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ORIGINAL ARTICLE

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Is the psychological refractory period effect for ideomotor compatible tasks eliminated by speed-stress instructions?

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Abstract It has been argued that the psychological refractory period (PRP) effect is eliminated with two ideomotor compatible tasks when instructions stress fast and simultaneous responding. Three experiments were conducted to test this hypothesis. In all experiments, Task 1 required spatially compatible manual responses (left or right) to the direction of an arrow, and Task 2 required saying the name of the auditory letter *A* or *B*. In Experiments 1 and 3, the manual responses were keypresses made with the left and right hands, whereas in Experiment 2 they were left–right toggle-switch movements made with the dominant hand. Instructions that stressed response speed reduced reaction time and increased error rate compared to standard instructions to respond fast and accurately, but did not eliminate the PRP effect on Task 2 reaction time. These results imply that, even when response speed is emphasized, ideomotor compatible tasks do not bypass response selection.

Introduction

Interference between two concurrent tasks is a common finding. Such interference has been extensively studied in the psychological refractory period (PRP) paradigm, in which a stimulus (S1) for Task 1 (T1) is presented, followed after a variable interval by a stimulus (S2) for Task 2 (T2). Subjects are to respond as rapidly as possible for the two tasks, sometimes being told explicitly to respond to T1 before T2. Response times and percentage of errors for T1 (RT1 and PE1, respectively) and T2 (RT2 and PE2, respectively) are measured. The typical PRP effect is that RT2 is longer at short intervals between stimulus onsets (or, stimulus onset asynchronies; SOAs) than at long intervals. Because the PRP effect is a pervasive phenomenon, it seems to reflect a basic limitation in the ability to perform two tasks simultaneously (e.g., Lien & Proctor, 2002; Pashler, 1994; Pashler & Johnston, 1998; but see also Meyer & Kieras, 1997).

The most widely accepted account of the PRP effect is the all-or-none central bottleneck model (see Fig. 1). According to this model, stimulus identification and response initiation for the two tasks can be performed concurrently with no cost, but response selection can proceed for only one task at a time (e.g., Pashler, 1994, 1998; Welford, 1952). At short SOAs, response selection for T2 must wait until that for T1 is completed, resulting in the PRP effect. An alternative model that also attributes the PRP effect to a limited-capacity central process is that of central-capacity sharing (Navon & Miller, 2002; Tombu & Jolicœur, 2003). According to this model, response selection for T1 and T2 can occur in parallel, but the process is slowed because limited-capacity resources must be divided between the two tasks. The capacity-sharing model includes the central bottleneck model as a subcase, where full capacity is devoted initially to Task 1. Because both models attribute the PRP effect to a bottleneck that arises at response selection due to limited processing capacity, we use the term *response-selection bottleneck* in this paper to encompass both models.

Given the pervasiveness of the PRP effect, there has been considerable interest in whether conditions exist under which the effect can be eliminated and the response-selection bottleneck bypassed (see Lien, Ruthruff, & Johnston, 2006, for a review). Several recent studies have examined whether the PRP effect is

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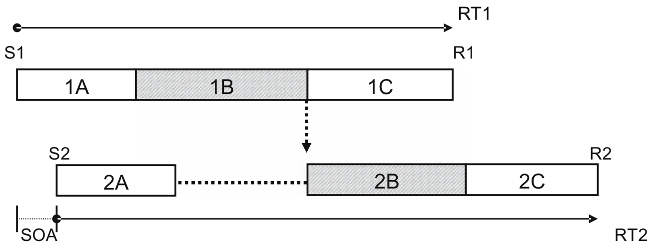

Fig. 1 All-or-none bottleneck model of dual-task performance. The key assumption is that stage 2B does not start until stage 1B is completed. Consequently, RT2 is delayed at short SOAs, causing the psychological refractory period effect. 1A, 1B, and 1C are, respectively, the pre-bottleneck, bottleneck, and post-bottleneck stages of Task 1. 2A, 2B, and 2C are the corresponding processes for Task 2. *S1* stimulus for Task 1; *S2* stimulus for Task 2; *R1* response for Task 1; *R2* response for Task 2; *RT1* response time for Task 1; *RT2* response time for Task 2; *SOA* stimulus onset asynchrony

eliminated after extensive practice (Hazeltine, Teague, & Ivry, 2002; Ruthruff, Johnston, & Van Selst, 2001; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003; Schumacher et al., 2001; Van Selst, Ruthruff, & Johnston, 1999). A few have shown that it is possible to virtually eliminate the PRP effect under some circumstances, but debate has continued over whether the bottleneck was actually eliminated in those studies (Hazeltine et al., 2002; Schumacher et al., 2001), or whether it was only latent (hidden) due to fast response selection for T1 (Ruthruff et al., 2001, 2003; Van Selst et al., 1999).

A separate issue is whether, for certain tasks in which the stimuli and responses are highly compatible, the response-selection bottleneck can be bypassed even without extensive practice. Greenwald and Shulman (1973) proposed that the bottleneck can be bypassed in this manner if the two tasks are both ideomotor compatible, that is, tasks for which the stimuli are physically similar to their sensory feedback (e.g., a shadowing task). Their basic idea was that for ideomotor compatible tasks the stimuli trigger their associated responses directly and do not require the normal response-selection mechanism. If such is in fact the case, it has significant implications for our understanding of perception-action relations (Prinz, 1987).

To test their proposal that ideomotor compatible tasks bypass response selection, Greenwald and Shulman (1973) had subjects move a joystick left to a left-pointing arrow in a left position or right to a right-pointing arrow in a right position for T1 and say "A" or "B" to the auditory stimulus *A* or *B* for T2. In Experiment 1, S1 and S2 were presented with a blocked 0-, 100-, 200-, 300-, 500-, or 1,000-ms SOA, and the instructions stressed that S2 always followed S1. RT2 showed a substantial PRP effect of approximately 100 ms for the condition in which both tasks were ideomotor compatible. In Experiment 2, only the 0-, 100-, 200-, and 1,000-ms SOAs were included, and subjects were told that the two stimuli would most often be presented simultaneously. In this case, there was no PRP effect for RT2, and the average of RT1 and RT2 did not vary significantly with SOA. Based on these results, Greenwald and Shulman concluded, "A major source of the PRP effect is a limited capacity mechanism that (a) translates between an encoded stimulus and a response code, and (b) is not needed when a task is ideomotor compatible" (p. 70).

For nearly 30 years, Greenwald and Shulman's (1973) study was widely accepted as having shown that perfect timesharing between T1 and T2 is possible, and the PRP effect can be eliminated with two ideomotor compatible tasks. However, certain aspects of their data did not seem in accord with their conclusion. Greenwald and Shulman's Experiment 1 showed a substantial PRP effect when both tasks were ideomotor compatible. Moreover, both of their experiments showed large PRP effects when one task was ideomotor compatible and the other was not, which would not be expected if the limited capacity response-selection mechanism were not needed for an ideomotor compatible task.

