 condition were significant for RT1, $\underline{F}(1, 36) = 11.59$, $\underline{p} < .01$, $\underline{MSE} = 41{,}543$, and $\underline{F}(1, 36) = 8.75$, $\underline{p} < .01$, $\underline{MSE} = 41{,}543$, respectively, but their interaction was not, $\underline{F}(1, 36) = 2.16$, $\underline{p} > .05$, $\underline{MSE} = 41{,}543$. The mean RT1 was 90 ms faster when T1 was the IM task than when it was the SR task, and 78 ms faster when T2 was the IM task than when it was the SR task. The main effect of SOA was significant, $\underline{F}(5, 180) = 10.36$, $\underline{p} < .001$, $\underline{MSE} = 2{,}093$, as well as the interaction with T1 condition, $\underline{F}(5, 180) = 8.16$, $\underline{p} < .001$, $\underline{MSE} = 2{,}093$. The RT1 was faster at the shortest and longest SOAs (see Figure 4). In addition, the difference in RT1 between the SR and IM tasks was 110, 139, and 127 ms at the 0-, 100-, and 200-ms SOA and decreased to 71, 40, and 51 ms at the 300-, 500-, and 1,000-ms SOA. Individual analyses for each group showed a significant main effect of SOA for each, $\underline{F}s(5, 45) \geq 7.46$, $\underline{p}s \leq .0023$. Although there was no consistent pattern of RT1 across SOAs for each group, RT1 tended to be slower at the range of 100- to 500-ms SOA.

For the PE data, no effects were significant.

Task 2 RT and PE

Similar to RT1, the main effects of T1 condition and T2 condition were significant for RT2, F(1, 36) = 6.95, $p < .05$, MSE = 42,253, and F(1, 36) = 44.41, $p < .001$, MSE = 42,253, respectively, but their interaction was not, F(1, 36) = 1.75, $p > .05$, MSE = 42,253. The mean RT2 was 70 ms faster when T1 was the IM task than when it was the SR task, and 177 ms faster when T2 was the IM task than when it was the SR task. The main effect of SOA was significant, F(5, 180) = 81.28, $p < .001$, MSE = 1,697. RT2 was 170 ms slower when SOA decreased from 1,000 ms to 0 ms. This indicates that a sizable PRP effect was obtained. The interaction of SOA and T2 condition was significant, F(5, 180) = 3.07, $p < .05$, MSE = 1,697. The difference in RT2 between the SR and IM tasks was 188, 213, and 185 ms at the 0-, 100-, and 200-ms SOA and decreased to 153, 160, and 162 ms at the 300-, 500-, and 1,000-ms SOA. Another way to describe the interaction of SOA and T2 condition was that the PRP effect was 183 ms when T2 was SR task but 157 ms when T2 was IM task. Separate ANOVAs of RT2 for each group showed a significant main effect of SOA for the IM-IM group as well as the other three groups, Fs(5, 45) ≥ 12.21, ps < .001. The SOA effect reflects that PRP effects were evident for all groups. The PRP effects were 222, 149, 143, and 164 ms, for the SR-SR, SR-IM, IM-SR, and IM-IM groups, respectively.

The PE data for both tasks are shown in Table 3. The PE data for T2 showed significant main effects of T2 condition, F(1, 36) = 4.72, $p < .05$, MSE = 0.0045, and SOA, F(5, 180) = 2.42, $p < .05$, MSE = 0.0007. Participants committed fewer errors when T2 was the IM task than when it was the SR task (PEs = .03 and .05, respectively).

Moreover, the PE increased from .03 to .05 as SOA decreased from 1,000 ms to 0 ms. As in the RT2 data, T2 condition interacted significantly with SOA, F(5, 180) = 3.62, p < .0038, MSE = 0.0007, with the difference in PE between the SR and IM tasks being .042 at 0-ms SOA and decreasing to .008 at 1,000-ms SOA. Another way to describe the interaction was that the PRP effect in the PE data was .034 when T2 was the SR task but 0 when T2 was the IM task. Individual ANOVAs were carried out for each group. The PE data showed a significant main effect of SOA for the SR-SR group, F(5, 45) = 2.54, p < .05, MSE = 0.0009, and the IM-SR group, F(5, 45) = 2.69, p < .05, MSE = 0.0006, but not for the IM-IM and SR-IM groups, Fs < 1.0. The PRP effect was .03 for the SR-SR group, whereas it was .02 for the IM-SR group. This indicates that the PRP effect was evident for errors when T2 was the SR task but not when T2 was the IM task, regardless of whether T1 was IM or SR.

Average RT and PE

The averaged RT data showed significant main effects of T1 condition, F(1, 36) = 11.28, p < .01, MSE = 33,839, and T2 condition, F(1, 36) = 28.75, p < .001, MSE = 33,839, as well as their interactions with SOA, F(5, 180) = 8.22, p < .001, MSE = 1,017, and F(5, 180) = 3.14, p < .01, MSE = 1,017, respectively. The average RT was 80 ms faster when T1 was the IM task than when it was the SR task, and was 127 ms faster when T2 was the IM task than when it was the SR task. In addition, the difference RT between the SR and IM tasks in T1 was 94 ms and 115 ms at the two shortest SOAs and then decreased to 55 ms and 49 ms at the two longest SOAs. Similarly, when T2 was the SR task rather than the IM task, RT1 was 134 ms and 149 ms slower at the two shortest

SOAs; the difference of RT1 then decreased to 124 ms and 104 ms at the two longest SOAs.

The main effect of SOA was significant as well, F(5, 180) = 44.12, p < .001, MSE = 1,017, with the average RT being slower as SOA decreased. This indicates that the PRP effect was evident. Individual ANOVAs of average RT were carried out for each group. The main effect of SOA was significant for each group, Fs(4, 45) ≥ 7.46, ps < .001, indicating that they all showed a PRP effect. The PRP effect was 147, 90, 76, and 70 ms for SR-SR, SR-IM, IM-SR, and IM-IM groups, respectively.

For the PE data, the main effect of SOA, F(5, 180) = 2.68, p < .05, MSE = 0.0005, and its interaction with T2 condition, F(5, 180) = 2.87, p < .05, MSE = 0.0005, were significant. Participants committed more errors when SOA decreased (PEs = .026, .025, .029, .032, .034, and .04, for 1,000-, 500-, 300-, 200-, 100-, and 0-ms SOA). In addition, the difference in PE between the SR and IM tasks in T2 increased from .01 to .03 as SOA decreased from 1,000 ms to 0 ms. Another way to describe the interaction of SOA and T2 condition in PE was that the PRP effect was .025 when T2 was the SR task but only .004 when T2 was the IM task. Individual analyses for each group showed that the main effect of SOA was not significant for any group, with the F ratio being greater than 1.0 only for the SR-SR and IM-SR groups.

Methods of Experiment 1B

Participants

Forty undergraduates at Purdue University, ranging in age from 18 to 23 years, participated in this experiment for course credit. Ten participants were randomly assigned to each group. They all had normal or correct-to-normal vision and had not participated in Experiment 1A.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 1A, except as noted. The primary differences were that keypress responses were required for T1. The keypress response was made to the two outer buttons in the response box, which were 1 cm square and separated by 8 cm, center-to-center.

Results of Experiment 1B

The mean RT1 and RT2, as well as the average of RT1 and RT2, are shown in Figure 5, and PEs for each task are showed in Table 4. Each measure was analyzed as a function of T1 condition (SR and IM), T2 condition (SR and IM), and SOA (0, 100, 200, 300, 500, and 1,000 ms).

Task 1 RT and PE

There were main effects of T1 condition and T2 condition, $\underline{F}$s(1, 36) = 29.86 and 6.36, $\underline{p}$s < .001 and .0162, MSE = 10,083, respectively. RT1 was 71 ms faster when T1 was IM task than when it was SR task, and was 33 ms faster when T2 was IM task than when it was SR task. The main effect of SOA was significant as well, $\underline{F}(5, 180) = 6.36$, $\underline{p} < .001$, MSE = 1,723, with RT1 tending to decrease as SOA increased (see Figure 5). Although no interactions of SOA with T1 and T2 conditions were statistically significant, individual analyses for each group showed a significant main effect SOA only for the SR-SR and IM-IM groups, $\underline{F}(5, 45) = 3.93$, $\underline{p} < .01$, MSE = 2,539, and $\underline{F}(5, 45) = 4.49$, $\underline{p} < .01$, MSE = 842, respectively. The RT1 was faster at the longest SOAs than the other

SOAs for the SR-SR group, whereas the RT1 was faster at the shortest SOA than the other SOAs for the IM-IM group.

The PE data for T1 yielded only a significant main effect of SOA, F(5, 180) = 5.56, p < .001, MSE = 0.0005. The PE was a U-shaped function of SOA, being smallest at 200-ms SOA (see Table 4). The three-way interaction of T1 condition, T2 condition, and SOA was not significant, F < 1.0. An individual analyses for each group showed a main effect of SOA only for IM-IM group, F(4, 45) = 5.79, p < .001, MSE = 0.0003. Participants in the IM-IM group committed more errors on T1 at the shortest SOA (PE = .03 at 0-ms SOA).

Task 2 RT and PE

There were main effects of T1 condition, F(1, 36) = 4.66, p < .05, MSE = 60,829, and T2 condition, F(1, 36) = 21.61, p < .001, MSE = 60,829. RT2 was 68 ms faster when T1 was the IM task than when it was the SR task, and was 140 ms faster when T2 was the IM task than when it was the SR task. The main effect of SOA was significant as well, F(5, 180) = 94.98, p < .001, MSE = 1,807, with RT2 decreasing as SOA increased (see Figure 5). Thus, a 181-ms PRP effect was obtained. Moreover, the interaction of SOA and T1 condition was significant, F(5, 180) = 3.93, p < .01, MSE = 1,807, as well as the three-way interaction of these variables with T2 condition, F(5, 180) = 2.52, p < .05, MSE = 1,807. The difference in RT2 when T1 was SR and IM tasks was 89-ms and 103-ms at the 0- and 100-ms SOA and decreased to 32-ms at the 1,000-ms SOA. The three-way interaction of SOA, T1 condition, and T2 condition indicates that the magnitude of the PRP effect obtained in each group was different. Individual analyses for each group showed a significant main effect of SOA for all groups, Fs(4, 45) ≥ 15.59, ps < .0001.

The PRP effect was 237-, 181-, 168-, and 136-ms for the SR-SR, SR-IM, IM-SR, and IM-IM groups, respectively. Thus, although the PRP effect was smallest in the IM-IM group, it was evident for all groups.

For the PE data, the main effects of T2 condition, *F*(1, 36) = 13.15, *p* < .001, *MSE* = 0.0021, and SOA, *F*(1, 36) = 3.93, *p* < .05, *MSE* = 0.0004, as well as their interaction, *F*(1, 36) = 3.99, *p* < .05, *MSE* = 0.0004, were significant. Participants committed more errors on T2 when T2 was the SR task than when it was the IM task (*PE*s = .04 and .02, respectively). The PE tended to increase from .02 to .04 as SOA decreased from 1,000 ms to 0 ms. Moreover, the difference in PE between the SR and IM tasks in T2 tended to increase as well as SOA decreased. Individual analyses of each group showed a significant main effect of SOA for the SR-SR group, *F*(5, 45) = 2.56, *p* < .05, *MSE* = 0.0005, and the IM-SR group, *F*(5, 45) = 3.27, *p* < .05, *MSE* = 0.0005. In the SR-SR group, the PE for T2 was .06 at the shortest SOA and decreased to .04 at the longest SOA. Similarly, in the IM-SR group, the PE for T2 was .05 at the shortest SOA and decreased to .03 at the longest SOA. In contrast, the SOA effect was not significant for the SR-IM and IM-IM groups, *F*s(5, 45) ≤ 1.42, *p*s ≥ .2339. This result indicates that the PRP effect was evident in the PE data for the SR-SR and IM-SR groups but not for the SR-IM and IM-IM groups.

Average RT and PE

The analyses of the averaged data for RT1 and RT2 showed significant main effects of T1 condition, *F*(1, 36) = 13.45, *p* < .001, *MSE* = 21,733, and T2 condition, *F*(1, 36) = 22.54, *p* < .001, *MSE* = 21,733, as well as their interactions with SOA, *F*(5, 180) = 5.88, *p* < .001, *MSE* = 839, and *F*(5, 180) = 3.48, *p* < .005, *MSE* = 839, respectively. The average RT was 70 ms faster when T1 was the IM task than when it was the SR task, and 90 ms faster when T2 was the IM task than when it was the SR task. In addition, the difference in RT between the SR and IM tasks in T1 was 85, 96, and 85 ms at the 0-, 100-, and 200-ms SOA and then decreased to 64, 46, and 43 ms at the 300-, 500-, and 1,000-ms SOA, respectively. Similarly, the difference RT between the SR and IM tasks in T2 tended to increase as SOA decreased (the difference RTs = 79, 80, 74, 87, 103, and 119 ms, for 1,000-, 500-, 300-, 200-, 100-, and 0-ms SOA, respectively).

The main effect of SOA was significant as well, $\underline{F}(5, 180) = 64.93$, $\underline{p} < .001$, $\underline{MSE} = 839$, with the average RT being slower as SOA decreased (see Figure 5). A 100-ms PRP effect was obtained across all groups in the average RT. More importantly, the three-way interaction of SOA, T1 condition, and T2 condition was significant, $\underline{F}(5, 180) = 2.3$, $\underline{p} < .05$, $\underline{MSE} = 839$. This indicates the pattern of SOA effect on average RT was different across the groups. Individual ANOVAs were carried out for each group. The main effect of SOA was significant for all groups, $\underline{F}s(5, 45) \geq 8.1$, $\underline{p}s < .001$, indicating that the PRP effect appeared for each group. However, the size of PRP effect was only 64 ms for the IM-IM group, but was 145, 97, and 95 ms for the SR-SR, SR-IM, and IM-SR groups.

For the PE data, the main effects of T2 condition, $\underline{F}(1, 36) = 5.83$, $\underline{p} < .05$, $\underline{MSE} = 0.0019$, and SOA, $\underline{F}(5, 180) = 4.6$, $\underline{p} < .001$, $\underline{MSE} = 0.0003$, were significant. The PE was smaller when T2 was the IM task (.03) than when it was the SR task (.04). Moreover, participants committed more errors when SOA decreased (PEs = .029, .027, .031, .027, .032, and .043, for 1,000-, 500-, 300-, 200-, 100-, and 0-ms SOA). Individual analyses for each group showed that the main effect of SOA was significant only for the

IM-IM group, F(5, 45) = 2.83, p < .05, MSE = 0.0002, and the IM-SR group, F(5, 45) = 2.65, p < .05, MSE = 0.0003, the two groups who showed that smallest PRP effects in the RT2 data (see Table 4). The PE was .03 at the 0-ms SOA and decreased to .02 at the 1,000-ms SOA in the IM-IM group whereas the PE was .05 at the 0-ms SOA and decreased to .03 at the 1,000-ms SOA in the IM-SR groups.

Comparison Between Experiments 1A and 1B

Task 1 RT and PE

The main difference between Experiments 1A and 1B was that keypress responses, instead of joystick movements, were used for T1. Data analyses including experiment as a variable were conducted to examine whether the patterns of RTs and PEs obtained in Experiment 1B were similar to those in Experiment 1A. Because the variable of experiment was the major concern in this particular data analysis, only the results that involved experiment are reported here. For RT1, there was a main effect of experiment, F(1, 72) = 83.55, p < .001, MSE = 25,813. The overall RT1 was 134 ms slower in Experiment 1A than in Experiment 1B. The three-way interaction of Experiment × T1 condition × T2 condition, F(1, 72) = 1.69, p > .05, MSE = 25,813, and the four-way interaction of these variables with SOA, F(5, 360) = 0.15, p > .05, MSE = 1,908, were not significant. Individual analyses for each task combination showed no interaction of Experiment × SOA, with only the F ratio in the IM-SR condition being greater than 1.0. The RT1 for each task combination, as well as their function with SOA, was not different across experiments.

As in RT1, the PE data showed only a significant main effect of experiment, F(1, 72) = 4.59, p < .05, MSE = 0.0025, with the PE being .01 lower in Experiment 1B than in

Experiment 1A. Individual analyses for each task combination showed no significant interaction of experiment and SOA, with the F ratio being greater than 1.0 only for the SR-IM and IM-IM conditions. The PE in Task 1 for each task combination showed a similar pattern across SOA for both experiments.

Task 2 RT and PE

No main effect or interaction of experiment with other variables was found on RT2, which indicates that there was no difference between Experiments 1A and 1B. Individual analyses for each task combination also showed no effect of experiment with SOA, with the F ratio being greater than 1.0 for the SR-IM and IM-IM conditions. Thus, the PRP effect for each task combination was similar for both experiments.

No effect relative to experiment was significant in the PE data.

Average RT and PE

The main effect of experiment was significant in the average RT data, $F(1, 72) = 19.37$, $p < .001$, $MSE = 27{,}786$, with the RT being 67 ms slower in Experiment 1A than in Experiment 1B. The interaction of experiment and SOA was not significant for each task combination, with the F ratio being greater than 1.0 only for the IM-IM and IM-SR conditions. The PRP effect obtained with average RT in each task combination did not differ for both experiments.

No effect associated with the variable of Experiment was significant in the PE data.

Discussion

In Greenwald and Shulman's (1973) Experiment 1, six different SOAs were used and instructions indicated that S2 always follows S1. In the IM-IM condition, they found a significant PRP effect of 89 ms when RT2 was considered alone but a nonsignificant

PRP effect of 18 ms when the average of RT1 and RT2 was analyzed. In their Experiment 2, only the three shortest SOAs and the longest SOA were used, and participants were instructed that most often S1 and S2 would be presented simultaneously. They found virtually no PRP effect for the IM-IM condition either when RT2 was concerned alone or when the average of RT1 and RT2 was considered (a PRP effect of –4 ms and –12 ms, respectively).

The results of Experiment 1A, which used a left/right movement with the dominant hand, as in Greenwald and Shulman's (1973) study, and the instructions they used in their Experiment 2, showed that a significant PRP effect was obtained for the SR-SR, SR-IM, and IM-SR groups, with the largest PRP effect being in the SR-SR group when both RT2 alone and the average of RT1 and RT2 were analyzed. In addition, for the SR-IM and IM-SR groups, PRP effects for RT2 of 149 and 143 ms, respectively, and for the average of RT1 and RT2 of 90 ms and 76 ms, were observed. These results are in agreement with those obtained in Greenwald and Shulman's Experiments 1 and 2. However, the results in our Experiment 1A showed a significant PRP effect of 164 ms for RT2 alone and 70 ms for the average of RTs in the IM-IM group. This outcome is in contrast with the absence of a PRP effect in Greenwald and Shulman's Experiment 2, which used similar instructions indicating that most often the two stimuli would occur simultaneously and used a left/right movement response for T1. The results for the IM-IM group are in closer agreement with the findings of Greenwald and Shulman's Experiment 1, which showed a PRP effect using the instructions that S1 would always follow S2.

The major methodological difference of Experiment 1B from Experiment 1A was that left/right keypress responses, rather than left/right movements, were used for T1. Similar to Experiment 1A, the results in Experiment 1B showed that the PRP effect was obtained in the SR-SR, SR-IM, and IM-SR groups, both for RT2 alone and the average of RT1 and RT2. The IM-IM group also showed a significant PRP effect of 137 ms for RT2 alone and 64 ms for the average of RT1 and RT2. The elimination of the PRP effect in Greenwald and Shulman's IM-IM group was not replicated in a left/right keypress response version.

The results of comparisons across Experiments 1A and 1B indicate that left/right movements are just as compatible with left/right arrow directions as are left/right keypress responses. The elimination of the PRP effect in Greenwald and Shulman's (1973, Experiment 2) IM-IM condition cannot be replicated in the closer replication of joystick movement version in Experiment 1A and of keypress response version in Experiment 1B. Although the overall RT1 was slower for the joystick movements than the keypresses (which may have been solely due to the longer distance required to move the joystick before a response was registered), similar PRP effects were obtained for the two response modes. This finding suggests that the two response modes are of similar compatibility with the arrow-direction stimuli and is consistent with other compatibility studies in which keypress responses have produced at least as large spatial compatibility effects as left/right aimed movements to one of two target locations (Proctor & Wang, 1997; Wang & Proctor, 1996), and as left-/right-hand joystick movements (Michaels, 1998; Proctor, Van Zandt, Lu, & Weeks, 1993).

Ideomotor compatibility theory assumes that the ideomotor compatible task does not require the normal processing of mapping stimuli onto responses, in other words, no S-R translation processing. If this assumption is true, then according to the traditional RSB model of a single response-selection stage, the PRP effect should be eliminated in the IM-IM condition, as well as in the IM-SR and SR-IM conditions, because of there should be no delay due to a response-selection bottleneck on T2. However, the interactive conception argues that S-R translation processing is a separate stage from the final response-selection stage. The S-R translation of T1 and T2 can be processed concurrently, whereas the final response selection for both tasks has to be performed sequentially. When there is no contingency relation between two tasks in the PRP paradigm, the processing of the tasks can be treated as two individual, noninteractive processing streams, but with the notion that the final response decision of T2 is not made until the final response decision of T1 is completed. Although the IM task can facilitate the processing of S-R translation, the final response decision for both tasks has to be made sequentially, regardless of whether the task is IM or SR. Thus, the PRP effect should be obtained in all task combinations, as found in Experiments 1A and 1B. Additionally, the comparison of results in Experiments 1A and 1B showed that a similar compatibility pattern in the joystick movement responses could be obtained with manual keypress responses. The elimination of the PRP effect was not obtained in the IM-IM condition when keypress responses for T1 were used.

EXPERIMENT 2

The purpose of Experiment 2 is to take a further step in examining the finding of the PRP effect in Experiments 1A and 1B, which used Greenwald and Shulman's (1973) ideomotor compatible tasks containing no contingency relations. In their Experiment 2, Greenwald and Shulman found no PRP effect when the two tasks were ideomotor compatible. In contrast, the interactive conception of the PRP effect predicts that the PRP effect should be evident, as it was in Experiments 1A and 1B, even when there is no contingency relation between two tasks. The effect is predicted because the final response decision of T2 cannot be made until the final response decision of T1 is completed, thus, delaying RT2.

Both Experiments 1A and 1B used the instructions of Greenwald and Shulman's (1973) Experiment 2, which they argued were crucial to eliminate the PRP effect in the IM-IM group. However, the results of these two experiments showed PRP effects for all groups. Particularly, the results in the IM-IM group showed that the PRP effect was 164 ms for RT2 alone and 71 ms for the average of RT1 and RT2 in Experiment 1A and 137 ms for RT2 alone and 64 ms for the average of RT1 and RT2 in Experiment 1B. Thus, the elimination of the PRP effect in Experiment 2 of Greenwald and Shulman's study was apparently not due directly to the use of "simultaneous" instructions, as they suggested.

One possible reason why the PRP effect was eliminated in Greenwald and Shulman's (1973) Experiment 2 but not in Experiments 1A and 1B is the SOAs used.

Although Greenwald and Shulman emphasized the difference in instructions between their Experiments 1 and 2, they not only adopted the simultaneous instructions in Experiment 2 but also removed the 300- and 500-ms SOAs “in order to appear consistent with these instructions” (p. 73). Thus, the elimination of the PRP effect in their Experiment 2 could be a consequence of the modification of the SOAs used, either alone or in conjunction with the instruction change.

Because Experiments 1A and 1B showed a large PRP effect with the simultaneous instructions, the aim of Experiment 2, therefore, was to examine whether the PRP effect could be eliminated with the four SOAs used in Greenwald and Shulman’s Experiment 2. Thus, Experiment 2 used a similar experimental design to that of Experiment 1A, but with only the three shortest SOAs (0, 100, 200 ms) and the longest SOA (1,000 ms) used. If the ideomotor compatibility effect obtained in Greenwald and Shulman’s (1973) study can be replicated, then the PRP effect should not be found in the IM-IM group but should be found in the other three groups. However, the traditional RSB model of a single response-selection stage, which is the locus of the bottleneck, would predict that no PRP effects should be obtained in the IM-IM as well as the IM-SR and SR-IM groups. That is because when one or both tasks are ideomotor compatible, the response-selection processing is bypassed for the ideomotor compatible task and thus should produce no delay of RT2. In contrast, the interactive conception predicts that the PRP effect should be evident for all four groups because the final response decision for both tasks, the locus of the bottleneck, has to be made regardless of what tasks are used in the PRP paradigm.

Method

Participants

Fifty-two undergraduates at Purdue University, ranging in age from 17 to 45 years, participated in this experiment for course credit. Thirteen participants were randomly assigned to each group. They all had normal or correct-to-normal vision and had not participated in Experiments 1A and 1B.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 1A, but with the primary difference that only the 0-, 100-, 200-, and 1,000-ms SOAs were used in this experiment. The number of trials per block and the number of blocks per SOA remained the same as in Experiment 1A, meaning that the total number of blocks was reduced from 18 to 12.

Results

Task 1 RT and PE

The individual RTs and the average of RT1 and RT2 for T1 and T2 are shown in Figure 6. The main effects of T1 condition and T2 condition were significant for RT1, $F(1, 48) = 14.03$, $p < .001$, $MSE = 26{,}000$, and $F(1, 48) = 6.67$, $p < .05$, $MSE = 26{,}000$, respectively, but their interaction was not, $F(1, 48) = 1.44$, $p > .05$, $MSE = 26{,}000$. RT1 was 83 ms faster when T1 was the IM task than when it was the SR task, and 57 ms faster when T2 was the IM task than when it was the SR task. The main effect of SOA was significant, $F(3, 144) = 45.86$, $p < .001$, $MSE = 1{,}570$, as well as the interaction with T2 condition, $F(3, 144) = 4.37$, $p < .05$, $MSE = 1{,}570$. RT1 was faster at the shortest SOAs and the longest SOAs than at the two intermediate SOAs (RT1 = 555, 585, 610, and 524 ms for 0-, 100-, 200-, and 1,000-ms SOAs). Moreover, RT1 was 65, 77, and 65 ms slower when T2 was SR task than when it was IM task at the 0-, 100-, and 200-ms SOA but only 25 ms slower at the 1,000-ms SOA. Individual analyses were carried out for each group. The results showed a significant main effect of SOA for each group, Fs(3, 36) ≥ 7.22, ps ≤ .001, with RT1 being faster at the shortest and longest SOAs than the other two intermediate SOAs.

The PE data for both tasks are shown in Table 5. The PE data for T1 showed that the main effect of SOA was significant, F(3, 144) = 3.35, p < .05, MSE = 0.0006. The error rate was .03 for 100-, 200-, and 1,000-ms SOAs but was .04 for 0-ms SOA. No other effects were found.

Task 2 RT and PE

Similar to RT1, the main effects of T1 condition and T2 condition were significant for RT2, F(1, 48) = 8.37, p < .05, MSE = 77,139, and F(1, 48) = 21.99, p < .001, MSE = 77,139, respectively, but their interaction was not, F < 1.0. The mean RT2 was 111 ms faster when T1 was the IM task than when it was the SR task, and 181 ms faster when T2 was the IM task than when it was the SR task. The main effect of SOA was significant, F(3, 144) = 89.47, p < .001, MSE = 3,068. RT2 was 168 ms slower when SOA decreased from 1,000 ms to 0 ms. This indicates that a sizable PRP effect was obtained. The interaction of SOA and T1 condition was significant, F(3, 144) = 19.61, p < .001, MSE = 3,068. The difference in RT2 between the SR and IM tasks was 158, 137, and 140 ms at the 0-, 100-, and 200-ms SOA and decreased to only 10 ms at the 1,000-ms SOA. Separate ANOVAs of RT2 for each group showed a significant main effect of SOA for the IM-IM group, as well as the other three groups, Fs(3, 36) ≥ 12.67,

ps < .001. The PRP effects were 271, 213, 104, and 85 ms, for the SR-SR, SR-IM, IM-SR, and IM-IM groups, respectively.

The PE data showed a significant main effect of SOA, $F(3, 144) = 3.14$, $p < .05$, $MSE = 0.0008$, with the error rate being .04 for 100- and 1,000-ms SOAs and .05 for 0- and 200-ms SOAs (see Table 5). The individual ANOVA was carried out for each group. The PE data showed a significant main effect of SOA for the SR-IM group, $F(3, 36) = 3.08$, $p < .05$, $MSE = 0.0007$, but not for the other three groups, Fs < 1.0. In the SR-IM group, the PE for T2 was .05, .03, .03, and .06 for 0-, 100-, 200-, and 1,000-ms SOAs. No other effects were found.

Average RT and PE

The analyses of the averaged RT1 and RT2 showed significant main effects of T1 condition, $F(1, 48) = 12.72$, $p < .001$, $MSE = 38{,}933$, and T2 condition, $F(1, 48) = 18.97$, $p < .001$, $MSE = 38{,}933$, as well as their interactions with SOA, $F(3, 144) = 16.40$, $p < .001$, $MSE = 1{,}152$, and $F(3, 144) = 6.30$, $p < .001$, $MSE = 1{,}152$, respectively. The average RT was 98 ms faster when T1 was the IM task than when it was the SR task, and was 120 ms faster when T2 was the IM task than when it was the SR task. In addition, the difference in RT between the SR and IM tasks in T1 was 129, 110, and 109 ms at the three shortest SOAs and then decreased to only 42 ms at the longest SOA. Similarly, the difference in average RT between the SR and IM tasks in T2 was 125, 141, 125 ms at the three shortest SOAs; it then decreased to 86 ms at the longest SOA. In other words, the PRP effect was 119 ms when T2 was the SR task and was 80 ms when T2 was the IM task. The three-way interaction of T1 condition, T2 condition, and SOA was not significant, $F(3, 144) = 1.54$, $p = .2060$, $MSE = 1{,}152$.

The main effect of SOA was significant as well, F(3, 144) = 104.47, p < .001, MSE = 1,152, with the average RT being 99 slower as SOA decreased from 1,000-ms SOA to 0-ms SOA (see Figure 6). This indicates that the PRP effect existed in these dual-task conditions. Individual ANOVAs indicated that the main effect of SOA was significant for each group, Fs(3, 36) ≥ 17.59, ps < .001, indicating that the PRP effect appeared for each group. The PRP effect on the average RT was 176, 109, 62, and 50 ms for SR-SR, SR-IM, IM-SR, and IM-IM groups.

For the PE data, the main effect of SOA, F(3, 144) = 3.42, p < .05, MSE = 0.0006, was significant, with the error rate being higher at 0- and 200-ms SOAs than at 100- and 1,000-ms SOAs (PEs = .044, .034, .042, and .031, for 0-, 100-, 200-, and 1,000-ms SOA). Individual analyses for each group showed that the main effect of SOA was not significant for any group, Fs(3, 36) ≤ 2.82, ps > .05.

Discussion

The results of Experiment 2, in which only the three shortest SOAs and one longest SOA from Experiment 1A were used, as in Greenwald and Shulman's (1973) Experiment 2, showed a significant PRP effect in all groups, with the effect being largest in the SR-SR group, intermediate in the SR-IM and IM-SR groups, and smallest in the IM-IM group. Although the size of the PRP effect in the IM-IM group was reduced relative to Experiments 1A and 1B, it was still substantial (85 ms for RT2 alone and 50 ms for the average of RT1 and RT2).

Because the SOAs, as well as the instructions, were the same as those used in Greenwald and Shulman's (1973) Experiment 2, the elimination of the PRP effect for the IM-IM group in their Experiment 2 apparently cannot be attributed to either the simultaneous instructions or the specific SOAs used. Instead, the results in the present Experiment 2 are consistent with the predictions of the interactive conception model of the PRP effect, which assumes that the delay of RT2 should be evident when the final response decisions have to be made for both tasks, even when there was no contingency relation between them.

Of the experiments that have been reported in which two ideomotor compatible tasks were performed together in the PRP paradigm, only Greenwald and Shulman's (1973) Experiment 2 showed no PRP effect. The outcome was not replicated in their Experiment 1, nor in the current Experiments 1 and 2 that used the same instructions and closely approximated Greenwald and Shulman's experimental designs. In addition, a substantial PRP effect also was obtained for two ideomotor compatible tasks in Brebner's (1977) study in which participants were required to press a button with the finger that was stimulated by upward pressure from a solenoid located underneath it. Not only is the PRP effect evident when both tasks are ideomotor compatible, but it also appears when only one task is. If the PRP effect has its basis in response selection, then the assumption that ideomotor compatible tasks bypass response selection is not supported by any evidence. In sum, it is simply incorrect to state that the PRP effect is eliminated when two tasks are ideomotor compatible. As predicted by the interactive conception, a residual PRP effect is still observed even when both tasks are highly compatible and there is no contingency relation.

EXPERIMENT 3

According to the interactive conception of the PRP effect, the final response-selection bottleneck is the cause of the delay on RT2 when there is no contingency relation between the two tasks. This approach predicts that when there is no contingency, the PRP effect should be eliminated when R1 is not required. Several comprehensive reviews on the PRP effect also indicate that both RT1 and RT2 were affected by the interaction of response tendencies aroused by two closely presented stimuli (e.g., Herman & Kantowitz, 1970; Kantowitz, 1974). Thus, no PRP effect on T2 should be evident when no response is required for T1 in the condition in which no contingency existed between the two tasks. In the present experiment, a similar design as the previous Experiment 2 was used, with the difference that no R1 was required. The interactive conception of the PRP effect predicts that no PRP effect should be found when R1 was not required in the task because there was no contingency relation between two tasks.

Method

Participants

Forty undergraduates at Purdue University participated in this experiment for course credit. Ten participants were randomly assigned to only one of four task-combination groups (SR-SR, SR-IM, IM-IM, or IM-SR group). They all were required to have not participated in previous experiments.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 1B, excepted as noted. Participants were instructed to respond to S2 only, by saying "A" to A or "B" to B into the microphone for the IM-IM and SR-IM conditions and "one" to A or "two" to B for the SR-SR and IM-SR conditions.

Results

Task 2 RT and PE

The RT2 and PE2, shown in Table 6, were analyzed as a function of T1 condition, T2 condition, and SOA. The main effect of T2 condition was significant for RT2, $\underline{F}(1, 36) = 6.77$, $\underline{p} < .05$, $\underline{MSE} = 35{,}633$. RT2 was 78 ms faster when T2 was the IM task than when it was the SR task. The main effect of SOA was significant as well, $\underline{F}(3, 108) = 8.19$, $\underline{p} < .001$, $\underline{MSE} = 657$. Different from the typical PRP effect, RT2 was slowest at the longest SOA, intermediate at the shortest SOA, and fastest at the two intermediate SOAs (RT2 = 567, 555, 552, and 577 ms for 0-, 100-, 200-, and 1,000-ms SOA). Separate ANOVAs of RT2 for each group showed a significant main effect of SOA for the IM-IM group, $\underline{F}(3, 27) = 5.51$, $\underline{p} < .05$, $\underline{MSE} = 598$, and the IM-SR group, $\underline{F}(3, 27) = 4.23$, $\underline{p} < .05$, $\underline{MSE} = 603$. The SOA effect in the IM-IM group did not show a normal PRP effect. Instead, the RT2 was 26 ms longer at the longest SOA than the shortest SOA (RT2 = 513, 501, 500, and 539 ms for 0-, 100-, 200-, and 1,000-ms SOA). In addition, the RT2 in the IM-SR group did not show a monotonic pattern across the SOA. RT2 was slowest at the 0-ms SOA, intermediate at 100- and 1,000-ms SOAs, and fastest at the 200-ms SOA (RT2 = 617, 589, 579, and 598 ms for 0-, 100-, 200-, and1,000-ms SOA).

The PE data showed that the two-way interaction of T1 condition and T2 condition was significant, F(1, 36) = 5.86, $p < .05$, MSE = 0.0019. When T1 was the IM task, participants committed .028 higher error rates when T2 was the IM task than when it was the SR task. However, when T1 was the SR task, participants committed only .005 higher error rates when T2 was the SR task than when it was the IM task. The individual ANOVAs showed that the main effect of SOA was not significant for any group, Fs(3, 27) ≤ 2.13, ps ≥ .05.

Discussion

The purpose of this experiment was to test the interactive conception of the PRP effect when R1 was not required using Greenwald and Shulman's (1973) ideomotor compatible tasks. In contrast to the standard PRP effect of RT2 increasing as SOA decreased, all groups showed that faster RT2 at the two intermediate SOAs than at the shortest and longest SOAs. More importantly, the results showed that RT2 decreased 26 ms when SOA decreased from 1,000 ms to 0 ms for the IM-IM group. In other words, a PRP effect was not evident when R1 was not required in the no contingency condition.

According to the interactive conception of the PRP effect, there should be no delay of RT2 in the PRP paradigm when R1 is not required if there is no contingency relation between the tasks. That is because the final response-selection bottleneck is the sole cause of the delay of RT2 in the performance of the PRP task when no contingency relations exist between two tasks. In addition, when R1 is not required, the final response selection of T2 does not need to wait until the processing of the final response selection for T1 is completed. Thus, no delay of RT2 should occur when R1 is not required, regardless of what task combination it is.

EXPERIMENT 4

As suggested by the interactive conception, the bottleneck in the final response-selection stage is responsible for the delay of RT2 when there is no contingency relation between the two tasks. Therefore, the PRP effect should be obtained when responses to both tasks are required, as shown in Experiments 1A, 1B, and 2. On the other hand, the PRP effect should be eliminated when R1 is not required in the PRP paradigm and no contingency relation exists between two tasks, as shown in Experiment 3.

According to the interactive conception, the between-task crosstalk and the noncurrent-task response association will delay the processing of T2 at the short SOA when there is a contingency between the two tasks (e.g., dimensional overlap or predictive relation). Therefore, when R1 is not required, the interactive conception predicts that the PRP effect should be evident if a contingency exists between two tasks and reduced or eliminated if a contingency is absent.

Davis (1959) conducted four PRP experiments to compare the RT2 obtained when R1 was required and when it was not. Simple RT for both tasks were used in which both tasks involved visual-visual stimulus combinations in Experiments 1 and 2 and visual-auditory stimulus combinations in Experiments 3 and 4. For T1, a single light was always presented on the left side of a cardboard tube for all experiments. In Experiments 1 and 3, participants were asked to respond to the light by pressing the left-hand key, whereas in Experiments 2 and 4 participants were instructed to ignore the light. For T2, a single light was presented on the right side of the cardboard tube in Experiments 1 and 2, and a click of moderate intensity was presented in the earphones that participants wore in Experiments 3 and 4. Participants in all experiments were required to make keypress responses to T2 by pressing the right-hand key. The delay in RT2 at short SOAs appeared for all stimulus combinations, regardless of whether the same or different stimulus modalities for S1 and S2 were used. More importantly, there was nearly as much delay present in RT2 when no R1 was required as when both R1 and R2 were required.

Van Selst and Johnston (1999), on the other hand, conducted PRP experiments using a go-nogo task for T1, with no response was required for T1 on the no-go trials. In their two experiments, T1 required participants to judge the pitch change between an initial reference tone (800-Hz) and a probe tone (S1). Four levels of probe tone pitch change occurred. Two levels of pitch increase (2,000- and 5,000-Hz) constituted go signals and two levels of pitch decrease (128- and 320-Hz) constituted no-go signals. Van Selst and Johnston reported that the PRP effect remained for both go and no-go trials.