Lien, Proctor, and Allen (2002) reopened the issue of whether ideomotor compatible tasks bypass the bottleneck. They reported four experiments similar to the design of Greenwald and Shulman's (1973) Experiment 2. However, none of Lien et al.'s experiments showed the absence of the PRP effect with two ideomotor-compatible tasks. Instead, the results were similar to those of Greenwald and Shulman's (1973) Experiment 1, which did show a PRP effect. Consequently, Lien et al. (2002) found no evidence that ideomotor compatible tasks, in general, bypass the response-selection bottleneck.

Greenwald (2003) challenged Lien et al.'s (2002) conclusions, attributing Lien et al.'s failure to replicate Greenwald and Shulman's (1973, Experiment 2) findings of perfect timesharing to three procedural differences: (1) Lien et al.'s manual task required subjects to stabilize the joystick with their non-dominant hand, which may have made the task non-ideomotor compatible; (2) Lien et al.'s instructions did not stress rapid and simultaneous responding to S1 and S2; (3) Lien et al.'s intervals between trial onsets varied between approximately 2 and 4 s, whereas those of Greenwald and Shulman were a constant 4 s.[1]

Greenwald (2003) reported a new experiment focusing on the second of these three procedural differences, which concerned the nature of the instructions. The experiment was similar to those of Greenwald and Shulman (1973) and Lien et al. (2002), except that the manual responses were keypresses made with the left and right index fingers instead of unimanual movements

[1] In Lien et al.'s (2002) study, the interval varied as a function of the subject's reaction time, the time for the experimenter to enter the identity of the vocal response into the computer, and whether error feedback of 1,000 ms was provided.

of a response device. Half of the subjects received Lien et al.'s instructions, which emphasized both speed and accuracy ("respond to each task as quickly and accurately as you can"). The other half received instructions that Greenwald recollected to be Greenwald and Shulman's instructions, which emphasized response speed ("respond as rapidly as you can while maintaining a high rate of accuracy", with a reminder to respond "very rapidly" before each block and, for the 0-ms SOA condition, "to make two responses at the same time"). Greenwald found a significant PRP effect of 43 ms using Lien et al.'s speed-and-accuracy instructions but no PRP effect on RT using the speed-stress instructions. Based on this latter finding, Greenwald concluded, "Both (a) the G&S [Greenwald & Shulman] finding of perfect timesharing of IM-compatible [ideomotor-compatible] tasks is replicable, and (b) replication of G&S's finding depends on instructions to respond simultaneously in the dual-task condition with ISI = 0 [interstimulus interval, or what we call SOA]" (p. 866).

Greenwald (2003) offered an alternative interpretation of the role of ideomotor compatibility in perfect timesharing that accounts for the dependence on instructions to respond rapidly and simultaneously. This account envisions

> response selection as done in large part by a preparation process that precedes stimulus presentation. This anticipatory preparation can be conceived as priming (or subthreshold activation) of the sensory and motor loci that are needed, respectively, to register the expected stimuli and to initiate the appropriate responses. This preparatory activation can be assumed to reduce the response-selection work that must be done after arrival of the stimulus. If the preparation includes a high level of activation of the task's needed sensorimotor pathways, then registration of a stimulus functions mainly as a trigger to activate the appropriate response. It may be especially easy to maintain high activation of sensorimotor pathways for IM-compatible tasks because of the (theorized) representational overlap between their sensory and motor sites. (p. 867)

In essence, the new account provided by Greenwald retains the view that, for ideomotor compatible tasks, a stimulus can directly trigger its response, but adds the stipulation that this direct triggering occurs only when the instructions have motivated subjects to engage in pre-activation of the sensorimotor pathways.

Consistent with Greenwald's (2003) account, speed-stress instructions led to shorter RTs and more errors than found with the more traditional instructions of the type used by Lien et al. (2002). However, these effects of speed stress create two problems for interpreting the lack of a significant PRP effect in the RT data. The first is that the PRP effect can be small, or even absent, without the response-selection bottleneck being bypassed. The reason is that the PRP equation derived from the all-or-none central bottleneck model (see Fig. 1),[2]

$$\mathrm{PRP} = \mathrm{RT1} - 1C - 2A - \mathrm{SOA},$$

implies that when RT1 is short, the PRP effect will be small (see Lien, McCann, Ruthruff, & Proctor, 2005; Ruthruff et al., 2003). The second problem is that, when speed is emphasized over accuracy, the PRP effect may shift from RT to PE. Note that Greenwald's depiction of anticipatory preparation "as priming (or subthreshold activation)" (p. 867) is that the initial level of activation at stimulus onset is closer to the threshold for responding. In sequential sampling models of RT and accuracy, in which accumulation of evidence toward a response threshold is presumed to be a noisy process, this is equivalent to setting the speed–accuracy criterion toward speed at the expense of accuracy (Ratcliff & Smith, 2004; Van Zandt, Colonius, & Proctor, 2000).

Greenwald's (2003) data provide evidence that the elimination of the PRP effect for RT with speed-stress instructions was due at least in part to a shift in speed–accuracy criterion setting because a PRP effect was evident in the error data (Lien, Proctor, & Ruthruff, 2003). The average PE for T1 and T2 with the speed-stress instructions was significantly larger at the 0-ms SOA (8.5%) than at the 1,000-ms SOA (6.05%), with this difference being apparent for both the visual–manual task (3.6 vs. 1.8%) and the auditory–vocal task (13.4 vs. 10.3%). These results contrasted with those Greenwald obtained using the speed-and-accuracy instructions, for which the error data showed no PRP effect (for the visual–manual task, 0.88 vs. 1.29% at 0- and 1,000-ms SOA, respectively, and for the auditory–vocal task, 10.96 vs. 10.17%), but the RT data did. Thus, the PRP effect in the RT data for the speed-and-accuracy instructions was evidently transferred to the error data for the speed-stress instructions, possibly through shifting the speed–accuracy criterion toward speed at the expense of accuracy.

As evidence against a speed–accuracy tradeoff interpretation of his results, Greenwald (2003) pointed out that the PRP effect on error rates with the speed-stress instructions was significant only for the last of four trial blocks, whereas the RT data showed no PRP effect for any of the blocks. However, a trend towards a PRP effect on error rates was evident numerically for all but

[2]Using the notation illustrated in Fig. 1, the central bottleneck model makes a simple prediction for RT2 at short SOAs and long SOAs. Assuming that a bottleneck delay occurs on every trial at short SOAs but never at long SOAs,

$$\mathrm{RT2}_{(\mathrm{longSOA})} = 2A + 2B + 2C$$

$$\mathrm{RT2}_{(\mathrm{shortSOA})} = 1A + 1B + 2B + 2C - \mathrm{SOA} = \mathrm{RT1} - 1C + 2B + 2C - \mathrm{SOA}.$$

Therefore,

$$\mathrm{PRP} = \mathrm{RT2}_{(\mathrm{shortSOA})} - \mathrm{RT2}_{(\mathrm{longSOA})} = 1A + 1B - 2A - \mathrm{SOA}.$$

It follows that,

$$\mathrm{PRP} = RT1 - 1C - 2A - \mathrm{SOA}.$$

the third trial block, and the likelihood of a Type II error occurring for blocks 1–3 is great because each block contained only 16 trials.