Although the findings from Davis's (1959) and Van Selst and Johnston's (1999) studies suggested that the PRP effect remains even when no R1 is required, the arguments they made on the basis of their methodologies and task arrangements are questionable. First, the task used in Davis's experiments was a simple RT task. There is empirical evidence to suggest that a simple RT task requires different information processing than does a choice RT task (see Gottsdanker, 1979, and Schubert, 1999, for detailed discussion). How the simple RT task affects performance in the PRP task is still controversial. Second, the go and no-go trials used by Van Selst and Johnston can only reflect an output processing effect because the two trial types were intermixed within a block. Participants had to judge the tone pitch change and make a final response decision on whether to execute the response for T1 in both go and no-go trials. This extensive processing of response activation and final response decision of T1 in the no-go trials likely would delay the processing of T2 in the same manner as in the go trials.

A more standard experimental design similar to the PRP paradigm, but in which R1 is not required, can be found in the SRC studies of irrelevant stimulus information effects. For example, in Proctor and Pick's (1998) Experiment 1, a low-pitch auditory warning tone was presented to left, right, or both ears. After a 200-ms or 400-ms interval, a high-pitch auditory tone was presented to either left or right ear. The S-R mapping for the relevant high-pitch tone was manipulated: Participants in the compatible mapping condition were instructed to respond to the location of the tone by pressing the corresponding key, whereas participants in the incompatible mapping condition were instructed to press the key that was opposite to the location of the tone. In the compatible mapping condition, RT was faster when the location of irrelevant auditory warning tone corresponded with the location of the relevant tone. Moreover, in the incompatible mapping condition, RT was faster when the location of warning tone did not correspond with that of the relevant tone than when it did. Given that the task procedure adopted by Proctor and Pick involved two individual stimuli and a time interval between their onsets, the findings can be considered as an S-R compatibility effect in a dual-task situation where the response to S1 is not required.

The correspondence effect found in Proctor and Pick's (1998) single-task performance when the onset of the irrelevant tone preceded that of the relevant stimulus suggests that the preceding stimulus, to which no response was required, interfered with the processing of the imperative stimulus. In an attempt to provide evidence for the hypothesis that delay of RT2 in the dual-task paradigm is not solely due to the final response-selection bottleneck, but also to either the crosstalk or noncurrent-task response association, a standard PRP procedure with two nonspatial visual stimuli was used in Experiment 4. The purpose of this experiment was to test the hypothesis that the PRP effect should be small or eliminated when there is no contingency relation between two tasks but regained and larger when a contingency relation exists. Participants received two dual-task conditions, with one condition having a contingency relation between two tasks and the other having no such relation. Participants were asked to respond to only S2 for both conditions. Instead of using auditory stimuli, visual color stimuli were used to determine whether the correspondence effect found with auditory stimuli in Proctor and Pick's experiment could be obtained with visual color tasks.

In the present experiment, each participant received two task conditions. For one condition there was S1-S2 color dimensional overlap (the overlap condition), and in the other there was no dimensional overlap (the no overlap condition). A red or green color rectangular frame was presented on the center of the screen as T1. After an SOA of 0, 150, 300, 500, 1,000 ms, a letter A or B in the no overlap condition, or a letter A in the overlap condition, was presented in the center of the rectangle as S2. Participants were required to ignore S1 and make keypress responses to S2 only. In the S1-S2 no overlap condition, the letter A or B was presented in white color. Participants were asked to respond to the letter identity. On the other hand, in order to produce equivalent perceptual information, only the letter A but in red or green color was used in the overlap condition. Participants were asked to respond to the color of the letter, rather than its identity. Therefore, the color of the rectangular frame in S1 and the color of the letter A in S2 were either congruent (e.g., a red rectangular frame with a red letter A or a green rectangular frame with a green letter A) or incongruent (e.g., a red rectangular frame with a green letter A or a green rectangular frame with a red letter A).

The traditional RSB model, which treats that the response-selection process as a single decision bottleneck, does not explicitly explain how the stimulus information on T1 affects the processing of T2. However, from the depiction of the RSB model, it predicts that the PRP effect should disappear when only R2 is required, regardless of whether dimensional overlap exists between S1 and S2. This prediction is made because the response-selection processing for T2 can start immediately after the perceptual processing of S2 when T1 does not require any response. In contrast, the interactive conception of the PRP effect predicts that the effect should be larger for the overlap condition than for the no overlap condition. This prediction is made because, according to the interactive conception, the contingency relations (e.g., dimensional overlap) between the two tasks should cause longer delay of RT2 even when R1 is not required.

Method

Participants

Eighty undergraduate students enrolled in Introductory Psychology at Purdue University participated in partial fulfillment of course requirements. Their mean age was 19 years, with a range of 17 to 43 years. Color vision was examined for each participant by using a red-green deficiency test (Schiffman, 1990). All participants were required to be able to identify a green “3” within a field of yellow dots in order to be considered to have normal color vision. They were required to have not participated in previous experiments.

Apparatus and stimuli

Stimulus presentation, timing, and data collection were controlled using the same apparatus as the previous experiments. S1 was a red (MEL color code 4) or green (MEL color code 2) color rectangular frame presented in the center of the screen. After an SOA of 0, 150, 300, 500, 1,000 ms, a visual letter “A” in the overlap condition or a visual letter “A” or “B” in the no overlap condition was presented in the center of the rectangular frame. In the overlap condition, the letter A was presented in either red or green color. Participants were instructed to respond to the color of the letter. In the no overlap condition, however, the letters A and B were presented in white and participants were instructed to respond to the letter identity instead. In other words, the letter color in the overlap condition and the letter identity in the no overlap condition were the relevant stimulus information.

The rectangular frame was 4 cm in width and 3 cm in height. At a viewing distance of 55 cm, the frame subtended a visual angle of 4.16° × 3.12°. The letters A and B were 0.5 cm in height and 0.4 cm in width. The letters subtended a visual angle of approximately 0.58° × 0.46°. All visual stimuli were presented on a black background monitor. Responses for T2 were made to the color or identity of letters by pressing the “z” or “m” keys in the standard keyboard with their left-index or right-index finger, respectively. In the no overlap condition, the left key was assigned to the letter “A” and the right key was assigned to the letter "B" for half of the participants. For the other half of the participants, the assignment of response keys to the letters was reversed. In the overlap condition, the left key was assigned to the red color of the letter and the right key was assigned to the green color of the letter for half of the participants. The assignments of keys to the color of the letters were reversed for the other half of the participants.

Design and procedure

Each participant received 10 regular blocks of 40 trials each, and two practice blocks of 20 trials each. The SOAs were constant within blocks and were varied over the 5 values of 0, 150, 300, 500, and 1,000 ms. The experimental design was 2 (overlap and no overlap) × 5 (SOAs). The trials were ordered for a given participant such that he or she received all five SOAs for one task condition before receiving the other task condition. Prior to the five SOAs for the first task condition, one practice block of 20 trials was given. Prior to the five SOAs for the second task condition, participants were given another practice block of 20 trials for that particular task condition. In the overlap condition, two S1-S2 relations were defined as congruent conditions (a green rectangular frame with the green color of the letter and a red rectangular frame with the red color of the letter) and two as incongruent conditions (a green rectangular frame with the red color of letter and a red rectangular frame with the green color of the letter). In the no overlap condition, a red or green rectangular frame with the white color of letter A or B was defined as a neutral condition.

Participants were instructed to ignore the rectangular frame and to make keypress responses to the letter identity of S2 in the no overlap condition or the letter color of T2 in the overlap condition. Both stimuli remained on the screen until participants made R2.

Feedback for incorrect responses, “Incorrect response”, was presented in the center of the screen for 1,000 ms. The following trial was presented 1,000 ms after the offset of the feedback message. Participants were instructed to make responses as quickly and accurately as possible. Only correct trials with RT2 greater than 100 ms and less than 2,000 ms were included in the RT data.

Results

Task 2 RT and PE

The RT and PE data on T2, shown in Table 7, were analyzed as a function of S1-S2 relation (overlap and no overlap) and SOA (0, 150, 300, 500, and 1,000 ms). The RT2 data showed that the main effects of S1-S2 relation, $\underline{F}(1, 79) = 201.58$, $\underline{p} < .001$, $\underline{MSE} = 5{,}798$, SOA, $\underline{F}(4, 316) = 27.6$, $\underline{p} < .001$, $\underline{MSE} = 1{,}922$, as well as their interaction, $\underline{F}(4, 316) = 3.75$, $\underline{p} < .01$, $\underline{MSE} = 1{,}862$, were significant. The RT was 76 ms slower in the overlap condition than in the no overlap condition. Moreover, the overall RT2 increased from 445 ms to 484 ms as SOA decreased from 1,000 ms to 0 ms. In other words, a PRP effect of 39 ms was evident. The interaction of S1-S2 relation and SOA indicated that the pattern of RT2 across SOAs was different for the overlap and no overlap conditions.

A separate ANOVA was performed for each S1-S2 relation condition. In the overlap condition, the main effect of SOA was significant, $\underline{F}(4, 316) = 16.82$, $\underline{p} < .001$, $\underline{MSE} = 2{,}492$. The RT2 decreased from 527 ms to 475 ms as SOA increased from 0 ms to 1,000 ms. In other words, a PRP effect of 52 ms was obtained in the overlap condition. Although the main effect of SOA was significant in the no overlap condition, F(4, 316) = 14.02, p < .001, MSE = 1,291, only a 25-ms PRP effect was obtained. The RT2 decreased from 440 ms to 415 ms as SOA increased from 0 ms to 1,000 ms.

The PE data for T2 showed the main effects of S1-S2 relation, F(1, 79) = 65.02, p < .001, MSE = 0.0012, and SOA, F(4, 316) = 5.12, p < .001, MSE = 0.0008, were significant. The error rate in the overlap condition was .02 higher than that in the no overlap condition. In addition, the error rate decreased from .04 to .03 when SOA increased from 0 ms to 1,000 ms. The result indicates that a PRP effect of .01 was obtained for PE2.

As in RT2, a separate ANOVA for each task condition was performed in PE2 and results showed that the main effect of SOA was significant only for the no overlap condition, F(4, 316) = 6.85, p < .001, MSE = 0.0005, but not for the overlap condition, F < 1.0. However, the magnitude of the PRP effect in PE2 for both overlap and no overlap conditions was similar, with the effect being .014 in the no overlap condition and .006 in the overlap condition.

Discussion

The purpose of this experiment was to conduct tests of the interactive conception of the PRP effect under dual-task conditions in which the dimensional overlap relation between two tasks was manipulated and no R1 was required. The RT2 data showed a significant PRP effect of 52 ms when there was dimensional overlap between S1 and S2 (e.g., a red color rectangular frame with a red color of letter A), but only a small but significant PRP effect of 25 ms when there was no dimensional overlap (e.g., a red color rectangular frame with a white color of letter A). As suggested by Davis (1959), a delay in RT2 at the short SOA when no response is required to S1 could be due to having to discriminate S2 from S1 when both stimuli are presented within the same modality. This suggestion is plausible, because there is evidence that attention is selectively allocated to objects within the visual filed and that all parts of the selected object receive attended processing (e.g., Duncan, 1984; Treisman, Kahneman, & Burkell, 1983). Thus, the direction of attention to S2 when it was presented in a close proximity with S1 may cause the delay of processing for T2. In the current experiment, S2 was a visual letter presented within S1, a visual rectangular frame. The direction of attention to the letter may be delayed at the short SOA due to the combined object, even when there was no dimensional overlap between S1 and S2.

A larger PRP effect was obtained in the dimensional overlap condition than in the nondimensional overlap condition, as predicted by the interactive conception account, implying that the bottleneck in the final response selection is not the sole cause of the PRP effect. The noncurrent-task response association, the dimensional overlap between two stimuli manipulated in this experiment, interfered with the processing of T2 and delayed RT2 even when R1 was not required. Therefore, attributing the PRP effect to the response-selection bottleneck does not seem promising. The finding obtained in this experiment is particularly important in providing evidence against the single response-selection route hypothesis of the RSB model, which predicts that the PRP effect should be eliminated when R1 is not required, regardless of what S1-S2 relation is.

EXPERIMENT 5

The purpose of Experiment 5 was to take a further step in examining the effects of between-task relations in the PRP tasks. A key assumption of the interactive conception of the PRP effect is that the processing of compatibility tasks in the PRP paradigm is affected by between-task crosstalk and noncurrent-task response association when there is a contingency information between the two tasks. It is assumed that the contingency is determined by the dimensional overlap, as well as by the strength of predictive relations between the two tasks. In addition, the interactive conception account suggests that the time elapsing between the availability of information from each task, that is, the SOA, affects the opportunity for one source to influence and be influenced by the other. Between-task crosstalk and noncurrent-task response association have stronger impact on RT1 and RT2 when the temporal overlap of the processing between two tasks is large. In other words, the effects of the predictive relations, as well as the dimensional overlap, between S1 and S2 should be larger at the short SOA than at the long SOA. Thus, the aim of Experiment 5 was to investigate the effect of predictive relations between S1 and S2 on the performance of the PRP task when there was no dimensional overlap between two tasks.

The nondimensional overlap task condition in Experiment 4 was used in this experiment, with the exception that T1 required a verbal response of “red” or “green” to the color of the rectangular frame. After a variable SOA, a visual letter A or B was presented in the center of the frame. Participants were required to make a left or right keypress in response to the visual letter A or B. Three levels of correlation, high (80%), low (20%), and neutral (50%), between S1 and S2 were used to determine whether the strength of correlation between S1 and S2 affects performance in the PRP task when there is no dimensional overlap between the two tasks. The traditional RSB model predicts that the PRP effect should be obtained for all correlation conditions because the response-selection processing of T2 has to wait until the response-selection processing of T1 is completed, regardless of S1-S2 correlation. Similarly, the interactive conception predicts that a PRP effect should be obtained for all correlation conditions because predictive relations between two stimuli will affect the dual-task performance even when there is no dimensional overlap.

In addition, the relative frequency of S1 and S2 can serve as cues for the response of T2. Given the presence of one particular element of S1 in the high correlation condition, one particular response that is assigned to one element of S2 is more likely to be correct than the other response. Then, the identity of the element of S1 could potentially act as a cue to the correct response for T2. For example, when the green rectangular frame of T1 is highly correlated with the letter A of T2, then the green rectangular frame can be a valid cue for the vocal “A” response of T2. If the system can take advantage of such cueing, RT2 should be faster in the high correlation condition, intermediate in the neutral condition, and slower in the low correlation condition.

Because the major concern was how the S1-S2 correlation affected the processing of T2 as well as T1, the individual comparisons between high/low, high/neutral, and low/neutral correlation conditions were examined as a function of SOA. The traditional

RSB model and the interactive conception account of the PRP effect make different predictions about the effect of S1-S2 predictive relation as a function of SOA on RT1 and RT2. According to the depictions of the traditional RSB model, the response-selection processing of T1 should be affected little by the S1-S2 predictive relation because the response-selection processing of T2 has not started until the selection of R1 is completed. Thus, the pattern of RT1 across SOAs among the three correlation conditions should show no difference. In addition, the assumption of a central bottleneck, located at response-selection stage, made by the RSB model can only predict either an underadditive interaction with SOA of variables affecting a stage prior to the decision-related stage or an additive effect of variables affecting the response-selection processing with SOA. In contrast, the interactive conception account assumes that an overadditive interaction of S1-S2 predictive relation with SOA on RT1 as well as RT2 should be obtained because the S1-S2 predictive relation has a stronger impact on RT1 and RT2 when the temporal overlap of the processing between two tasks is large, at the short SOA. That is, the effect of S1-S2 predictive relation on RT1 and RT2 should decrease as SOA increase.

Method

Participants

There were 55 participants in this experiment. They were undergraduate students from the same participant pool as in the previous experiments, but none had participated in those experiments. As in Experiment 4, color vision was examined for each participant by using a red-green deficiency test (Schiffman, 1990). All participants were required to be able to identify a green “3” within a field of yellow dots in order to be considered to have normal color vision.

Apparatus and stimuli

The major change from the nondimensional overlap condition in Experiment 4 was that participants were asked to make responses to T1 as well as to T2. Participants wore headphones with an integrated microphone (Labtec LVA8550), which registered vocal responses. Responses for T1 were made to the color of rectangular frame by vocally speaking “red” to the red color rectangular frame and “green” to the green color rectangular frame into the microphone.

Design and procedure

The S1-S2 correlation (high, low, and neutral) was a within-subjects variable. Each participant received 10 regular blocks of 40 trials each, and one practice block of 32 trials. The SOAs, which were constant within blocks, were varied over the five values of 0, 150, 300, 500, and 1,000 ms, with onset of T1 always preceding onset of T2. Within each of 2 subsets of 5 blocks of trials, the five SOA conditions each appeared once, in a random order for each correlation condition. There was a total of four stimulus combinations for T1 and T2: a red rectangular frame with A, a red rectangular frame with B, a green rectangular frame with A, and a green rectangular frame with B. For the neutral condition, each of the four possible stimulus combinations in a block appeared in a random order with equal probability. For the high/low correlation condition, the combinations of red color of rectangular frame with the letter A and green color of rectangular frame with the letter B appeared 80% of the time for half of the participants, whereas the other half received 80% of the combinations of red color of rectangular frame with the letter B and green color of rectangular frame with the letter A. On the other hand, the other task combinations were classified as 20% low correlation condition.

The first trial in each block was initiated by the experimenter, who pressed the space bar of the keyboard, when a prompt appeared on the screen prior to the first trial of each block. One-thousand ms after the experimenter pressed the space bar, the red or green rectangular frame (S1) was displayed on the center of the screen. The visual letter A or B (S2) followed S1 after one of five SOAs and was presented in the center of the rectangular frame. Both stimuli stayed on the screen until participants made responses to both tasks and then disappeared simultaneously. Responses for T2 were made by pressing the far left or far right of the response box of five buttons with the index fingers of the left or right hand, respectively. For half of the participants, the far left button was assigned to the letter "A" and the far right button was assigned to the letter "B", whereas the assignment of letters to the response buttons was reversed for the other half of the participants. The identity of each spoken response was entered into the computer by the experimenter, who pressed either the "1", "2", or "0" key on the computer keyboard for "A", "B", or "no response", respectively.

Feedback for incorrect responses, "Incorrect T1/T2 response", was presented in the center of the screen for 1,000 ms. The following trial was presented 1,000 ms after the offset of the feedback message. Participants were instructed to respond to S1 before S2 and as quickly and accurately as possible for both tasks, as in most PRP experiments. Only correct trials with both RT1 and RT2 greater than 100 ms and less than 2,000 ms were included in the RT data. The proportion of errors for each task was determined without regard to whether the response for the other task was correct.

Results

The mean RT1 and RT2 are shown in Figure 7, and PE1 and PE2 are shown in Table 8. Each measure was analyzed as a function of correlation condition (high, low, and neutral correlation) and SOA (0, 150, 300, 500, and 1,000 ms).

Task 1 RT and PE

The RT1 data showed that the main effects of SOA, F(4, 216) = 7.34, p < .001, MSE = 63,666, correlation condition, F(2, 108) = 28.23, p <.001, MSE = 41,762, and their interaction, F(8, 432) = 6.45, p <.001, MSE = 14,345, were significant. RT1 was slower at the three intermediate SOAs (737, 756, and 696 ms for 150-, 300-, and 500-ms SOA) than at the shortest and longest SOAs (666 and 648 ms for 0- and 1,000-ms SOA). Participants responded to T1 faster for the high correlation condition (RT1 = 652 ms), intermediate for the neutral condition, (RT1 = 687 ms), and slower for the low correlation condition (RT1 = 777 ms).