Greenwald's (2003) study also suffered from the fact that his software allowed only one response to be recorded on any given trial when the tasks were simultaneous (i.e., the 0-ms SOA; see Greenwald's Footnote 4). Consequently, the software randomly selected one response, vocal or manual, to record for each trial. Because error feedback was provided only when the computer recorded an incorrect response, the error-feedback message would have been absent in the 0-ms SOA blocks for many trials on which an error was made. This lack of accurate feedback for the 0-ms SOA condition (but not the 1,000-ms SOA) may have caused subjects to respond faster, at the expense of more errors, than they would if the error feedback were accurate.

The present study

Greenwald (2003) interpreted his data as showing perfect timesharing of two ideomotor compatible tasks with speed-stress instructions, but they are inconclusive, for the reasons described above. Because of the importance of determining whether speed-stress instructions enable perfect timesharing or only alter the speed–accuracy criterion, the present study was designed to obtain more conclusive data. Experiment 1 was a replication of Greenwald's Experiment 1 using the same visual–manual task with keypress responses for T1 and the same auditory–vocal task for T2. Experiment 2 was similar but used unimanual left–right movements of a toggle switch, instead of keypresses, to more accurately replicate the visual–manual task in Greenwald and Shulman's (1973) original demonstration of apparently perfect timesharing, as well as in Lien et al.'s (2002) nonreplication. In Experiment 3, some minor procedural differences between the present Experiment 1 and Greenwald's (2003) experiment were eliminated.

In response to Greenwald's (2003) concern about using one hand to stabilize the response apparatus, we secured the apparatus to a table. As in Greenwald's experiment, two different instructions, speed-and-accuracy and speed-stress, were used. The main question was whether the PRP effect evident with speed-and-accuracy instructions would vanish with speed-stress instructions, as would be expected if perfect timesharing requires not only ideomotor compatibility but also an emphasis on response speed.

Experiment 1

Experiment 1 was a close replication of Greenwald's (2003) Experiment 1 in which instructions were manipulated. The intent was to determine whether a speed emphasis would eliminate the PRP effect for RT, as in his experiment, and, if so, whether the PRP effect would be transferred to the error data. T1 required left–right keypresses to the direction of an arrow presented on a computer screen, and T2 required vocal responses of "A" and "B" to the spoken letter names, *A* and *B*. Blocks of single-task trials were tested in addition to blocks of dual-task trials, as in his experiment. The speed-stress instructions emphasized rapid and simultaneous responding, as in Greenwald's experiment, whereas the speed-and-accuracy instructions emphasized the importance of both speed and accuracy, as in Lien et al.'s (2002) experiment and many other PRP studies. RTs for both T1 and T2 should be shorter in the speed-stress instruction condition than in the speed-and-accuracy instruction condition. The question of interest is to what degree the PRP effect is influenced by the reduction of RTs when the speed-stress instructions are used.

Method

Subjects

Twenty-four undergraduate students enrolled in an introductory psychology course at Purdue University participated in partial fulfillment of course requirements. All subjects had normal or corrected-to-normal vision and normal hearing. Half of the subjects were assigned at random to the speed-and-accuracy instruction condition and half to the speed-stress instruction condition.

Apparatus and stimuli

The experiment was controlled by software developed with the Micro Experimental Laboratory (MEL 2.1) system. Stimuli were presented on a 14-in CRT display screen of a personal computer, and viewing distance was approximately 60 cm.

Visual stimuli for T1 were left- and right-pointing arrows that measured 1.4 cm wide and 0.8 cm high. The left- and right-pointing arrows were positioned 3 cm to the left or right, respectively, of the center of the screen. Subjects responded to the left arrow by pressing the leftmost button of a MEL 2 standard serial response box with the left index finger and to the right arrow by pressing the rightmost button with the right finger. The distance between the two response keys was 6.7 cm, and the size of each key was 1.0 cm^2. The response box was fixed on a table by a clamp, and subjects were asked to keep each index finger on the designated key.

Auditory stimuli for T2 were presented via a headphone from electronic files. They were equated for rise time, duration (approximately 200 ms), and amplitude (approximately 65 dB, the sound of normal speech at a distance of 3 ft). These stimuli were the letter *A* or *B*, pronounced by a female. Correct responses for T2 were made by saying "A" to the stimulus "A" and "B" to the stimulus "B" into a microphone that was connected to the voice key of the response box. The microphone was positioned so that the subjects did not have to move their heads toward the microphone when they responded.

Procedure and design

Subjects were seated in front of the monitor, and the experimenter remained in the room throughout the experimental session. Written task instructions appeared on the screen. The introductory instructions were similar for the two instruction conditions, except that both speed and accuracy were emphasized for the group receiving speed-and-accuracy instructions but speed was emphasized for the group receiving speed-stress instructions. Specifically, the speed-and-accuracy instructions stated, as in Lien et al.'s (2002) study and Greenwald's (2003) replication of their instruction condition, "Your job is to respond to each task as quickly and accurately as you can. Do not wait for the other task to appear." In contrast, the speed-stress instructions stated, as in Greenwald's speed-stress condition, "Throughout this experiment, it is important for you to respond as rapidly as you possibly can while maintaining a high rate of accuracy."

Each subject completed 12 blocks of 36 trials each, in three sets of four blocks. Each set of blocks included one block for the dual task with 0-ms SOA, one block for the dual task with 1,000-ms SOA, one block for the single T1, and one block for the single T2. The order of the blocks within each set was determined randomly, and the order of trials in each block was also randomized. At the beginning of each block, subjects were told whether the trials would be single or dual task and, if single task, which task it would be. Before each block, subjects in the speed-and-accuracy group were reminded, "Remember that speed and accuracy are important," whereas those in the speed-stress group were reminded to respond "very rapidly". Prior to dual-task blocks, they were told in addition "You are to make responses at the same time when the two tasks are presented simultaneously" (i.e., for the 0-ms SOA condition). Also, the experimenter verbally encouraged subjects in the speed-stress group to respond fast.