The significant interaction of correlation and SOA reflects that the pattern of RT1 changed differently as SOA increased for the three correlation conditions. An individual ANOVA was conducted for pair-wise comparisons of correlation conditions: high with low, high with neutral, low with neutral. The interaction of correlation condition and SOA was significant for the comparison between the high and low correlation conditions, F(4, 216) = 19.92, p < .001, MSE = 8,512. The mean difference of RT1 between high correlation and low correlation conditions decreased as SOA increased (mean difference RT1s were 197, 190, 154, 64, and 21 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). In other words, an overadditive interaction of S1-S2 correlation and SOA on RT1 was obtained for the high and low correlation conditions.

The interaction of correlation condition and SOA was also significant for the comparison between the high and neutral correlation conditions, F(4, 216) = 3.26, p < .05, MSE = 7,763, and between the low and neutral correlation conditions F(4, 216) = 4.57, p < .01, MSE = 16,637. The difference of RT1 between the high and neutral correlation conditions tended to decrease as SOA increased (different RT1s were 57, 50, 53, 31, and -16 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). Similarly, the difference of RT1 between the low and neutral conditions tended to decrease as SOA increased (different RT1s were 140, 140, 101, 33, and 37 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). As in the comparison of high and low correlation, an overadditive interaction of S1-S2 correlation and SOA on RT1 was obtained for the high and neutral correlation conditions and for the low and neutral correlation conditions.

The PE1 data showed that the main effects of SOA, F(4, 216) = 5.23, p < .001, MSE = 0.0047, correlation condition, F(2, 108) = 23.18, p < .001, MSE = 0.0062, and their interaction, F(8, 432) = 2.90, p < .01, MSE = 0.0039, were significant. The PE1 was higher at the three shortest SOAs than at the others (PE1s were .05, .06, .06, .04, and .04 for 0-, 150-, 300-, 500-, and 1,000-ms SOA). Participants committed more errors for the low correlation condition (PE1 = .08) than for the neutral condition (PE1 = .04) and less the high correlation condition (PE1 = .03).

As in RT1, the interaction between SOA and correlation condition on PE1 indicates that the pattern of PE1 changed differently across SOA for the three correlation conditions. An individual ANOVA for PE1 was conducted for the comparison between two correlation conditions. For the analysis of the high and low correlation conditions, the PE1 showed a significant interaction of correlation condition and SOA, F(4, 216) =

4.30, p < .01, MSE = 0.005. The difference of PE1 between high correlation and low correlation conditions was larger at the 150- and 300-ms SOAs than the others (PE1s were .03, .07, .07, .03, and .02 for 0-, 150-, 300-, 500-, and 1,000-ms SOA). In contrast, the interaction of correlation condition and SOA was not significant for the comparisons between the high and neutral conditions and between the low and neutral conditions.

Task 2 RT and PE

The RT2 data showed the main effect of SOA was significant, F(4, 216) = 291.64, p < .001, MSE = 29,765, with RT2 increasing as SOA decreased. This reflects that a sizable 489-ms PRP effect was found (RT2s were 923, 845, 705, 572, and 434 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). The main effect of correlation condition, F(2, 108) = 58.36, p < .001, MSE = 34,044, as well as its interaction with SOA, F(8, 432) = 11.47, were significant. Responses were fastest for the high correlation condition (RT2 = 619 ms), intermediate for the neutral condition (RT2 = 688 ms), and slowest for the low correlation condition (RT2 = 788 ms).

The significant interaction between correlation condition and SOA showed that the PRP effect was larger for the low correlation condition than the other two (the PRP effect was 406, 611, and 469 ms, for high, low, and neutral correlation conditions). As in RT1, an individual ANOVA was conducted for the comparison between two correlation conditions. For the analysis of the high and low correlation conditions, the RT2 showed a significant interaction of correlation condition and SOA, F(4, 216) = 26.39, p < .001, MSE = 8,655. The mean difference of RT2 between high and low correlation conditions decreased as SOA increased (mean difference RT2s were 251, 245, 201, 100, and 46 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). That is, an overadditive interaction of S1-

S2 correlation and SOA on RT2 was obtained for the high and low correlation conditions. Another way to interpret the interaction of SOA and correlation condition is that a PRP effect of 406 ms was obtained for the high correlation condition, whereas the effect was 611 ms for the low correlation condition.

For the analysis between the high and neutral correlation conditions, the interaction of correlation condition and SOA was also significant, F(4, 216) = 5.78, $p < .001$, MSE = 5,363. The difference in RT2 between the high and neutral conditions tended to decrease as SOA increased (different RT2s were 88, 104, 80, 38, and 27 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). Again, an overadditive interaction of S1-S2 correlation and SOA on RT2 was obtained for the high and neutral conditions. In other words, the PRP effect was 406 ms for the high correlation condition and 467 ms for the neutral condition. The interaction of correlation condition and SOA was also significant for the comparison between the low and neutral conditions, F(4, 216) = 8.54, $p < .001$, MSE = 11,160. The difference in RT2 between the low and neutral conditions tended to decrease as SOA increased (different RT2s were 163, 141, 121, 62, and 19 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). An overadditive interaction of S1-S2 correlation and SOA on RT2 was also obtained for the low and neutral conditions. Another way to interpret the interaction is that the PRP effect was 611 ms for the low correlation condition and was 467 ms for the neutral condition.

The PE2 data showed that the main effect of correlation condition, F(2, 108) = 36.19, $p < .001$, MSE = 0.0156, as well as its interaction with SOA, F(8, 432) = 1.99, $p < .05$, MSE = 0.0053, were significant. The PE2 was larger for the low correlation condition (PE2 = .12), intermediate for the neutral condition (PE2 = .12), and smaller for the high correlation condition (PE2 = .03). The interaction of correlation condition with SOA indicates the size of the PRP effect being different for the three correlation conditions: .02, .03, and .002 for the high, low, and neutral condition.

As in RT2, an individual ANOVA for PE2 was carried for the comparison between two correlation conditions. However, the interaction of the correlation condition and SOA was not significant for any one of the comparisons.

Discussion

The RTs for both tasks showed ordinary correlation effects, except the RT1 for the high and neutral correlation conditions at the longest SOA. That is, RT1 and RT2 were slower when the S1-S2 predictive relation was low, intermediate when it was neutral, and faster when it was high. In addition, the effect of SOA was significant for RT2 in each correlation condition, reflecting a substantial PRP effect. The PRP effect was 406, 469, and 611 ms for the high, neutral, and low correlation conditions. The PRP effect was largest on trials for which the S1-S2 correlation was only 20%, intermediate on trials for which it was 50%, and smallest on trials for which it was 80%. Although the PRP effect on PE2, as in RT2, was largest in the low correlation condition, it was smaller in the neutral condition than in the high correlation condition.

The interactive conception of the PRP effect assumes that S-R translation for both T1 and T2 can be processed concurrently prior to the final response-selection bottleneck, thus, allowing the cross-task interaction. Therefore, the account suggests that the S1-S2 correlation manipulation, primarily affecting the prebottleneck processing of response activation and S-R translation, should show effects on RT1 as well as RT2. Figure 7 shows RT1 and RT2 as a function of S1-S2 correlation condition and SOA. As can be seen in the figure, RT1 as well as RT2 showed an overadditive interaction of S1-S2 correlation condition with SOA, and this was confirmed in the two-way interaction of correlation condition with SOA in the individual ANOVA of the comparison between two correlation conditions. The effect of S1-S2 predictive relation on both RT1 and RT2 being largest at the short SOA than at the long SOA reflects that response activation of T1 as well as T2 is affected by the degree of temporal overlap of the processing between two tasks, as predicted by the interactive conception of the PRP effect but not the traditional RSB model.

EXPERIMENT 6

Recently, studies of the PRP effect have suggested that the spatial correspondence between the two manual response tasks may contribute to the PRP effect, as described in the introduction (Hommel, 1998; Lien & Proctor, 2000). Thus, the purpose of Experiment 6 was to examine whether the effect of S1-S2 correlation on RT1 and RT2 obtained with the vocal-manual response combination in Experiment 5 differs from the results obtained with the manual-manual response combination. A similar experimental design to that of Experiment 5 was used except that a manual keypress response was required for T1. Participants were required to make a left/right keypress response to S1 with one hand and a left/right keypress response to S2 with another hand. The spatial relations of responses for T1 and T2 could be classified as two forms: If each task required the leftmost response or each required the rightmost response, the responses corresponded spatially; otherwise, the responses did not correspond spatially.

The spatial correspondence effect, found in the studies where manual responses were required for both tasks, has shown that RT1 and RT2 are faster when the response location of T1 corresponds to the response location of T2 than when it does not (see Lien & Proctor, 2001, for a review). Such crosstalk effects have been shown to increase when SOA decreases. According to the interactive conception account of the PRP effect, the effects of crosstalk and response association on both RT1 and RT2 are determined largely by the time elapsing between the availability of information from each task, that is, the

SOA. Thus, the interactive conception account predicts an overadditive interaction of these variables with SOA on RT1 and RT2.

Method

Participants

Forty-eight undergraduate students from the same participant pool as in the previous experiments participated for course credit. Similar to Experiment 5, color vision was examined for each participant by using a red-green deficiency test (Schiffman, 1990). They all were required to have not participated in previous experiments.

Apparatus, stimuli, and procedure

The method for Experiment 6 was the same as that of Experiment 5 with the exception that the keypress responses were used for both tasks. The keypress responses were made on the “Z” and “X” keys with the left middle and index fingers for one task and the “N” and “M” keys with the right middle and index fingers for the other task. These pairs of keys were located on the bottom row of a standard computer keyboard, with a 6.3 cm gap between the two pairs, and were centered about the body midline. Half of the participants used the “Z” and “X” keys for T1 and the “N” and “M” keys for T2, and half used the reverse assignment.

Results

The mean RT1 and RT2 are shown in Figure 8, and PE1 and PE2 are shown in Table 9. Three data analyses were performed, with one was examining the effect of S1-S2 correlation on RTs and PEs, as in the Experiment 5. Another data analysis examined the effect of R1-R2 correspondence (correspondent or noncorrespondent) as a function of SOA for individual high, low, and neutral correlation conditions. Third, comparisons across Experiments 5 and 6 were conducted including experiment as a between-subject variable to provide further information about whether the effect of S1-S2 correlation shows any difference with that in Experiment 5 when the variable of R1-R2 correspondence was manipulated in Experiment 6.

Effects of Correlation

The mean RTs and PEs across the spatial correspondence for both tasks were analyzed, as in Experiment 5, as a function of correlation condition (high, low, and neutral condition) and SOA (0, 150, 300, 500, and 1,000 ms).

Task 1 RT and PE. The RT1 data showed that the main effects of SOA, $F(4, 188) = 4.23$, $p < .01$, $MSE = 78{,}667$, and correlation condition, $F(2, 94) = 31.98$, $p < .001$, $MSE = 63{,}966$, were significant. The RT1 was faster at the shortest SOA than at the others (735, 812, 829, 817, and 841 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). Participants responded fastest for the high correlation trials (RT1 = 732 ms), intermediate for the neutral condition trials (RT1 = 792 ms), and slowest for the low correlation trials (RT1 = 912 ms).

In addition, the interaction of SOA and correlation condition was significant, $F(8, 376) = 9.06$, $p < .001$, $MSE = 22{,}792$. An individual ANOVA was conducted for the comparison between each pair of correlation conditions: high with low, high with neutral, low with neutral. For the analysis of the high and low correlation conditions, RT1 showed a significant interaction of correlation condition and SOA, $F(4, 188) = 25.87$, $p < .001$, $MSE = 13{,}568$. The mean difference in RT1 between high correlation and low correlation conditions decreased as SOA increased (mean difference RT1s were 327, 237, 213, 107, and 14 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). In other words, an overadditive interaction of correlation and SOA was obtained for the high and low correlation conditions. For the analysis between the high and neutral correlation conditions, RT1 also showed a significant interaction of correlation condition and SOA, F(4, 188) = 15.27, p < .001, MSE = 16,201. The difference in RT1 between the high and neutral conditions tended to decrease as SOA increased (different RT1s were 137, 138, 70, 30, and -75 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). Again, an overadditive interaction of correlation and SOA was obtained for the high and neutral conditions.

In contrast to the previous two analyses, the interaction of correlation condition and SOA was not significant for the comparison between the low and neutral conditions, F(4, 188) = 1.95, p > .10, MSE = 35,532. Although it was not significant, the effect of S1-S2 correlation was larger at the 0- and 300-ms SOAs (difference = 190 and 143 ms) than at the 150-, 500-, and 1,000-ms SOAs (difference = 90, 77, and 89 ms).

The PE1 data showed that the main effects of SOA, F(4, 188) = 6.87, p < .001, MSE = 0.0117, and correlation condition, F(2, 94) = 30.85, p < .001, MSE = 0.0236, were significant. PE1 showed a tendency of decreasing as SOA increased (PE1s were .13, .11, .10, .08, and .09 for 0-, 150-, 300-, 500-, and 1,000-ms SOA). Participants committed more errors in the low correlation condition (PE1 = .17) than the other two correlation conditions (PE1s were .06 and .09 for the high and neutral conditions, respectively).

The two-way interaction of correlation and SOA was significant, F(8, 376) = 3.51, p < .001, MSE = 0.010. An individual ANOVA for PE1, as in RT1, was carried out for the comparison between each pair of correlation conditions. For the analysis of the high and low correlation conditions, the PE1 showed a significant interaction of correlation condition and SOA, F(4, 188) = 6.87, p < .001, MSE = 0.0091. The difference of PE1 between high correlation and low correlation conditions decreased as SOA increased (PE1s were .18, .13, .10, .06, and .06 for 0-, 150-, 300-, 500-, and 1,000-ms SOA). As in RT1, an overadditive interaction of correlation and SOA was obtained on PE1 for the high and low correlation conditions. For the analysis between the high and neutral correlation conditions, the interaction of correlation and SOA was also significant, F(4, 188) = 6.42, p < .001, MSE = 0.006. The difference of PE1 between high correlation and neutral conditions decreased as SOA increased (PE1s were .09, .04, .03, .02, and -.01 for 0-, 150-, 300-, 500-, and 1,000-ms SOA). In other words, an overadditive interaction of correlation and SOA was obtained for the high and neutral conditions. Although the interaction of correlation and SOA was not significant for the comparison between the low and neutral conditions, F(4, 188) = 1.03, p > .10, MSE = 0.0149, the effect of S1-S2 correlation on PE1 tended to decrease from .10 to .03 when SOA increased from 0 ms to 500 ms, then increased to .07 when SOA increased to 1,000 ms.

Task 2 RT and PE. The RT2 data showed the main effect of SOA was significant, F(4, 188) = 282.27, p < .001, MSE = 21,479, with RT2 increasing as SOA decreased. This reflects that a sizable 436-ms PRP effect was found (RT2s were 986, 915, 813, 671, and 550 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). The main effect of correlation condition, F(2, 94) = 54.47, p < .001, MSE = 55,198, as well as its interaction with SOA, F(8, 376) = 13.42, p < .001, MSE = 14,992, were significant. Participants responded to T2 faster for the high correlation trials (RT2 = 667 ms), intermediate for the neutral condition trials (RT2 = 796 ms), and slower for the low correlation trials (RT2 = 890 ms).

In addition, the PRP effect was only 275 ms for the high correlation condition, 437 ms for the neutral condition, and 596 ms for the low correlation condition.

As in RT1, an individual ANOVA was carried for the comparison of two correlation conditions. For the analysis of the high and low correlation conditions, the RT2 showed that the interaction of correlation condition and SOA was significant, $\underline{F}(4, 188) = 30.79$, $\underline{p} < .001$, $\underline{MSE} = 12{,}473$. The mean difference of RT2 between high correlation and low correlation conditions decreased as SOA increased (mean difference RT2s were 368, 288, 265, 145, and 47 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). An overadditive interaction of correlation and SOA on RT2 was obtained for the high and low correlation condition. This two-way interaction of correlation condition and SOA reflects that a PRP effect of 275 ms was obtained for the high correlation condition, whereas the effect of 596 ms for the low correlation condition.

The two-way interaction of correlation condition and SOA was also significant for the analysis between the high and neutral correlation conditions, $\underline{F}(4, 188) = 16.11$, $\underline{p} < .001$, $\underline{MSE} = 8{,}777$, and for the low and neutral correlation conditions, $\underline{F}(4, 188) = 6.07$, $\underline{p} < .001$, $\underline{MSE} = 22{,}886$. The difference in RT2 between the high and neutral conditions tended to decrease as SOA increased (difference in RT2s were 194, 186, 126, 103, and 32 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). A similar decreasing function was also for the low and neutral conditions (difference in RT2s were 174, 102, 139, 42, and 15 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA). An overadditive interaction of correlation and SOA on RT2 was evident for the high and neutral conditions as well as for the low and neutral conditions. In other words, the PRP effect was 275 ms for the high correlation condition, 437 ms for the neutral condition, and 595 ms for the low correlation condition.

The PE2 data showed that only the main effect of correlation condition was significant, F(2, 94) = 44.00, p < .001, MSE = 0.0210. The PE2 was higher for the low correlation condition (PE2 = .19), intermediate for the neutral condition (PE2 = .11), and lower for the high correlation condition (PE2 = .07). No other effects were found to be significant.

As in RT2, an individual ANOVA for PE2 was carried for the comparison between two correlation conditions. The interaction of correlation condition and SOA in PE2 was significant only for the analysis between the high and neutral correlation conditions, F(4, 188) = 4.64, p < .01, MSE = 0.0054. The difference in PE2 between the high and neutral conditions showed a tendency of decreasing as SOA increased (difference of PE2 were .09, .04, .03, .04, and .01 for 0-, 150-, 300-, 500-, and 1,000-ms SOA, respectively). An overadditive interaction of correlation and SOA on PE2 was evident for the high and neutral conditions. In other words, the PRP effect was .03 for the neutral condition whereas the effect was -.05 for the high correlation condition.

Effects of Spatial Correspondence

The main purpose of performing the data analyses on the effect of spatial correspondence on the high, low, and neutral correlation trials individually was to examine whether the effect of S1-S2 correlation on RTs and PEs for both tasks was affected by the R1-R2 spatial correspondence. Thus, the data in each correlation condition were analyzed as a function of R1-R2 correspondence (correspondent and noncorrepondent) and SOA (0, 150, 300, 500, and 1,000 ms). Figure 9 shows RT1, and

Figure 10 shows RT2, as a function of correlation condition, spatial correspondence, and SOA. No effects involving correspondence on RT and PE for both tasks were found to be significant in high, low, and neutral correlation conditions, Fs ≤ 2.16, ps ≥ .075. Apparently, the spatial correspondence relation between R1 and R2 did not affect the effect of S1-S2 correlation on RTs and PEs across SOA.

Comparisons between Experiments 5 and 6

Although the manipulation of spatial correspondence relation between R1 and R2 did not show any impact on the magnitude of the S1-S2 correlation effect, a comparison of the S1-S2 correlation effect between Experiments 5 and 6 was conducted to provide further information on whether the effect of S1-S2 correlation on the two tasks was obtained similarly for the experimental designs that one with R1-R2 spatial correspondence manipulation (Experiment 6) and one without (Experiment 5). The data were analyzed as a function of experiment, correlation condition, and SOA. Only effects involving experiment were reported below.

Task 1 RT and PE. The RT1 showed that the main effect of experiment, F(1, 101) = 9.34, p < .01, MSE = 468,601, and its interaction with SOA, F(4, 404) = 4.47, p < .01, MSE = 59,821, were significant. The overall RT1 was 107 ms faster in Experiment 5 than in Experiment 6. In other words, the vocal response on T1 in Experiment 5 was made faster than the manual response on T1 in Experiment 6 when T2 required a manual response. In addition, RT1 in Experiment 6 showed a tendency of increasing as SOA increased, but the trend was not apparent in Experiment 5.