The experimenter initiated the first trial of each block by pressing the spacebar of the keyboard. In the dual-task blocks for which the SOA was 1,000 ms, the visual arrow (S1) was displayed on the computer screen until the subject made a keypress response (R1), and then it disappeared. The onset of the auditory stimulus (S2) followed that of S1 by 1,000 ms, and its duration was 200 ms. The identity of each spoken response to the auditory stimulus was entered into the computer by the experimenter, who pressed 1 to "A" and 2 to "B". An incorrect response was followed by visual feedback (*incorrect T1 response* or *incorrect T2 response*) presented in the center of the screen for 1,000 ms. The feedback messages were presented simultaneously in the dual-task blocks if errors were made for both tasks. The next trial began 1,000 ms after completing both responses or, on trials with an error, after the offset of the feedback. Thus, the interval between completion of a trial and the start of the next was constant, as in most of PRP studies (e.g., Hazeltine et al., 2002; Lien et al., 2005; Ruthruff et al., 2001; Van Selst et al., 1999), rather than the interval between onset of the auditory stimulus for one trial and the start of the next, as in Greenwald's (2003) study.

The procedure for the dual-task blocks with 0-ms SOA was identical to that of the dual-task blocks with 1,000-ms SOA, except that S1 and S2 were presented simultaneously. In the single T1 blocks, each trial began with the presentation of the visual arrow stimulus and lasted until R1 was made. No auditory stimulus was presented. In the single T2 blocks, only the auditory stimulus was presented. The other procedures were identical to those in the dual-task blocks.

Results

Trials with RT1 and RT2 less than 100 ms or greater than 2,000 ms were excluded from analysis ($<$ 1.21% of all trials). Single-task trials were analyzed separately from dual-task trials. For single-task trials, mean RT and PE for each task were calculated for each subject as a function of block, and analyses of variance (ANOVAs) were performed for each task with block and instruction (speed-stress vs. speed-and-accuracy) as independent variables. For dual-task trials, RT1, RT2, combined averages of RT1 and RT2, PE1, PE2, and combined averages of PE1 and PE2 were calculated for each subject as a function of SOA (0 and 1,000 ms) and block (1, 2, and 3; the means are provided as a function of block in Table 1 and collapsed across block in Fig. 2). ANOVAs were conducted with SOA and block as within-subject factors and instruction as a between-subject factor.

Single-task RT and PE

Response time was shorter with speed-stress instructions than with speed-and-accuracy instructions (272 vs. 301 ms for the visual–manual task and 389 vs. 474 ms for the auditory–vocal task), $Fs(1, 22) = 7.30$ and 10.73, $Ps < 0.015$, MSEs = 2,073 and 12,873. The reverse trend was found for PE, though nonsignificantly, $Fs(1, 22) \leq 1.83$, $Ps \geq 0.19$: PE tended to be slightly higher with speed-stress instructions than with speed-and-accuracy instructions for both the visual–manual task (1.91 vs. 1.13%) and auditory–vocal task (0.80 vs. 0.43%). For the auditory–vocal task, the main effect of block was significant for RT, $F(2, 44) = 50.65$, $P < 0.001$, MSE = 8,858, and PE, $F(2, 44) = 3.26$, $P < 0.048$, MSE = 0.0004. RT decreased across blocks, but PE increased. In addition, for the auditory–vocal task, block interacted with instructions on RT, $F(2, 44) = 6.45$, $P < 0.005$, MSE = 1,373: The decrease in RT across blocks was larger with speed-stress instructions than with speed-and-accuracy instructions.

Table 1 Mean response time (RT) in milliseconds and percent error (PE) as a function of task, condition, and block for Experiment 1

	Speed-and-accuracy condition			Speed-stress condition		
	Block 1	Block 2	Block 3	Block 1	Block 2	Block 3
Single task						
T1 RT	308	304	291	277	265	274
PE	(0.78)	(1.3)	(1.3)	(1.56)	(1.82)	(2.34)
T2 RT	516	473	438	470	350	344
PE	(0.26)	(0.52)	(0.52)	(0.26)	(0.53)	(1.60)
Visual–manual task (T1) for dual task						
0-ms SOA RT	377	345	317	310	262	262
PE	(0.52)	(0.52)	(0.78)	(1.30)	(3.39)	(3.65)
1,000-ms SOA RT	369	330	324	318	307	301
PE	(0.26)	(0.26)	(0.00)	(1.04)	(1.30)	(1.04)
Auditory–vocal task (T2) for dual task						
0-ms SOA RT	574	521	480	504	428	409
PE	(1.58)	(1.60)	(0.53)	(1.04)	(2.08)	(0.79)
1,000-ms SOA RT	511	439	410	471	375	333
PE	(1.32)	(0.00)	(0.53)	(0.80)	(1.60)	(2.34)
Combined dual task						
0-ms SOA RT	476	433	399	407	345	336
PE	(1.05)	(1.06)	(0.66)	(1.17)	(2.74)	(2.22)
1,000-ms SOA RT	440	385	367	395	341	317
PE	(0.79)	(0.13)	(0.27)	(0.92)	(1.45)	(1.69)

Dual-task RT1 and PE1

Visual–manual RT (RT1) was 44 ms shorter with the speed-stress instructions (M = 286 ms) than with the speed-and-accuracy instructions (M = 330 ms), $F(1, 22) = 8.14$, $P < 0.01$, MSE = 11,178, but PE1 was higher (1.94 vs. 0.64%), $F(1, 22) = 5.99$, $P < 0.05$, MSE = 0.001, indicating the effectiveness of the instructions. RT1 was nonsignificantly shorter at 0-ms SOA (M = 312 ms) than at 1,000-ms SOA (M = 324 ms), $F(1, 22) = 1.83$, $P = 0.190$, MSE = 3,148, but with a higher error rate (1.69 vs. 0.65%), $F(1, 22) = 6.78$, $P < 0.05$, MSE = 0.001. The interaction of instruction and SOA approached statistical significance for RT1, $F(1, 22) = 3.74$, $P = 0.066$, MSE = 3,148, with the difference between the two task instructions tending to be larger at 0-ms SOA (67 ms) than at 1,000-ms SOA (32 ms).

The main effect of block was significant for RT1, $F(2, 44) = 19.72$, $P < 0.0001$, MSE = 1,213: RT1 decreased across blocks (Ms = 344, 311, and 301 ms for blocks 1, 2, and 3, respectively). This block effect was nonsignificantly larger at 0-ms SOA (Ms = 344, 304, and 290 ms) than at 1,000-ms SOA (Ms = 344, 319, and 313 ms), $F(2, 44) = 2.97$, $P = 0.062$, MSE = 557. No block effect was found for PE1.