The three-way interaction of experiment, correlation condition, and SOA was significant on RT1 as well, F(8, 808) = 2.27, p < .05, MSE = 13,957. Individual

ANOVAs were conducted on RT1 to examine the interaction between experiment and SOA for each correlation condition. The interaction of experiment and SOA was only significant for the high correlation condition, $\underline{F}(4, 404) = 9.57$, $\underline{p} < .001$, $\underline{MSE} = 22{,}050$, reflecting that RT1 in Experiment 6 showed a monotonic increasing function as SOA increased whereas RT1 in Experiment 5 elevated at the three shortest SOAs then declined at the two longest SOAs.

The major concern of this data analysis was whether the difference in RTs and PEs as a function of SOA for each comparison between two correlation conditions were different in Experiments 5 and 6. Another ANOVA was carried out for the comparison of two correlation conditions. Only a significant three-way interaction of experiment, correlation condition, and SOA for each comparison are reported. For the analysis between the high and low correlation conditions, the three-way interaction of experiment, correlation condition, and SOA was significant, $\underline{F}(4, 404) = 2.82$, $\underline{p} < .05$, $\underline{MSE} = 10{,}865$. Although the mean difference of RT1 between high and low correlation conditions decreased as SOA increased for both Experiments 5 and 6, the magnitude of this overadditive effect across SOAs was larger in Experiment 6 than in Experiment 5 (difference RT1s were 197, 190, 154, 64, and 21 ms in Experiment 5 and were 327, 237, 213, 107, and 14 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA).

For the analysis between the high and neutral correlation conditions, the three-way interaction of experiment, correlation condition, and SOA was also significant, $\underline{F}(4, 404) = 4.65$, $\underline{p} < .01$, $\underline{MSE} = 9{,}773$. As in the comparison of high and low correlation conditions, although the mean difference of RT1 between high and low correlation conditions decreased as SOA increased for both Experiments 5 and 6, the magnitude of this overadditive effect across SOAs was larger in Experiment 6 than in Experiment 5 (difference RT1s were 57, 50, 53, 31, and -16 ms in Experiment 5 and were 137, 138, 70, 30, and -75 ms for 0-, 150-, 300-, 500-, and 1,000-ms SOA).

In contrast, the three-way interaction of experiment, correlation condition, and SOA was not significant for the comparison between the low and neutral conditions, F(4, 404) < 1.0. The difference RT1 as a function of SOA for both experiments showed a similar decreasing pattern as SOA increased to 500 ms then the difference RT1 increased as SOA increased from 500 ms to 1,000 ms.

The PE1 showed that the main effect of experiment was significant, F(1, 101) = 18.42, p < .001, MSE = 0.069. The overall PE1 was .06 larger in Experiment 6 than in Experiment 5. The experiment also interacted significantly with SOA, F(4, 404) = 2.47, p < .05, MSE = 0.0079, and with correlation condition, F(2, 202) = 10.37, p < .001, MSE = 0.0125. The PE1 dropped .01 as SOA increased in Experiment 5, whereas it dropped .03 in Experiment 6. In addition, participants committed approximately twice as many errors for all correlation conditions in Experiment 6 than in Experiment 5 (.06, .17, and .09 in Experiment 6 and .03, .07, and .04 in Experiment 5 for the high, low, and neutral correlation conditions, respectively).

The three-way interaction of experiment, correlation condition, and SOA was significant on PE1, F(8, 808) = 3.31, p < .001, MSE = 0.0059. The two-way interaction of experiment and SOA was significant for the neutral condition, F(4, 404) = 3.52, p < .01, MSE = 0.0028, the high correlation condition, F(4, 404) = 3.64, p < .01, MSE = 0.0026, and the low correlation condition, F(4, 404) = 2.74, p < .05, MSE = 0.0143. In Experiment 6, PE1 tended to increase as SOA increased for the high correlation condition and decrease for the neutral and low correlation conditions. However, in Experiment 5, PE1 tended to decrease as SOA increased for the high correlation condition. In addition, PE1 for the neutral and low correlation condtions showed a tendency of increasing function at the three shortest SOA and decreasing at the two longest SOAs.

As for RT1, another ANOVA was conducted for the comparison of two correlation conditions. For the analysis between the high and low correlation conditions, the three-way interaction of experiment, correlation condition, and SOA was significant, $\underline{F}(4, 404) = 5.05$, $\underline{p} < .001$, $\underline{MSE} = 0.0069$. The mean difference in PE1 between high and low correlation conditions decreased as SOA increased in Experiment 6 (PE1s were .18, .13, .10, .06, and .06 for 0-, 150-, 300-, 500-, and 1,000-ms SOA), but the decreasing function was not monotonic in Experiment 5 (PE1s were .03, .07, .07, .03, and .02 for 0-, 150-, 300-, 500-, and 1,000-ms SOA).

For the comparison between the high and neutral correlation conditions, the three-way interaction of experiment, correlation condition, and SOA was significant as well, $\underline{F}(4, 404) = 6.34$, $\underline{p} < .001$, $\underline{MSE} = 0.0028$. The mean difference in PE1 between high and neutral conditions decreased as SOA increased in Experiment 6 (PE1s were .09, .04, .03, .02, and .01 for 0-, 150-, 300-, 500-, and 1,000-ms SOA), but the decreasing function was not monotonic in Experiment 5 (PE1s were 0, .03, .02, 0, and .01 for 0-, 150-, 300-, 500-, and 1,000-ms SOA).

As for RT1, the three-way interaction of experiment, correlation condition, and SOA was not significant for the comparison between the low and neutral correlation conditions, $\underline{F}(4, 404) < 1.0$. The pattern of difference in PE1 between low and neutral conditions as a function of SOA was similar for both Experiments 5 and 6.

Task 2 RT and PE. The RT2 showed that the main effect of experiment, F(1, 101) = 8.66, p < .01, MSE = 327,974, and its interaction with SOA, F(4, 404) = 2.57, p < .05, MSE = 21,498, were significant. The overall RT2 was 86 ms faster in Experiment 5 than in Experiment 6. The PRP effect was 495 ms in Experiment 5, whereas the effect was 436 ms in Experiment 6. The two-way interaction of experiment and correlation was also significant, F(2, 202) = 4.03, p < .05, MSE = 34,744. For Experiment 5, participants responded 101 ms slower in the low correlation condition than in the neutral condition, but only 68 ms faster in the high correlation than in the neutral condition. For Experiment 6, however, participants responded only 95 ms slower in the low correlation condition than in the neutral condition but 128 ms faster in the high correlation than in the neutral condition.

Although the three-way interaction of experiment, correlation condition, and SOA was not significant for RT2, F(8, 808) = 1.62, p > .10, individual ANOVAs were conducted to examine the interaction between experiment and SOA for each correlation condition. As in RT1, the interaction of experiment and SOA was significant only for the high correlation condition, F(4, 404) = 8.40, p < .001, MSE = 7,763. The PRP effect was only 275 ms in Experiment 6 and 406 ms in Experiment 5. The result suggests that the PRP effect was reduced when R1 and R2 were manual responses and when S1 and S2 were highly correlated.

The major concern of this data analysis was whether the difference in RT2 and PE2 as a function of SOA for each comparison between two correlation conditions were different in Experiments 5 and 6. Another ANOVA was conducted for each of the two correlation conditions. Only the comparison between high and neutral correlation conditions showed a significant three-way interaction of experiment, correlation condition, and SOA on RT2, $F(4, 404) = 3.25$, $p < .05$, $MSE = 5{,}935$. The PRP effect was 63 ms larger in the neutral condition than in the high correlation condition for Experiment 5, but was 162 ms larger for Experiment 6 (see Figures 7 and 8).

The PE2 showed that only the main effect of experiment was significant, $F(1, 101) = 15.30$, $p < .001$, $MSE = 0.078$. The overall PE2 was .06 higher in Experiment 6 than in Experiment 5. The three-way interaction of experiment, correlation condition, and SOA was not significant, $F(8, 808) = 1.90$, $p > .05$, $MSE = 0.0069$. An individual ANOVA for each correlation condition was conducted to examine the two-way interaction of experiment and SOA. Results showed that the interaction of experiment and SOA was significant for the high correlation condition, $F(4, 404) = 4.68$, $p < .01$, $MSE = 0.0026$, and the neutral condition, $F(4, 404) = 2.59$, $p < .05$, $MSE = 0.0028$. PE1 increased as SOA increased for both high and neutral conditions in Experiment 6, whereas PE1 in Experiment 5 tended to decrease as SOA increased for the high correlation condition and showed a constant error rate across SOAs for the neutral condition.

Another ANOVA for the comparison between two correlation conditions was conducted. As in RT2, only the individual ANOVA of the comparison between high and neutral correlation conditions showed a significant three-way interaction of experiment, correlation condition, and SOA on RT2, $F(4, 404) = 5.86$, $p < .001$, $MSE = 0.0026$. The PRP effect on PE2 was .01 higher in the high correlation condition than in the neutral condition for Experiment 5, but was .08 lower for Experiment 6.

Discussion

The data replicate patterns of correlation effects obtained in Experiment 5: RT1 and RT2 were slowest when the S1-S2 correlation relation was low, intermediate when it was neutral, and fastest when it was high, with the exception that the RT1 for the high and neutral conditions at the longest SOA. In addition, the effect of SOA was significant for RT2 in each correlation condition, reflecting a substantial PRP effect. The PRP effect was 275, 437, and 596 ms for the high, neutral, and low correlation conditions. Again, as in Experiment 5, the PRP effect on RT2 was largest on trials for which the S1-S2 correlation was only 20%, intermediate on trials for which it was 50%, and smallest on trials for which it was 80%. In contrast to RT2, the PRP effect on PE2 was larger in the neutral condition than the other two correlation conditions. More errors were made when S1 and S2 correlation relation was neutral (50%).

The overadditive interaction of correlation condition and SOA on both RT1 and RT2 obtained in Experiment 5 was also replicated in the present experiment. Although the comparison of low and neutral correlation conditions on RT1, PE1, and PE2 did not show a significant two-way interaction of correlation and SOA, there was a tendency toward to overadditive interaction. As predicted by the interactive conception, the S1-S2 correlation manipulation, primarily affecting the pre-bottleneck processing of S-R translation, should show crosstalk effects on RT1 as well as RT2. Such crosstalk effects were also affected strongly by the degree of temporal overlap of the processing between two tasks: larger temporal overlap between two tasks, larger crosstalk effect. Thus, the overadditive interaction of correlation condition and SOA obtained in the RT1 and RT2 data support the interaction conception hypothesis and contradict the hypothesis of the RSB model that decision-related processing of T2 cannot go on in parallel with T1.

The main focus of this experiment was the contrast of S1-S2 correlation effect between Experiments 5 and 6. In Experiment 5, a vocal response was used for T1 and a manual response for T2, whereas in Experiment 6, manual responses were used for both T1 and T2. The overall RTs were faster and the overall PEs smaller for both tasks in Experiment 5 than in Experiment 6, indicating that responses were made faster and more accurately when vocal and manual responses were used than when manual and manual responses were used. Although the three-way interaction of experiment, correlation, and SOA was significant for the comparisons of high/low and high/neutral correlation on RT1 and PE1 and for the comparisons of high/neutral correlation on RT2 and PE2, the effect of correlation across SOAs showed similar patterns between the two experiments. As we can see from Figures 7 and 8, the overadditive interaction of correlation and SOA on both RT1 and RT2 was larger in Experiment 6 than in Experiment 5. Thus, the combination of keypress responses for both tasks produce stronger overadditive interaction of correlation effect and SOA than the combination of vocal and keypress responses.

GENERAL DISCUSSION

The main purpose of the present study was to test implications of the interactive conception of the PRP effect, according to which response selection is not a single and unique processing stage, as most PRP models suggest. The interactive conception elaborates Hommel's (1998) two-process approach to response selection and suggests that the S-R translation of T2 can be processed automatically and simultaneously with the processing of T1, whereas the final response selection of T2 has to wait until the response selection of T1 is completed. As the S-R translation is assumed to proceed in parallel, the interactive conception predicts that between-task crosstalk and noncurrent-task response association, which primarily affect the pre-bottleneck S-R translation processing, will have an underadditive interaction with SOA when there is a contingency relation between the two tasks. Alternatively, when there is no contingency-based information included in the PRP experimental design, the two mechanisms of between-task crosstalk and noncurrent-task response association will not be activated. The interactive conception of the PRP effect, then, can be treated as a traditional RSB model but incorporating the distinction between two response-selection components. In short, the interactive conception implies that the contingency information activated during the S-R translation processing, such as between-task crosstalk and noncurrent-task response association, as well as the bottleneck in the final response-selection stage, will lead to a delay of RT2 to some extent. Moreover, the task contingency-based interaction is strongly determined by the time elapsing between the availability of information from each task, that is, the SOA in the PRP paradigm.

Summary of Experimental Findings

Experiments 1A and 1B were designed to examine whether when the contingency information was absent between two tasks, the interactive conception of the PRP effect could be treated as the traditional RSB model, but with two response-selection components. The visual-manual and auditory-vocal tasks in Greenwald and Shulman's (1973) study were used because they met the criterion of no contingency relations between the two tasks. The interactive conception predicts that the PRP effect should be obtained in the IM-IM condition because of the final response-selection bottleneck. In contrast to this prediction, Greenwald and Shulman concluded that the PRP effect was eliminated when the two tasks were ideomotor compatible because response selection was bypassed for these tasks. However, the general conclusion they drew from their study is questionable. Their two experiments offered conflicting outcomes, with one showing a PRP effect for the IM-IM group and the other not. One cannot be sure that either of these outcomes is replicable under the conditions in which they were obtained. Moreover, even if the results of both experiments are replicable, Greenwald and Shulman's interpretation that there is no PRP effect for the IM-IM combination relies on a strong assumption: The PRP effect in Experiment 1 is an artifact of the instructions that S2 would always follow S1, and the absence of the PRP effect in Experiment 2 is the valid measure of the extent to which two ideomotor compatible tasks can be performed concurrently.

The present Experiments 1A and 1B included the six SOAs from Greenwald and Shulman's Experiment 1, but used the instructions from their Experiment 2 that the stimuli would occur simultaneously on most trials. In Experiment 1A, a significant PRP effect of over 100 ms was again evident for all groups, with the effect in the IM-IM group being 164 ms for RT2 alone and 70 ms for the average of RT1 and RT2. In Experiment 1B, a design similar to that of Experiment 1A was used, except that the responses were left-right keypresses, rather than left-right joystick movements. Left-right keypress responses have been suggested to be as highly compatible with left-right arrow directions as are left-right switch movements (e.g., Eimer, 1995; Wang & Proctor, 1996). Results in Experiment 1B showed significant PRP effects for all groups, with that for the IM-IM group being 136 ms for RT2 alone and 64 ms for the average of RT1 and RT2. There was no significant difference between Experiments 1A and 1B in the magnitude of the PRP effect for any of the four groups, indicating that tasks involving joystick movements and keypresses yield similar PRP effects.

A closer procedure to Greenwald and Shulman's (1973) Experiment 2 was adopted in Experiment 2, with only the three shortest SOAs (0, 100, and 200 ms) and the longest SOA (1,000 ms) being used. The results showed a significant PRP effect for all groups, with the effect in the IM-IM group being 85 ms for RT2 alone and 50 ms for the average of RT1 and RT2. Compared to Experiments 1A and 1B, the size of the PRP effect for the IM-IM group was reduced in Experiment 2, but it was not eliminated as in Greenwald and Shulman's Experiment 2. Thus, neither instructing participants that most often S1 and S2 would be presented simultaneously (Experiments 1A, 1B, and 2), nor using only 0-, 100-, 200-, and 1000-ms SOAs (Experiment 2) seems to be responsible for the absence of a PRP effect for the IM-IM group in Greenwald and Shulman's Experiment 2.

The data in Experiments 1 and 2 showed consistently that a PRP effect was evident when both RT2 alone and the average of RT1 and RT2 were analyzed in close replications of Greenwald and Shulman's (1973) experiments, in which no contingency existed between two tasks. Greenwald and Shulman argued that the PRP effect could be eliminated when two tasks were ideomotor compatible, as shown in their Experiment 2, because the S-R translation and response selection for these tasks were bypassed. However, the interactive conception assumes that although the S-R translation of T2 can proceed automatically and in parallel with that of T1, the final response decision has to be made sequentially for both tasks. Thus, when final response decisions must be made for both tasks, the PRP effect should be evident even with two highly ideomotor compatible tasks. The results in the present Experiments 1A, 1B, and 2 are consistent with predictions of the interactive conception in showing a significant PRP effect when the two tasks were ideomotor compatible. If, as suggested by Greenwald and Shulman, the disappearance of the PRP effect for the IM-IM group in their Experiment 2 was due to instructing participants that most often the stimuli for the two tasks would be presented simultaneously, then a significant PRP effect should not have been evident with those instructions in the present experiments. In fact, although Greenwald and Shulman depict the instructions as being the crucial methodological factor differentiating their Experiment 1 from Experiment 2, their experiments also differed in the SOAs included and in whether or not single-task blocks were intermixed with the dual-task blocks. Thus, it is not apparent which, if any, of these variables is responsible for eliminating the

PRP effect in their Experiment 2 but not their Experiment 1. Moreover, the contention that the elimination of PRP effects is due entirely to the type of tasks used, as most citations of Greenwald and Shulman's study indicate, is unsustainable on the basis of the results obtained in Experiments 1 and 2.

The purpose of Experiment 3 was to test the prediction of the interactive conception that no PRP effect should be found when R1 is not required in the dual task where no contingency exists. It also provided further evidence pertaining to the hypothesis that S-R translation and final response decision are two distinct processing components, as proposed by the interactive conception of the PRP effect. An experimental design similar to that of Experiment 2 was used, with the only difference being that participants were instructed to ignore S1 and only respond to T2 in Experiment 3. Although a significant main effect of SOA on RT2 was found in both IM-SR and IM-IM groups, the RT2 did not show a monotonic decreasing pattern when SOA increased, as in a typical PRP effect. Specifically, the RT2 decreased 26 ms when SOA decreased from 1,000 ms to 0 ms in the IM-IM condition. Moreover, the PRP effect on PE2 was not evident in the IM-IM condition. According to the interactive conception, the final response-selection bottleneck is responsible for the delay of RT2 when there is no contingency between two tasks. By requiring only R2 in the dual-task conditions, the final response selection of T2 should not be delayed because of the absence of the final response-selection processing of T1. Thus, when there is no contingency, the PRP effect should be eliminated when only R2 is required, regardless of what the task combinations are, as shown in Experiment 3.

Although several experiments have provided evidence that the PRP effect is obtained even when no R1 is required, this outcome can be questioned. A close examination of the task arrangements used in these studies, such as a simple RT task in Davis's (1959) experiments and a go/no-go task in Van Selst and Johnston's (1999) studies, suggested that they are not appropriate designs to test the response-selection processing. Experiment 4 was conducted to examine the possibility of the PRP effect obtained due to the contingency bias between T1 and T2, rather than the final response-selection bottleneck. S1 and S2 had dimensional overlap color for one condition and not for another condition. Participants were required to respond to T2 only. From the depiction of the traditional RSB model, no dual-task interference should be found when R1 is not required regardless of S1-S2 relations. However, a significant PRP effect of 52 ms was obtained in the dimensional overlap condition, whereas only a 25 ms PRP effect was evident in the no overlap condition. The larger PRP effect obtained when there was dimensional overlap between S1 and S2 than when there was not implies that the contingency bias between T2 and T2, in addition to the final response-selection bottleneck, could delay the processing of T2 even when R1 was not required. This outcome confirms the predictions of the interactive conception.