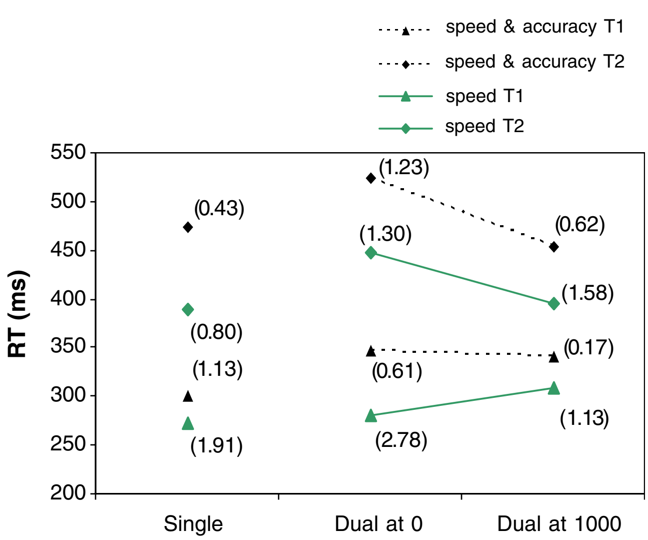

Fig. 2 Experiment 1: Mean response time (*RT*) for T1 and T2 for the single task, dual task at 0-ms SOA (*Dual at 0*), and dual task at 1,000-ms SOA (*Dual at 1,000*) as a function of instructions (speed-and-accuracy vs. speed-stress), with percentage error in *parentheses*

Dual-task RT2 and PE2

Auditory–vocal RT (RT2) was 75 ms shorter with the speed-stress instructions (M = 410 ms) than with speed-and-accuracy instructions (M = 485 ms), $F(1, 22) = 5.19$, $P < 0.05$, MSE = 32,964, and PE2 tended to be slightly greater (1.27 vs. 1.10%), $F(1, 22) = 1.648$, $P = 0.213$. RT2 decreased across blocks (Ms = 515, 441, and 408 ms for blocks 1, 2, and 3, respectively), $F(2, 44) = 35.83$, $P < 0.0001$, MSE = 1,891.

More important, RT2 was longer at 0-ms SOA (M = 486 ms) than at 1,000-ms SOA (M = 424 ms), $F(1, 22) = 21.47$, $P < 0.0001$, MSE = 6,589, indicating a PRP effect of 62 ms. The interaction of SOA and task instruction was not significant, $F(1, 22) < 1.0$. Simple main effects analyses showed the SOA effect to be significant with both speed-and-accuracy instructions (0-ms SOA 524 ms; 1,000-ms SOA 454 ms), $F(1, 11) = 8.51$, $P < 0.05$, MSE = 10,815, and speed-stress instructions (0-ms SOA 447 ms; 1,000-ms SOA 395 ms), $F(1, 11) = 22.11$, $P < 0.005$, MSE = 2,362. The PRP effect was 70 ms with the speed-and-accuracy instructions and 52 ms with the speed-stress instructions.

Averaged RT and PE

Following Greenwald and Shulman (1973), we conducted data analyses for dual-task trials based on average RT and PE for T1 and T2. RT1 and RT2, as well as PE1 and PE2, were averaged on each trial and then submitted to the final analyses.

For the average RT analysis, all main effects were significant. The average RT was longer at 0-ms SOA (M = 399 ms) than at 1,000-ms SOA (M = 374 ms), $F(1, 22) = 14.42$, $P < 0.05$, MSE = 1,571, and decreased across blocks (Ms = 429 ms, 376 ms, and 365 ms for blocks 1, 2, and 3, respectively), $F(2, 44) = 33.51$, $P < 0.0001$, MSE = 2,126. The average RT was shorter with speed-stress instructions (M = 358 ms) than with speed-and-accuracy instructions (M = 417 ms), $F(1, 22) = 7.35$, $P < 0.0001$, MSE = 17,353. The interaction of SOA and task instruction was significant, $F(1, 22) = 4.40$, $P < 0.05$, MSE = 1,571. Average RT for the two tasks was 38 ms longer at the 0-ms SOA than at the 1,000-ms SOA with speed-and-accuracy instructions, $F(1, 11) = 16.98$, $P < 0.05$, MSE = 1,608, but only a nonsignificant 12 ms longer with speed-stress instructions, $F(1, 11) = 1.48$, $P = 0.25$, MSE = 2,266. No other interaction was significant, Fs < 1.0.

In the average PE analysis, more errors were made at 0-ms SOA (1.48%) than at 1,000-ms SOA (0.88%), $F(1, 22) = 11.99$, $P < 0.005$, MSE = 0.896. The average PE was greater with speed-stress instructions (1.70%) than with speed-and-accuracy instructions (0.66%), $F(1, 22) = 6.11$, $P < 0.05$, MSE = 5.313. No interactions were significant, $F\text{s} \le 2.167$, $P\text{s} \le 0.127$. However, separate ANOVAs were performed for the speed-and-accuracy and speed-stress conditions to evaluate the significance of the SOA effect separately for each. The effect was only marginally significant for the speed-and-accuracy condition (PE of 0.92% at 0-ms SOA and 0.40% at 1,000-ms SOA), $F(1, 11) = 4.34$, $P = 0.061$, but it was significant for the speed-stress condition (PE of 2.04% at 0-ms SOA and 1.36% at 1,000-ms SOA), $F(1, 11) = 9.03$, $P = 0.012$.

Discussion

Experiment 1 evaluated whether performing two ideomotor compatible tasks with a speed emphasis would eliminate the PRP effect on RT, and if so, whether the emphasis of speed would lead the PRP effect to be evident in the error data. RT was 44 ms faster for T1 and 75 ms faster for T2 with the speed-stress instructions than with the speed-and-accuracy instructions, and PE was higher with the speed-stress instructions for both tasks, with the difference being significant for T1 and the combined analysis, yielding an overall difference of 0.93%. These speed-stress effects are similar to those of Greenwald (2003; 49 ms for RT1 and 102 ms for RT2, and an overall 1.0% difference in error rate). Thus, the speed-stress instructions were effective at getting subjects to respond faster at the expense of more errors to a similar, but slightly lesser, extent than in Greenwald's study.

Even though the overall effects of the instructional manipulation on RT and PE were similar to those obtained by Greenwald (2003), the PRP effect was still evident with speed-stress instructions: RT2 was 52 ms slower at 0-ms SOA than at 1,000-ms SOA. Even with speed stress, both RT1 and RT2 decreased across blocks, which suggests that subjects were not initially performing as fast as they possibly could. However, the PRP effect for RT2 tended to increase across blocks, being 33, 53, and 76 ms in blocks 1, 2, and 3, $F(2, 22) = 2.605$, $P = 0.097$, rather than to decrease. This increase is the opposite of what would be expected if bottleneck bypass occurs only when subjects are emphasizing response speed. When RT1 and RT2 were averaged, a procedure that, as described in the General discussion, is based on questionable assumptions, the difference in RT between the 0- and 1,000-ms SOAs for the speed-stress condition was only a nonsignificant 12 ms. However, this difference was accompanied by a significantly higher error rate at 0-ms SOA than at 1,000-ms SOA (difference of 0.68%). Thus, even with speed-stress instructions, the standard measure of the PRP effect showed a quite substantial effect, and the average RT and PE for T1 and T2 also does not suggest perfect timesharing either.

The relationship between RT1 and RT2 can be examined by performing an analysis based on RT1 quintiles for the 0-ms SOA, where bottleneck-related delays are most likely to occur (Lien et al., 2005; Pashler, 1993, 1994; Pashler & O'Brien, 1993). For this analysis, individual subjects' trials were divided into five bins (quintiles) based on the speed of RT1, and mean RT2 for each RT1 bin was computed. The results of this analysis are shown in Fig. 3. As can be seen, RT2 increased monotonically as RT1 increased with both the speed-and-accuracy and speed-stress instructions. The slope relating RT2 and RT1 was approximately 0.78 with speed-and-accuracy instructions and 1.16 with speed-stress instructions. This dependency between RT1 and RT2 is in agreement with the hypothesis that a central bottleneck limits performance in both instruction conditions, and the slope with speed-stress instructions actually exceeds slightly the ideal bottleneck model prediction (slope = 1). Greenwald (2005) has suggested that relations of the type shown here between RT1 and RT2 may reflect momentary fluctuations in attention or arousal that add a constant to both measures. However, if this were the case, the correlation should be equally evident under conditions that yield little PRP effect. Yet, Hazeltine et al. (2002) found the correlation between RT1 and RT2 to be quite small ($M \approx 0.2$) for subjects tested after they had practiced enough to show little dual-task interference.

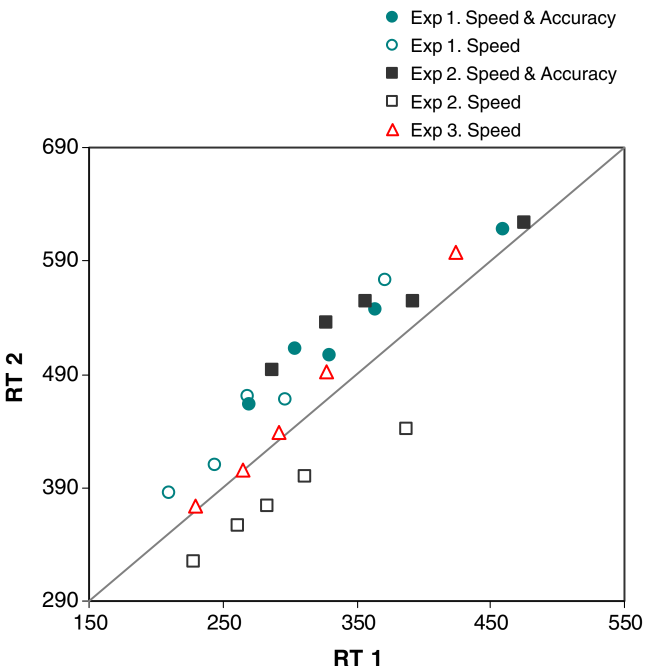

Fig. 3 Task 2 response time (*RT2*) as a function of Task 1 response time (*RT1*), in milliseconds, at the 0-ms SOA for different instruction conditions (speed-and-accuracy vs. speed-stress) in Experiments 1 to 3. There are five data points for each condition, corresponding to the five RT1 quintiles. The *solid line* indicates a slope of 1.0

Although Greenwald (2003) obtained no PRP effect for RT2 with speed-stress instructions, his PE2 data showed a PRP effect: PE2 was higher at 0-ms SOA than at 1,000-ms SOA. Thus, our results are in agreement with Greenwald's in suggesting that the two tasks did not show perfect timesharing in either case.

Experiment 2

Although our Experiment 1 and Greenwald's (2003) Experiment 1 do not show evidence of perfect time-sharing, even when speed-stress instructions are used, these experiments differed from those of Greenwald and Shulman (1973) and Lien et al. (2002) in the use of keypresses for the manual responses instead of unimanual left–right joystick movements. Greenwald classified the task of responding to arrow direction with keypresses as ideomotor compatible, but one might argue that they are not truly ideomotor compatible because the instructed stimulus dimension of left–right arrow direction does not correspond with the downward direction of movement made to press a key. Because Greenwald stated that he thought that Greenwald and Shulman used speed-stress instructions, it is important to determine whether the PRP effect can be eliminated with two ideomotor compatible tasks using such instructions when the visual–manual task involves left–right directional movements. Therefore, in Experiment 2, we replicated the instructional manipulation of Experiment 1 but using unimanual switch movements instead of keypresses for Task 1.

Method

Subjects

Thirty-two new undergraduate students from the same subject pool as in the previous experiment participated. Sixteen were randomly assigned to each of two different instruction conditions.

Apparatus, stimuli and procedure

The apparatus, stimuli, and procedure were identical to those of Experiment 1, except that responses for T1 were made to the arrow direction by pushing a toggle switch left or right. The toggle switch was mounted on a panel (43 × 17.5 × 6 cm) interfaced with a MEL 2.0 standard serial response box. The height of the toggle switch was 7.5 cm. The toggle switch was fixed on the table by two clamps, and the subjects were asked to grasp the lever with the thumb and index finger of their dominant hand.

Results

Outliers (0.4% of trials) were excluded using the same criteria as for Experiment 1. Data analyses for single-task trials and dual-task trials were similar to those of Experiment 1. The mean values are shown in Table 2 and Fig. 4 for the speed-stress and speed-and-accuracy instruction groups.

Single-task RT and PE

Speed-stress instructions were effective at reducing RT compared to speed-and-accuracy instructions for both the visual–manual task (299 vs. 352 ms) and the auditory–vocal task (350 vs. 450 ms), Fs(1, 30) ≥ 10.66, Ps ≤ 0.005, but at the cost of more errors (1.38 vs. 0.39% for the visual–manual task and 1.33 vs. 0.20% for the auditory–vocal task), Fs(1, 30) ≥ 5.49, Ps ≤ 0.05. Both tasks also showed an interaction of instructions with block on RT, Fs(2, 60) = 6.40 and 7.43, P < 0.01, MSEs = 602 and 1,953. For the visual–manual task, RT tended to increase from Block 1 to Blocks 2 and 3 with the speed-and-accuracy instruction but to decrease with speed-stress instruction, resulting in no main effect of block, F < 1.0. For the auditory–vocal task, RT decreased across blocks for both instruction conditions, as indicated by a main effect of block, F(2, 60) = 20.03, P < 0.001, but more so with the speed instructions than with the speed-and-accuracy instructions.