Experiment 5 examined the effects of S1-S2 correlation on the performance of the PRP task. The no overlap condition used in Experiment 4 was employed, with the major difference that a vocal response was required for T1 and manual response for T2. Three levels of correlation between S1 and S2, high (80%), low (20%), and neutral (50%), were used. An ordinary correlation effect was obtained for both RT1 and RT2, with the responses being faster in the high correlation trials, intermediate in the neutral trials, and slower in the low correlation trials. RT1 showed a reverse U-shape function of SOA, with the correlation effect being larger at the short SOAs than at the long SOAs. In addition, a substantial PRP effect was obtained for each correlation condition, with the effect being larger when the S1-S2 correlation was low than when it was neutral or high. This overadditive interaction of S1-S2 correlation with SOA obtained for both RT1 and RT2 reflects the fact that the effect of noncurrent-task response association is affected by the temporal overlap of the processing of the two tasks. That is, the effect of noncurrent-task response association decreases as SOA increases. This finding is important for ruling out the depiction of individual processing streams of two tasks in the PRP paradigm proposed by the traditional RSB model.

Experiment 6 examined whether the overadditive interaction of S1-S2 correlation and SOA could be obtained when left-right keypress responses were required for both tasks. Although RT1 was slower in the high correlation condition than in the neutral condition at the longest SOA, an ordinary correlation effect was, again, obtained for both RT1 and RT2 at the other SOAs. Responses were fastest in the high correlation trials, intermediate in the neutral trials, and slowest in the low correlation trials. RT1 showed an increasing function as SOA increased for the high correlation condition, whereas the function approached being flat for the neutral and low correlation conditions when SOA increased from 150 ms to 1,000 ms. For RT2, a substantial PRP effect was also obtained for each correlation condition, with the effect being largest when S1-S2 correlation was low (the PRP effect = 596 ms), intermediate when it was neutral (the PRP effect = 437 ms), and smallest when it was high (the PRP effect = 275 ms). The data analysis on the effect of S1-S2 correlation, as in Experiment 5, showed that an overadditive interaction of S1-S2 correlation with SOA obtained for both RT1 and RT2. This overadditive interaction reflects that the effect of noncurrent-task response association is strongly affected by the temporal overlap of the processing of the two tasks.

Although several studies have shown that cross-task crosstalk contributes to the PRP effect when the input or output for the tasks involve the same codes (e.g., Hommel, 1998; Lien & Proctor, 2000; Logan & Schulkind, 2000), Experiment 6 showed no effect involving R1-R2 spatial correspondence to be significant for each correlation condition. However, the R1-R2 spatial correspondence tended to slow the processing of T2 in the low correlation condition and speed the processing of T2 in the high correlation condition at the short SOAs more in Experiment 6 than in Experiment 5. Typically, the cross-task crosstalk effect in the PRP paradigm has been attributed to automatic response activation (e.g., Hommel, 1998; Lien & Proctor, 2000) and tends to decrease as SOA increases. In addition, Umiltá, Snyder, and Snyder (1972) attributed the consistently slower RT in the low probability condition than in the high probability condition to participants' knowledge of objective event probabilities that enabled them to respond faster to the more likely events. Accordingly, R1-R2 spatial correspondence relation tended to produce a larger correlation effect at the short SOA.

The comparison of Experiments 5 and 6 showed that the overall RTs were slower and PEs higher for both tasks in Experiment 6 than in Experiment 5. This finding indicates that requiring manual responses for both tasks may induce conflicts in response selection and execution, thus increasing RTs and error rates (e.g., De Jong, 1993; Ruthruff, Johnston, & Van Selst, 2001; Van Selst et al., 1999). Moreover, only RT1 and RT2 in the high correlation condition were affected by the combination of response modalities for both tasks. In going from vocal-manual (Experiment 5) to manual-manual (Experiment 6) task, the increasing of RT1 when SOA increased from 0 ms to 1,000 ms was elevated from 63 ms in Experiment 5 to 290 ms in Experiment 6. In contrast, the PRP effect was reduced dramatically from 406 ms to 275 ms. Interestingly, the overadditive interaction of correlation condition and SOA obtained on RT1 and RT2 for each pair-wise comparison of correlation conditions in Experiment 5 was replicated in Experiment 6, with the effect being larger at the short SOA in Experiment 6 than in Experiment 5. Given the assumption of the traditional RSB model that response selection on T2 has not started while the decision-related processing of T1 is going on, the effect of S1-S2 correlation on RT1 being larger at the short SOA than the others is not easily accommodated by the model.

Previous Studies of Response Selection

Previous research on S-R compatibility effects has suggested that there are at least two processing components within the response-selection system: automatic response activation and intentional S-R translation (e.g., Kornblum et al., 1990). When a stimulus is presented, it automatically activates its corresponding response even when that response is not the one assigned to the task. This automatic activation can occur even for stimulus attributes that are irrelevant to the task but will decay if the activated response is defined as irrelevant. According to Kornblum and his colleagues, the strength of automatic activation is a function of the similarity (or dimensional overlap), both conceptually and perceptually, among the relevant stimulus dimension, irrelevant stimulus dimension, and the response dimension. On the other hand, the intentional translation is presumed to occur on the basis of task-defined S-R associations. When the relation between stimuli and responses is systematic, translation can occur by application of a single rule, for example, same (corresponding) or opposite (mirror), rather than by means of the specific S-R association. On the whole, studies of S-R compatibility effects have shown evidence that response selection is a consequence of interactive activation of responses from a number of sources and is affected by variables such as timing and S-R modalities.

In contrast, the RSB model for the PRP effect depicts response-selection processing as a single component forming a bottleneck that can only deal with one task at a time. The model assumes that T2 processing prior to the bottleneck can proceed in parallel with T1, whereas T2 processing after the bottleneck must wait for the completion of the response selection for T1. Evidence supporting the RSB model is that manipulations of perceptual variables on T2 typically have underadditive interactions with SOA, and manipulations of response-selection difficulty on T2 often have additive effects with SOA.

In order to account for the S-R compatibility effect in a PRP paradigm, Hommel's (1998) two-process approach was developed on the basis of two components of response selection hypothesis that was drawn from the S-R compatibility literature. The underadditive interactions of R2-S1 and R2-R1 compatibility effects with the effect of SOA found in Hommel's Experiment 3 indicate a fundamental distinction between the processing of S-R translation and final response selection: S-R translation of T2 is active while S-R translation of T1 is active, but the final response decision for T2 cannot be made until that for T1 is completed. Evidence of crosstalk between T1 and T2 questions the assumption of a single response-selection mechanism made by the RSB model.

Nevertheless, the S-R sets used in Hommel's experiment overlapped in a very specific manner: R2 was related to S1 or R1. This leads to a possibility that crosstalk between S-R translations of two tasks occurs when there is contingency between the two task sets.

The Interactive Conception Account

As discussed throughout this study, the overall pattern of compatibility effects in the PRP paradigm obtained in the present research can be explained by the interactive conception. This account of the PRP effect, as Hommel's (1998) two-process approach, assumes that S-R translation and final response selection are two distinct processing components, with the S-R translation being processed concurrently and the final response selection successively for two tasks. More importantly, the interaction between two tasks in the PRP paradigm is determined by the between-task crosstalk and noncurrent-task response association mechanisms. However, the effects produced by these two mechanisms are contingency based and are determined by the degree of the temporal overlap between the processing of the two tasks.

The interactive conception predicts that when there is no contingency included in the PRP experimental design, the between-task crosstalk and noncurrent-task response association mechanisms are not activated. Consequently, the interactive conception of the PRP effect acts as the traditional RSB model, but with the modification that S-R translation is a distinct component from the final response-selection bottleneck and can proceed concurrently for both tasks. The PRP effect, thus, can be attributed primarily to a bottleneck in the final response-selection stage. The unique prediction of the interactive conception is made for the conditions where the contingency exists in the PRP paradigm. Accordingly, the contingency relation between two tasks is determined by (1) the dimensional overlap, (2) the strength of correlation, and (3) the temporal overlap of processing between two tasks. The effect of contingency relation is primarily on the S-R translation stage and allows crosstalk to occur between two tasks. Thus, a bi-directional crosstalk effect on RT1 and RT2 would be evident with the effect being larger at the short SOA than at the long SOA.

The PRP Effect

The results from Experiments 1-3 showed evidence in support of predictions made by the interactive conception of the PRP effect under no-contingency circumstances. Most important is that when no contingencies were included in the design of a PRP task, the delay of RT2 at the short SOA was predicted well by the assumption that independent response decisions concerning each task are made sequentially. The primary exception to obtaining the PRP effect in such situations is the result found in Greenwald and Shulman's (1973) Experiment 2, in which two tasks of high ideomotor compatibility were used and the instructions did not emphasize the order of presentation for S1 and S2. The seeming reason why this experiment showed little or no PRP effect, whereas others did, is that in addition to the component tasks being highly ideomotor compatible, there was no contingency between the two tasks. That is, S1 and R1 did not have dimensional overlap with S2 and R2 (T1 was visual left-right arrow directions mapped to left-right joystick movements and T2 was auditory letters A and B mapped to vocal responses "A" and "B").

A close procedure to Greenwald and Shulman's (1973) Experiment 2 was adopted in Experiments 1-2. The results in Experiments 1A, 1B, and 2 showed a significant PRP effect for all groups, with the effect in the IM-IM group being 164 ms, 137 ms, and 85 ms for RT2 alone and 70 ms, 64 ms, and 50 ms in Experiment 1A, 1B, and 2, respectively. If, as suggested by Greenwald and Shulman, the disappearance of the PRP effect for the IM-IM group in their Experiment 2 was due to instructing participants that most often the stimuli for the two tasks would be presented simultaneously, then a significant PRP effect should not have been evident with those instructions in Experiments 1 and 2. Moreover, Greenwald and Shulman suggested that the IM-IM tasks produced little PRP effect because response-selection processing for each task is bypassed. The contention that the elimination of PRP effects is due entirely to the type of tasks used, as most citations of Greenwald and Shulman's study indicate, is unsustainable on the basis of results obtained in Experiments 1 to 2. In addition, when R1 was not required in tasks of the type used by Greenwald and Shulman, as examined in the present Experiment 3, the typical PRP effect was not observed.

One possible explanation for the residual PRP effect obtained in Experiments 1 and 2 but not in Experiment 3 is that of a response-selection bottleneck. According to the interactive conception account, the final response decisions for two tasks are processed in sequence when both R1 and R2 are required in the task, thus showing a delay in RT2 at the short SOA. The evidence from Experiments 1 and 2, which followed Greenwald and Shulman's (1973) methods closely, indicates that it is simply incorrect to state that the PRP effect is eliminated when two tasks are ideomotor compatible. Moreover, the data suggest that a stubborn residual bottleneck can remain even with two highly compatible tasks and no inter-task contingency, which is consistent with the distinctions between S-R translation and final response selection hypothesized by the interactive conception account.

Contingency Effect

Although the PRP effect obtained in Experiments 1-2 was due to the bottleneck, the magnitude of the effect showed sensitivity to the contingency relation of dimensional overlap (Experiment 4) and correlation (Experiments 5 and 6) between two tasks that are assumed to affect primarily the S-R translation processing of T1 and T2. The effect produced by the contingency on RT1 and RT2 is also affected by the temporal overlap between the processing of the two tasks. As predicted by the notion that the contingency relation of S1-S2 dimensional overlap delays RT2 at the short SOA, the results in Experiment 4 showed that a 52-ms PRP effect was evident in the dimensional overlap condition even though R1 was not required. Although the PRP effect was also obtained significantly in the no overlap condition, the effect was only 25 ms. A possible reason for obtaining a small PRP effect in the no overlap condition is because the conditions were varied as a within-subject variable, which may produce a carry-over effect from the condition with dimensional overlap to the one without.

If S-R translation processing is sensitive to the contingency information, and the magnitude of the contingency effect is determined by the temporal overlap between the two tasks, as the interactive conception proposes, the overadditive interaction of correspondence effect on RT2 found in previous studies can be easily explained. In addition, the hypothesis of parallel processing of S-R translation for both tasks in the interactive conception of the PRP effect allows the forward and backward crosstalk to affect the processing of T1 and T2 at short SOAs. Thus, the overadditive interaction of the effect with SOA should be obtained in both RT1 and RT2. This prediction was confirmed by the findings of Experiment 5, in which the correlation relation between S1 and S2 showed an overadditive interaction with SOA for both RT1 and RT2. This overadditive interaction was even stronger when a left/right keypress response was required for both tasks in Experiment 6 than when a vocal response was used for T1 and a keypress response for T2 in Experiment 5. It is not surprising that a residual PRP effect was also obtained in both Experiments 5 and 6 because of the crosstalk effect on the S-R translation processing and the bottleneck on the final response selection stage.

In sum, the interactive conception predicts that the PRP effect disappears only when there are no contingency relations between two tasks and when R1 is not required. The PRP effect is evident when a contingency exists between two tasks, regardless of whether R1 is required. This is because the interactive conception of the PRP effect assumes that the between-task crosstalk effect, in addition to the bottleneck, contributes to the delay in RT2. The results from Experiments 1-6 support the proposed architecture of the interactive conception of the PRP effect, which places the locus of inter-task contingency effects within the S-R translation processes and the locus of the bottleneck within the final response-decision processes. In other words, these results verify the hypothesis of the distinction between S-R translation and final response decision in the response-selection mechanism.

Implications for the PRP Literature

There are two major implications that can be drawn from the present study for the PRP literature: Two components of response selection must be distinguished, and a residual PRP effect exists when there is contingency between two tasks. As described in several PRP studies, little dual-task interference was found in certain cases where one or both tasks involved an extremely compatible mapping between stimuli and responses (e.g., Greenwald & Shulman, 1973; McLeod & Posner, 1984; Pashler, Carrier, & Hoffman, 1998). Particularly, Greenwald and Shulman's study has been widely cited in the dual-task performance literature for the past 28 years as showing that the PRP effect is eliminated when the two tasks are ideomotor compatible (e.g., Brebner, 1977; De Jong, 1995, 1997; Meyer & Kieras, 1997a, 1999; Pashler, 1998, 2000; Schumacher, et al., 1999; Van Selst, Ruthruff, & Johnston, 1999).

However, the elimination of the PRP effect in Greenwald and Shulman's (1973) Experiment 2 failed to replicate in the present Experiments 1A, 1B, and 2. Greenwald and Shulman suggested that the two ideomotor compatible tasks produced little PRP effect because each task did not require the normal process of translating stimuli into arbitrarily assigned responses. According to them, the stimulus for each task in the IM-IM condition generated a mental code that was already in the correct format for the response; therefore, no response-selection processing was necessary for these S-R mappings. If their assumption regarding the ideomotor compatible task is correct, then the traditional RSB model predicts that the PRP effect should be eliminated for conditions in which only one or two tasks are ideomotor compatible. Because the response-selection bottleneck can be bypassed for one or both tasks, there should be no delay of RT2 at short SOAs. However, Greenwald and Shulman's Experiments 1 and 2 showed PRP effects for the conditions in which one of the two tasks was ideomotor compatible. The present Experiments 1 and 2 similarly showed no indication of the PRP effect disappearing for either the SR-IM or IM-SR group. Moreover, even for the IM-IM group, significant PRP effects were obtained in the present experiments.

If the conception of ideomotor compatibility is correct, then it is reasonable to question the categorization of “S-R translation” and “response selection” as a single, conjoint response-selection process, as most PRP models have. Several recent PRP studies, however, have provided evidence leading to the conclusion that the S-R translation of T2, which can proceed automatically and concurrently with that of T1, is different from the response-selection decision (e.g., Hommel, 1998; Lien & Proctor, 2000; Logan & Schulkind, 2000). The hypothesis of two response selection components, as the interactive conception account suggests, is important in interpreting the PRP effect obtained in Greenwald and Shulman’s Experiment 1, the present Experiments 1 and 2, as well as other’s studies with two ideomotor compatible tasks (e.g., Brebner, 1977). Greenwald and Shulman’s logic regarding ideomotor compatibility seems to imply only that the S-R translation is not necessary for the ideomotor compatible task because the stimulus code serves as the response code. However, the final response-selection processing is still carried out for the ideomotor compatible task. The hypothesis of a final response-selection bottleneck in the interactive conception account predicts that a PRP effect should be evident, regardless of whether one or both tasks are ideomotor compatible.

The fact that the PRP effect was obtained within no-contingency conditions (Experiments 1 and 2) and contingency conditions (Experiments 4 and 6) implies that it would be extremely unlikely to eliminate to the PRP effect entirely. Several studies have attempted to eliminate the PRP effect with extensive practice, but all show little evidence that the PRP effect is abolished (e.g., Karlin & Kestenbaum; Ruthruff, Johnston, &Van Selst, 2001; Van Selst & Jolicoeur, 1997; Van Selst, et al., 1999). Although in some cases the PRP effect was reduced substantially with extensive practice, such dramatic reduction of the effect has been attributed primarily to the reduction in RT1. Automatization of S-R translation for both tasks may benefit from extensive practice, but the bottleneck remains at the locus of final response selection and may never be eliminated entirely. This results in a residual PRP effect (see the detailed discussion of the practice effect in Ruthruff et al., 2001), implying that the PRP effect is a robust phenomenon that is not eliminated through practice.

Conclusion

It seems clear now that Pashler's RSB model and Hommel's two-process approach of the PRP effect are insufficient to account for various results obtained in the present study. This is because the S-R compatibility manipulation cannot be adequately modeled by an approach that deals only with a single component of response selection (the RSB model) or one that deals with two distinct components of response selection without unambiguously defining how the variables affect them (the two-process approach).

The interactive conception of the PRP effect identifies between-task crosstalk and noncurrent-task response association in the S-R translation processing and the bottleneck in the final response-selection processing as the two primary factors in the PRP effect. More explicitly, the interactive conception addresses the fact that effects of between-task crosstalk and noncurrent-task response association become relevant to dual-task performance only if the two tasks include contingency information. In sum, the results obtained in this study provide insight into the PRP effects, emphasizing that the complex activation pattern between various task manipulations will affect dual-task performance. Therefore, better control and examination of relations between tasks, as well as within tasks, is necessary and crucial in the study of the compatibility effect within a PRP paradigm. Choosing response-selection variables more systematically on the basis of their likely effects on information processing is also critical in providing a complete understanding of dual-task performance.

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APPENDICES

Appendix A

Tables

Table 1.

A Taxonomy of Stimulus-Response Ensembles From Kornblum's Dimensional Overlap Model. From "Dimensional Overlap and Dimensional Relevance in Stimulus-Response and Stimulus-Stimulus Compatibility," by S. Kornblum, 1992, in G. E. Stelmach & J. Requin (Eds.), Tutorials in Motor Behavior II, pp. 743-777, Table 2.

Ensemble Type	**Overlapping Ensemble Dimensions**		
	Stimulus-Response Dimensions		Stimulus-Stimulus Dimensions
	Relevant	Irrelevant	
1	No	No	No
2	Yes	No	No
3	No	Yes	No
4	No	No	Yes
5	Yes	Yes	No
6	Yes	No	Yes
7	No	Yes	Yes
8	Yes	Yes	Yes

Table 2.

The Possible Sources of Correspondence Effects for Task 1 (T1) and Task 2 (T2) in a PRP Paradigm. S1r = the Relevant Information of the First Stimulus; S1ir = the Irrelevant Information of the First Stimulus; S2r = the Relevant Information of the Second Stimulus; S2ir = the Irrelevant Information of the Second Stimulus; R1 = the First Response; R2 = the Second Response.

Task	**Overlapping Dimensions**				
	Within-Task		Between-Task		
	Stimulus-Response Dimensions		Stimulus-Response Dimensions		Response-Response Dimensions
T1	S1r-R1	S1ir-R1	S2r-R1	S2ir-R1	R2-R1
T2	S2r-R2	S2ir-R2	S1r-R2	S1ir-R2	R1-R2

Table 3.