Table 2 Mean response time (RT) in milliseconds and percent error (PE) as a function of task, condition, and block for Experiment 2

	Speed-and-accuracy condition			Speed-stress condition		
	Block 1	Block 2	Block 3	Block 1	Block 2	Block 3
Single task						
T1 RT	336	360	360	309	297	292
PE	(0.39)	(0.39)	(0.39)	(0.78)	(1.37)	(1.98)
T2 RT	465	455	430	413	322	314
PE	(0.00)	(0.20)	(0.39)	(1.00)	(1.61)	(1.40)
Visual–manual task (T1) for dual task						
0-ms SOA RT	391	360	352	311	283	288
PE	(1.58)	(0.78)	(0.39)	(2.35)	(4.11)	(3.73)
1,000-ms SOA RT	444	403	368	337	310	315
PE	(0.39)	(0.39)	(0.59)	(0.20)	(0.78)	(0.78)
Auditory–vocal task (T2) for dual task						
0-ms SOA RT	583	554	530	426	372	346
PE	(0.80)	(0.60)	(0.20)	(2.41)	(3.03)	(2.39)
1,000-ms SOA RT	553	486	451	398	322	297
PE	(0.60)	(0.00)	(0.00)	(0.63)	(0.81)	(1.81)
Combined dual task						
0-ms SOA RT	487	457	441	369	328	317
PE	(1.19)	(0.69)	(0.30)	(2.38)	(3.57)	(3.06)
1,000-ms SOA RT	499	445	410	368	316	306
PE	(0.50)	(0.20)	(0.30)	(0.42)	(0.80)	(1.30)

Dual-task RT1 and PE1

Response time for T1 was 61 ms shorter with the speed-stress instructions (M = 314 ms) than with the speed-and-accuracy instructions (M = 375 ms), $F(1, 30) = 10.26$, $P < 0.005$, MSE = 29,236. The main effect of block was significant, $F(2, 60) = 7.84$, $P < 0.005$, MSE = 3,615, with RT1 decreasing across blocks. Even though there was a tendency for RT1 to be shorter at 0-ms SOA (M = 333 ms) than at 1,000-ms SOA (M = 365 ms), the main effect of SOA only approached statistical significance, $F(1, 30) = 3.86$, $P = 0.059$, MSE = 12,669. Although the overall effect of SOA was not significant, simple main effect analyses showed that the effect of SOA was significant with speed-stress instructions, $F(1, 15) = 26.75$, $P < 0.000$, MSE = 645 (0-ms SOA 294 ms; 1,000-ms SOA 321 ms), but not with speed-and-accuracy instructions, $F(1, 15) = 1.33$, $P = 0.266$, MSE = 24,694 (0-ms SOA 368 ms; 1,000-ms SOA 405 ms).

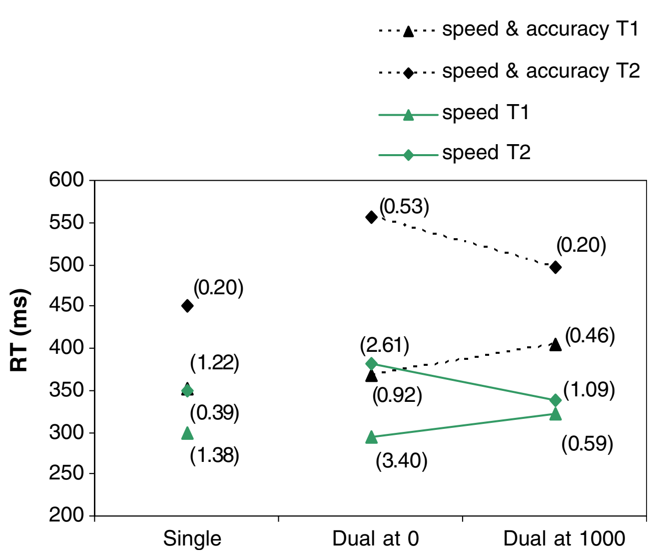

Fig. 4 Experiment 2: Mean response time (*RT*) for T1 and T2 for the single task, dual task at 0-ms SOA (*Dual at 0*), and dual task at 1,000-ms SOA (*Dual at 1,000*) as a function of instructions (speed-and-accuracy vs. speed-stress), with percentage error in *parentheses*

Percentage of errors for T1 was greater with the speed-stress instructions (1.61%) than with the speed-and-accuracy instructions (0.58%), $F(1, 30) = 5.97$, $P < 0.05$, MSE = 13.70. PE1 was also higher at 0-ms SOA (2.15%) than at 1,000-ms SOA (0.48%), $F(1, 30) = 14.96$, $P < 0.005$, MSE = 8.58. A two-way interaction of SOA and instruction was significant, $F(1, 30) = 7.73$, $P < 0.01$, MSE = 8.58. PE1 was 3.40% at 0-ms SOA and 0.59% at 1,000-ms SOA with the speed-stress instructions, whereas it was 0.92% at 0-ms SOA and 0.46% at 1,000-ms SOA with the speed-and-accuracy instructions. That is, the increase in PE1 at 0-ms SOA compared to 1,000-ms SOA was greater with the speed-stress instructions (2.81%) than with the speed-and-accuracy instructions (0.46%). PE1 did not change across blocks, $F(2, 60) < 1.0$, but, the interaction of block and instruction was significant, $F(2, 60) = 3.37$, $P < 0.05$, MSE = 3.69. PE1 tended to decrease across blocks with the speed-and-accuracy instructions (0.79, 0.52, and 0.46% for blocks 1, 2, and 3, respectively), whereas it tended to increase across blocks with the speed-stress instructions (1.11, 2.09, and 2.16%, respectively).

Dual-task RT2 and PE2

Similar to the RT1 results, RT2 was shorter with the speed-stress instructions (M = 371 ms) than with the speed-and-accuracy instructions (M = 500 ms), $F(1,$

30) = 41.21, $P < 0.0001$, MSE = 5,338. RT2 was longer at 0-ms SOA (M = 468 ms) than at 1,000-ms SOA (M = 418 ms), $F(1, 30) = 20.54$, $p < 0.0001$, MSE = 5,974. That is, a 50-ms PRP effect was obtained. The simple main effect for SOA was significant with both speed-and-accuracy instructions, $F(1, 15) = 8.52$, $P < 0.05$, MSE = 9,760 (0-ms SOA 556 ms; 1,000-ms SOA 497 ms), and speed-stress instructions, $F(1, 15) = 19.59$, $P < 0.000$, MSE = 2,189 (0-ms SOA 381 ms; 1,000-ms SOA 339 ms). Although this PRP effect was slightly smaller with the speed-stress instructions (42 ms) than with the speed-and-accuracy instructions (59 ms), the interaction of SOA and task instruction was not significant, $F(1, 30) < 1.0$, as in Experiment 1.

The main effect of block was significant, $F(2, 60) = 47.96, p < 0.0001$, MSE = 2,433. RT2 decreased across blocks (Ms = 473, 418, and 395 ms for blocks 1, 2, and 3, respectively). Although the interaction of block and SOA only approached significance, $F(2, 60) = 2.76$, $P < 0.072$, MSE = 2,100, the block effect was more evident at 1,000-ms SOA than at 0-ms SOA. That is, RT2 tended to decrease more at 1,000-ms SOA (Ms = 476, 404, and 374 ms for blocks 1, 2, and 3, respectively) than at 0-ms SOA (Ms = 504, 463, and 438 ms, respectively), resulting in PRP effects increasing across blocks (29, 59, and 64 ms for block 1, 2, and 3, respectively).