Error Proportions for Task 1, Task 2, and Their Average, in Experiment 1A as a Function of T1 Condition (Stimulus-Response Compatible Condition and Ideomotor Compatible Condition), T2 Condition (Stimulus-Response Compatible Condition and Ideomotor Compatible Condition), and Stimulus Onset Asynchrony (0, 100, 200, 300, 500, and 1,000 ms).

Task Combination	SOA 0	100	200	300	500	1,000
			Task 1			
SR-SR	.05	.04	.04	.04	.04	.04
SR-IM	.05	.03	.03	.04	.03	.05
IM-IM	.05	.02	.02	.02	.02	.03
IM-SR	.05	.03	.02	.03	.03	.04
			Task 2			
SR-SR	.06	.06	.04	.05	.04	.03
SR-IM	.02	.03	.02	.03	.02	.02
IM-IM	.02	.01	.02	.02	.02	.01
IM-SR	.06	.04	.04	.03	.02	.03
			Average			
SR-SR	.06	.05	.04	.04	.04	.04
SR-IM	.03	.03	.02	.04	.02	.03
IM-IM	.03	.01	.02	.02	.02	.02
IM-SR	.05	.04	.03	.03	.02	.03

Note. For Task 1, Task 2, and Average, the first of the task combination terms in each row refers to the task condition in Task 1 and the second to the task condition in Task 2. SR = stimulus-response compatible; IM = ideomotor compatible.

Table 4.

Error Proportions for Task 1, Task 2, and Their Average, in Experiment 1B as a Function of T1 Condition (Stimulus-Response Compatible Condition and Ideomotor Compatible Condition), T2 Condition (Stimulus-Response Compatible Condition and Ideomotor Compatible Condition), and Stimulus Onset Asynchrony (0, 100, 200, 300, 500, and 1,000 ms).

	SOA					
Task Combination	0	100	200	300	500	1,000
			Task 1			
SR-SR	.05	.04	.04	.03	.03	.03
SR-IM	.02	.02	.02	.03	.02	.01
IM-IM	.03	.02	.02	.02	.01	.02
IM-SR	.03	.03	.02	.01	.01	.02
			Task 2			
SR-SR	.08	.06	.06	.04	.04	.04
SR-IM	.03	.02	.03	.03	.02	.02
IM-IM	.03	.03	.03	.05	.04	.04
IM-SR	.06	.05	.04	.03	.03	.03
			Average			
SR-SR	.07	.05	.05	.04	.03	.04
SR-IM	.02	.02	.02	.03	.02	.01
IM-IM	.03	.03	.03	.03	.02	.03
IM-SR	.04	.04	.03	.02	.02	.03

Note. For Task 1, Task 2, and Average, the first of the task combination terms in each row refers to the task condition in Task 1 and the second to the task condition in Task 2. SR = stimulus-response compatible; IM = ideomotor compatible.

Table 5.

Error Proportions for Task 1, Task 2, and Their Average, in Experiment 2 as a Function of T1 Condition (Stimulus-Response Compatible Condition and Ideomotor Compatible Condition), T2 Condition (Stimulus-Response Compatible Condition and Ideomotor Compatible Condition), and Stimulus Onset Asynchrony (0, 100, 200, and 1,000 ms).

	SOA			
Task Combination	0	100	200	1,000
		Task 1		
SR-SR	.04	.06	.03	.03
SR-IM	.02	.03	.02	.03
IM-IM	.03	.04	.03	.04
IM-SR	.02	.03	.02	.03
		Task 2		
SR-SR	.06	.05	.04	.05
SR-IM	.05	.03	.03	.06
IM-IM	05	.06	.04	.06
IM-SR	.04	.03	.03	.05
		Average		
SR-SR	.05	.05	.03	.04
SR-IM	.04	.03	.02	.04
IM-IM	.04	.05	.03	.05
IM-SR	.03	.03	.03	.04

Note. For Task 1, Task 2, and Average, the first of the task combination terms in each row refers to the task condition in Task 1 and the second to the task condition in Task 2. SR = stimulus-response compatible; IM = ideomotor compatible.

Table 6.

Mean Reaction Times (in ms) and Error Proportions for Task 2, in Experiment 3 as a Function of T1 Condition (Stimulus-Response Compatible Condition and Ideomotor Compatible Condition), T2 Condition (Stimulus-Response Compatible Condition and Ideomotor Compatible Condition), and Stimulus Onset Asynchrony (0, 100, 200, and 1,000 ms).

Task Combination	SOA 0	SOA 100	SOA 200	SOA 1,000
	Reaction Times			
SR-SR	605	603	603	621
SR-IM	534	528	526	551
IM-IM	513	501	500	539
IM-SR	617	589	579	598
	Error Proportions			
SR-SR	.05	.04	.07	.05
SR-IM	.05	.05	.04	.05
IM-IM	.06	.04	.07	.06
IM-SR	.04	.03	.03	.02

Note. For reaction times and error proportions, the first of the task combination terms in each row refers to the task condition in Task 1 and the second to the task condition in Task 2. SR = stimulus-response compatible; IM = ideomotor compatible.

Table 7.

Mean Reaction Times (in ms) and Error Proportions for Task 2, in Experiment 4 as a Function of S1-S2 Relations (dimensional overlap and no dimensional overlap) and Stimulus Onset Asynchrony (0, 100, 200, and 1,000 ms).

S1-S2 Relations	SOA				
	0	150	300	500	1,000
			Reaction Times		
Overlap	527	500	482	472	475
No Overlap	440	408	406	403	415
			Error Proportions		
Overlap	.04	.05	.04	.04	.04
No Overlap	.03	.03	.02	.02	.02

Table 8.

Error Proportions for Task 1 and Task 2, in Experiment 5 as a Function of S1-S2 Correlation (High, Low, and Neutral Correlation Conditions) and Stimulus Onset Asynchrony (0, 150, 300, 500, and 1,000 ms).

S1-S2 Correlation	SOA				
	0	150	300	500	1,000
			Task 1		
High (80%) Correlation	.04	.03	.03	.03	.03
Low (20%) Correlation	.07	.10	.11	.05	.05
Neutral (50%) Correlation	.04	.05	.05	.03	.03
			Task 2		
High (80%) Correlation	.04	.02	.03	.03	.03
Low (20%) Correlation	.12	.11	.15	.11	.09
Neutral (50%) Correlation	.05	.05	.05	.04	.05

Table 9.

Error Proportions for Task 1 and Task 2, in Experiment 6 as a Function of S1-S2 Correlation Relation (High, Low, and Neutral Correlation Conditions), R1-R2 spatial relation (Corresponence and Noncorrespondence), and Stimulus Onset Asynchrony (0, 150, 300, 500, and 1,000 ms).

Task Relation	SOA				
	0	150	300	500	1,000
			Task 1		
High-Corr	.05	.05	.05	.06	.07
High-Noncorr	.04	.07	.07	.05	.09
Low-Corr	.22	.19	.18	.15	.17
Low-Noncorr	.23	.19	.14	.08	.11
Neutral-Corr	.13	.10	.07	.09	.08
Neutral-Noncorr	.13	.11	.10	.06	.07
			Task 2		
High-Corr	.04	.05	.06	.07	.08
High-Noncorr	.05	.07	.07	.07	.11
Low-Corr	.23	.22	.20	.17	.20
Low-Noncorr	.15	.18	.17	.15	.18
Neutral-Corr	.14	.10	.09	.12	.11
Neutral-Noncorr	.13	.09	.10	.10	.10

Note. The first of the task relation terms in each row refers to the S1-S2 correlation and the second to R1-R2 spatial relation. High = 80% correlation; Low = 20% correlation; Neutral = 50% correlation; Corr = response 1 and response 2 correspondent; Noncorr = response 1 and response 2 noncorrespondent.

APPENDIX B

Figures

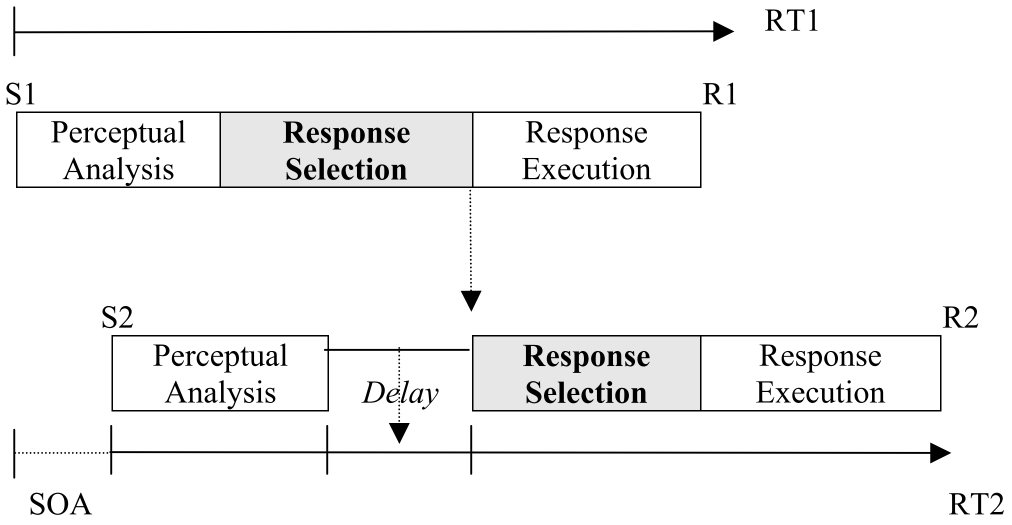
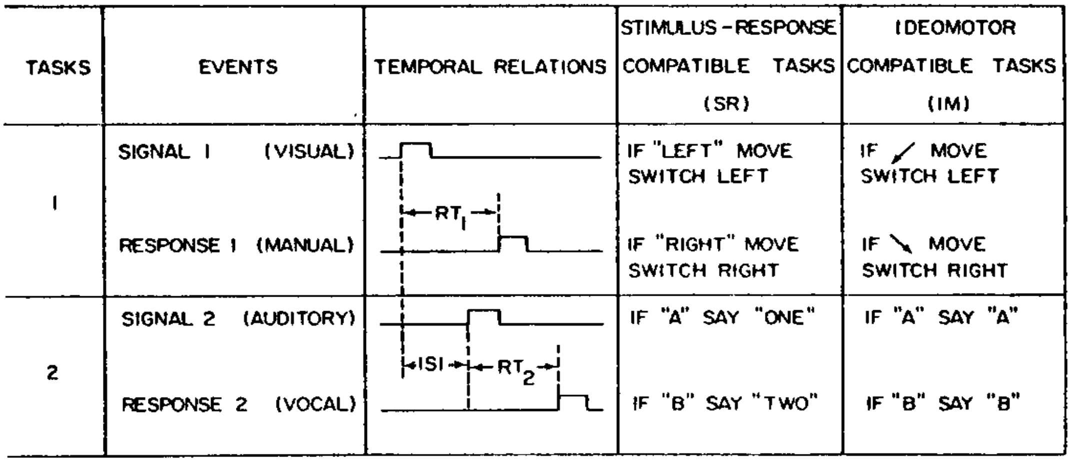


Figure 1. Pashler's response-selection bottleneck model for dual-task performance. The response selection stage for Task 2 (T2) cannot begin until the response selection for Task 1 (T1) has been completed. S1 = the first stimulus; S2 = the second stimulus; R1 = response to S1; R2 = response to S2; RT1 = reaction time for T1; RT2 = reaction time for T2; SOA = stimulus onset asynchrony.

PSYCHOLOGICAL REFRACTORY PERIOD EXPERIMENTS
PROCEDURE



TASKS	EVENTS	TEMPORAL RELATIONS	STIMULUS-RESPONSE COMPATIBLE TASKS (SR)	IDEOMOTOR COMPATIBLE TASKS (IM)
1	SIGNAL 1 (VISUAL)		IF "LEFT" MOVE SWITCH LEFT	IF ↙ MOVE SWITCH LEFT
	RESPONSE 1 (MANUAL)	RT_1	IF "RIGHT" MOVE SWITCH RIGHT	IF ↘ MOVE SWITCH RIGHT
2	SIGNAL 2 (AUDITORY)		IF "A" SAY "ONE"	IF "A" SAY "A"
	RESPONSE 2 (VOCAL)	ISI RT_2	IF "B" SAY "TWO"	IF "B" SAY "B"

FIG. 1. Tasks and procedures. (RT = reaction time; ISI = interstimulus interval.)

Figure 2. The tasks and procedures used in Greenwald and Shulman's study. From "On doing two things at once: II. Elimination of the psychological refractory period effect," by A. G. Greenwald & H. G. Shulman, 1973, Journal of Experimental Psychology, 101, 70-76, Figure 1.

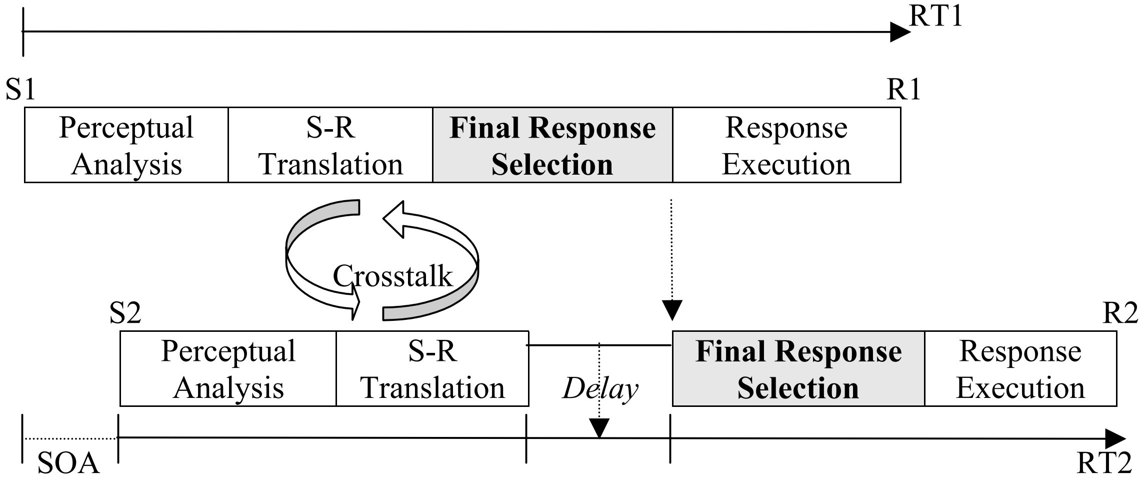


Figure 3. The two response-selection components approach proposed by Hommel (1998). The stimulus-response (S-R) translation of Task 2 can be processed with that of Task 1 in parallel and allow crosstalk to affect the response activation for both tasks. The final response selection of T2 cannot be made until the final response decision of T1 has been completed. S1 = the first stimulus; S2 = the second stimulus; R1 = response to S1; R2 = response to S2; RT1 = reaction time for T1; RT2 = reaction time for T2; SOA = stimulus onset asynchrony.

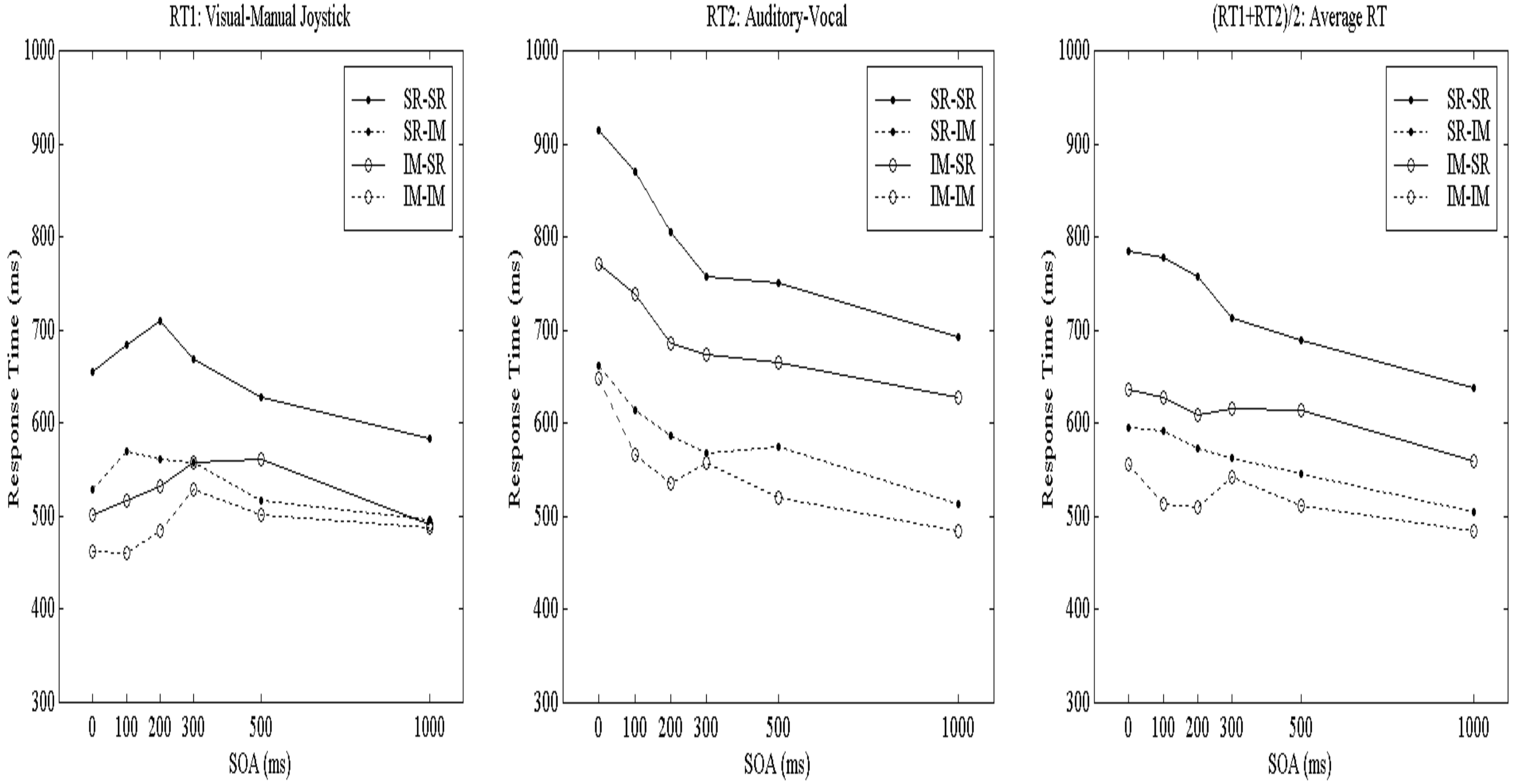


Figure 4. Results of Experiment 1A. (SR = stimulus – response compatible; IM = ideomotor compatible; RT1= response time for Task 1; RT2= response time for Task 2; Average RT = the average of response time for Task 1 and Task 2).

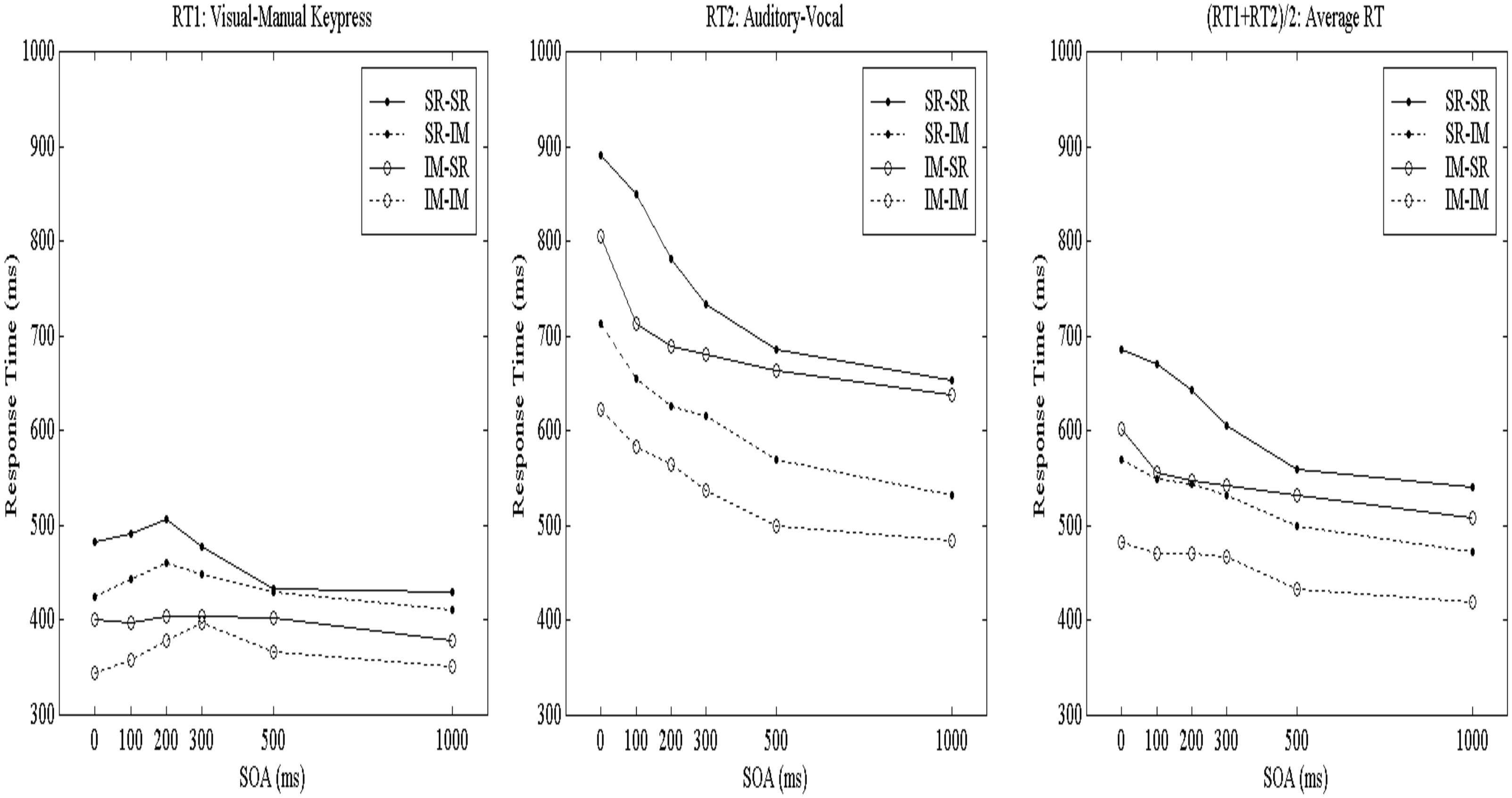


Figure 5. Results of Experiment 1B. (SR = stimulus – response compatible; IM = ideomotor compatible; RT1= response time for Task 1; RT2= response time for Task 2; Average RT = the average of response time for Task 1 and Task 2).

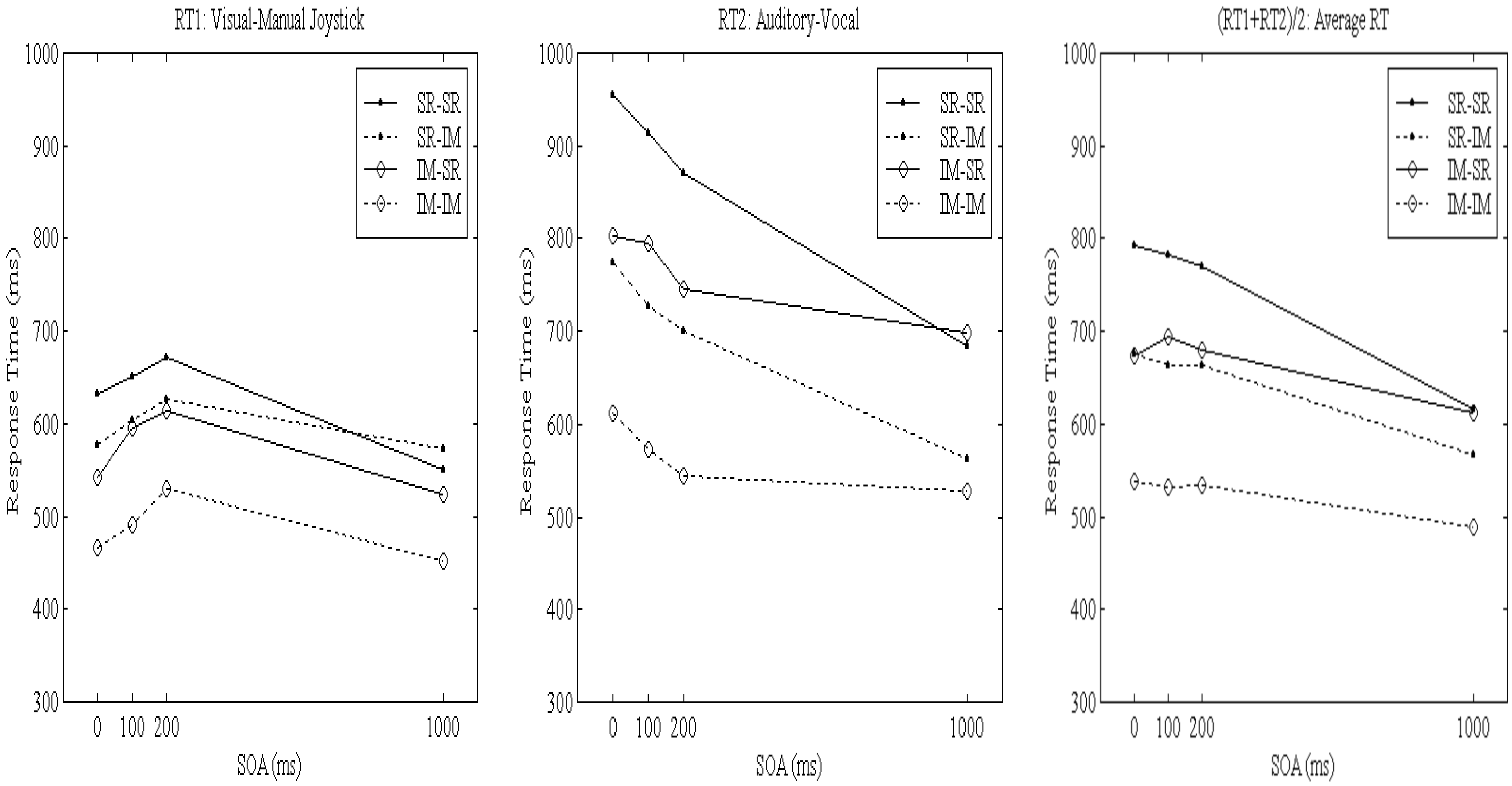


Figure 6. Results of Experiment 2. (SR = stimulus – response compatible; IM = ideomotor compatible; RT1= response time for Task 1; RT2= response time for Task 2; Average RT = the average of response time for Task 1 and Task 2).

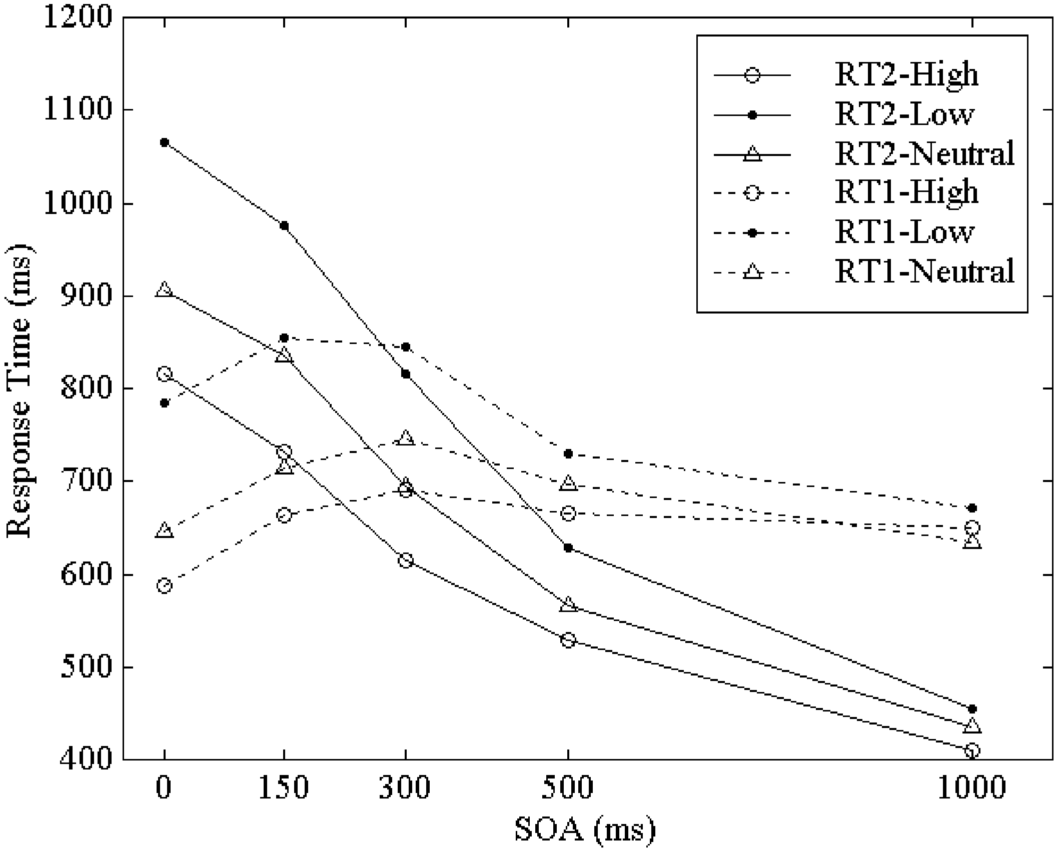


Figure 7. Mean response times (ms) for Task 1 and Task 2 in Experiment 5 as a function of S1-S2 correlation (high, low, and neutral) and SOA (0, 150, 300, 500, and 1,000 ms). (RT1 = response time for Task 1; RT2 = response time for Task 2; High = 80% correlation between S1 and S2; Low = 20% correlation between S1 and S2; Neutral = 50% correlation between S1 and S2).

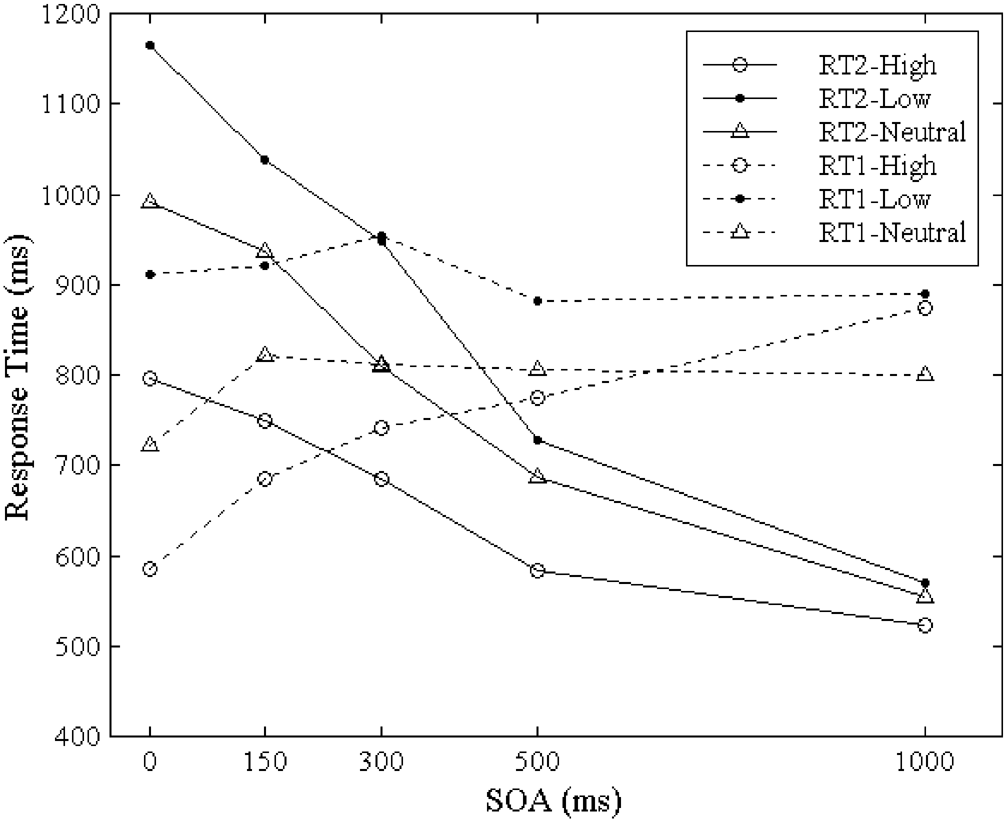


Figure 8. Mean response times (ms) for Task 1 and Task 2 in Experiment 6 as a function of S1-S2 correlation (high, low, and neutral) and SOA (0, 150, 300, 500, and 1,000 ms). (RT1 = response time for Task 1; RT2 = response time for Task 2; High = 80% correlation between S1 and S2; Low = 20% correlation between S1 and S2; Neutral = 50% correlation between S1 and S2).

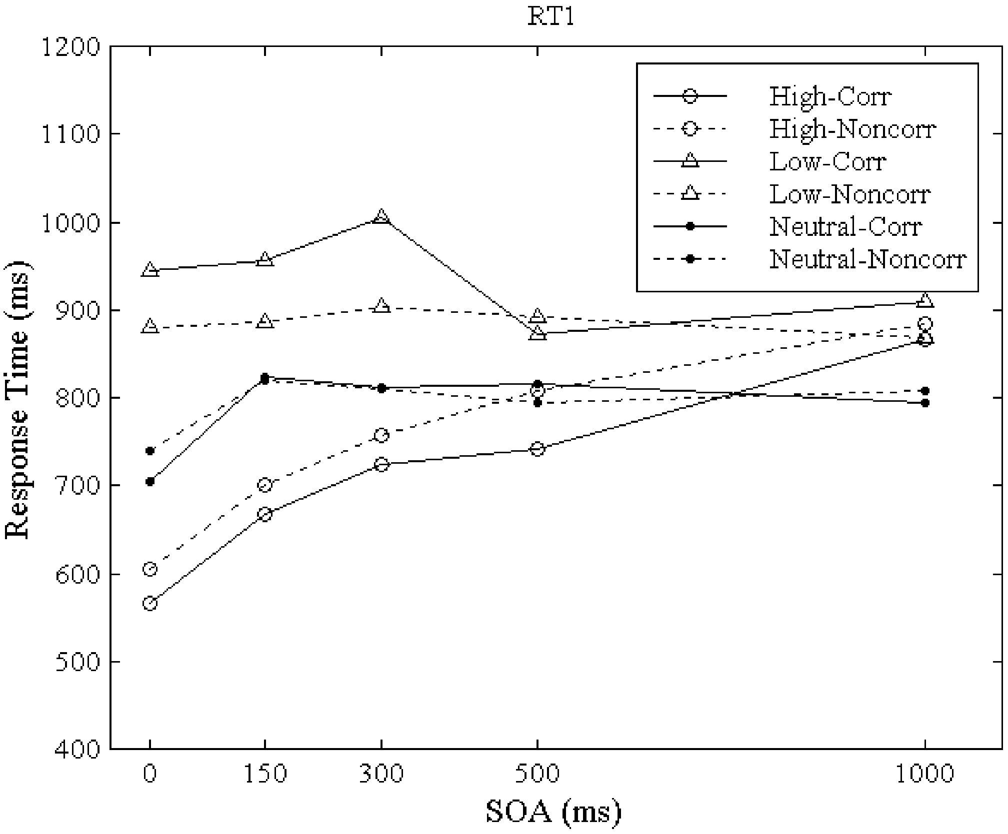


Figure 9. Mean response times (ms) for Task 1 in Experiment 6 as a function of S1-S2 correlation (high, low, and neutral correlation conditions), R1-R2 correspondence (correspondent and noncorrespondent), and SOA (0, 150, 300, 500, and 1,000 ms). (RT2 = response time for Task 2; Corr = response 1 and response 2 correspondent; Noncorr = response 1 and response 2 noncorrespondent).

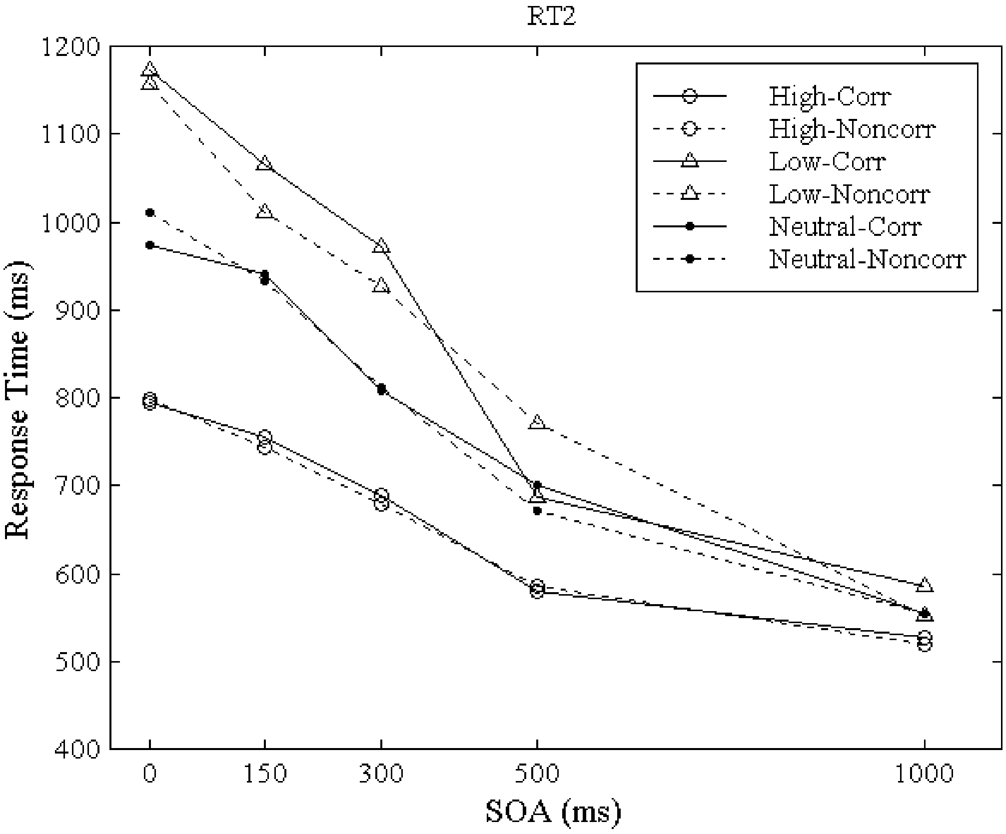


Figure 10. Mean response times (ms) for Task 2 in Experiment 6 as a function of S1-S2 correlation (high, low, and neutral correlation conditions), R1-R2 correspondence (correspondent and noncorrespondent), and SOA (0, 150, 300, 500, and 1,000 ms). (RT2 = response time for Task 2; Corr = response 1 and response 2 correspondent; Noncorr = response 1 and response 2 noncorrespondent).

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EDUCATION

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PUBLICATIONS

Allen, P. A., Smith, A. F., Lien, M.-C., Weber, T. A., & Madden, D. J. (1997). Word frequency effects at brief exposure duration: Comment on Raap and Johansen (1994). Journal of Experimental Psychology: Human Perception and Performance, 23, 1792-1797.

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