PE2 was greater with the speed-stress instructions (1.61%) than with the speed-and-accuracy instructions (0.31%), $F(1, 30) = 21.15$, $P < 0.0001$, MSE = 4.98. The main effect of SOA was significant, $F(1, 30) = 10.99$, $P < 0.005$, MSE = 3.77. PE2 was higher at 0-ms SOA (1.56%) than at 1,000-ms SOA (0.57%). The main effect of block was not significant, $F(2, 60) < 1.0$, indicating that practice had no effect on PE2.

Average RT and PE

Average RT was shorter with the speed-stress instructions (M = 334 ms) than the speed-and-accuracy instructions (M = 457 ms), $F(1, 30) = 28.02$, $P < 0.0001$, MSE = 25,708. The block effect was also found, $F(2, 60) = 25.99$, $P < 0.0001$, MSE = 2,471. Average RT decreased across blocks (Ms = 430, 386, and 368 ms for block 1, 2, and 3, respectively). Although RT was 9 ms slower at the 0-ms SOA than at the 1,000-ms SOA, the main effect of SOA was not significant, $F(1, 30) < 1.0$. The interaction of SOA and task instructions also was not significant, $F(1, 30) < 1.0$, with the difference in average RT between the two SOAs being 8 ms with the speed-stress instructions and 11 ms with the speed-and-accuracy instructions. No other effect was significant.

More errors were made with speed-stress instructions (1.92%) than with speed-and-accuracy instructions (0.53%), $F(1, 30) = 23.00$, $P < 0.0001$, MSE = 5.44. PE was greater at 0-ms SOA (1.87%) than at 1,000-ms SOA (0.59%), $F(1, 30) = 23.01$, $P < 0.0001$, MSE = 2.88. A two-way interaction of block and instruction was significant, $F(2, 60) = 4.016$, $P < 0.05$, MSE = 1.65. PE decreased across blocks with the speed-and-accuracy instructions (0.8, 0.4, and 0.3% for block 1, 2, and 3, respectively), whereas it increased across blocks with the speed-stress instructions (1.40, 2.18, and 2.18%). Finally, instruction also interacted with SOA, $F(1, 30) = 11.53$, $P = 0.002$, MSE = 2.876. The SOA effect was only marginally significant for the speed-and-accuracy condition (PE of 0.73% at 0-ms SOA and 0.33% at 1,000-ms SOA), $F(1, 15) = 4.33$, $P = 0.055$, but it was significant for the speed-stress condition (PE of 3.01% at 0-ms SOA and 0.84% at 1,000-ms SOA), $F(1, 15) = 18.92$, $P < 0.001$.

Discussion

In this experiment, in which T1 involved unimanual toggle-switch responses, rather than keypresses, RT1 was 79-ms shorter and RT2 167-ms shorter using speed-stress instructions. This shorter RT was accompanied by an overall 1.39% increase in error rate with the speed-stress instructions. Thus, the speed-stress instructions were effective at getting subjects to respond faster at the expense of more errors. Note that the instruction effects were larger than those of Greenwald (2003), as well as those of the present Experiment 1. Nevertheless, the PRP effect was still evident with speed-stress instructions: RT2 was 42-ms slower at the 0-ms SOA than at the 1,000-ms SOA. When RT1 and RT2 were averaged, the difference was only 8 ms (with speed-stress instructions), but, as in Experiment 1, it was accompanied by a higher error rate at 0-ms SOA than at 1,000-ms SOA (difference was 2.17%).

Mean RT generally decreased across blocks, but the PRP effect was not eliminated in RT2 or PE2. As in Experiment 1, RT2 tended to decrease more with practice at the 1,000-ms SOA than at the 0-ms SOA, resulting in a tendency for the PRP effect to increase across blocks.

Mean RT2 was computed as a function of RT1 bin, as in the previous experiment. RT2 was an increasing function of RT1, with the slopes being 0.64 and 0.73 for the speed-and-accuracy and speed-stress instructions, respectively. Although these slopes are shallower than for Experiment 1 (see Fig. 3), they still are consistent with a central bottleneck model and, more important, the slope is at least as great with speed-stress instructions as with speed-and-accuracy instructions.

Even though some of the specific interaction effects were different from those of Experiment 1 and the combined analysis showed little RT difference between the two SOAs, the general results of Experiment 2 were similar to those of Experiment 1: responses for T1 were faster at 0-ms SOA than at 1,000-ms SOA, and RT2 showed a PRP effect, for both the speed-stress and speed-and-accuracy instructions.

Experiment 3

The conditions with speed-stress instructions in Experiments 1 and 2 were conducted similarly to those of Greenwald (2003; Experiment 1), but they differed in several minor respects: (a) the number of blocks (12 vs. 16); (b) the number of trials in each block (36 in each vs. 16 for single-task blocks and 64 for dual-task blocks); (c) the order in which the single and dual tasks were administered within each set of four blocks (random in Experiment 1 and 2; the two single-task blocks before the two dual-task blocks in Greenwald's experiment); and (d) the spacing of trials (constant interval between completion of a trial and the start of the next versus constant interval between onset of the auditory stimulus for one trial and the start of the next). Although we do not think that these differences are responsible for the presence of the PRP effect in our experiments, it seemed prudent to rule out this possibility. Therefore, we conducted an additional experiment that adopted the design choices of Greenwald's Experiment 1. One difference, however, is that in the present Experiment 3 we used the speed-stress instructions only. We used the keypress version of the visual–manual task, just as in Experiment 1 and in Greenwald's study. We continued to use left and right pointing arrows, rather than arrows angled 45° to the left or right, however, since left–right direction and position of the arrows are the properties that make the stimuli ideomotor compatible with left–right manual responses.

Method

Twelve subjects from the same pool as in Experiments 1 and 2 were tested. For the single-task condition, the visual–manual and auditory–vocal tasks were presented in 16-trial blocks consisting of eight each of the two arrow stimuli or the two letter name stimuli, respectively, in randomized order. For the dual-task trials, the 0- and 1,000-ms SOAs were presented in separate blocks of trials, with each block consisting of 64 trials, 16 each of the four possible combinations of visual and auditory stimuli, in random sequence. The interval between onset of S2 (the auditory stimulus) for one trial and the start of the next trial was a constant 2.5 s. This value was slightly longer than the 2-s value used by Greenwald (2003), to allow the experimenter to record the vocal response. The maximum latency allowed for responses to either task was 1,500 ms. As in Greenwald's experiment, the preliminary instructions included "Throughout this experiment, it is important for you to respond as rapidly as you possibly can while maintaining a high rate of accuracy," and subjects were reminded to respond "very rapidly" prior to each block of trials. Also, in the dual-task SOA = 0 ms condition, the instructions prior to each block reminded subjects "YOU ARE TO MAKE TWO RESPONSES AT THE SAME TIME."

As in Greenwald (2003, Experiment 1), 16 blocks of trials, in four sets of 4 blocks, were tested. Each set of 4 blocks included a block of the visual–manual single-task condition, a block of the auditory–vocal single-task condition, a block of the 0-ms SOA dual-task condition, and a block of the 1,000-ms SOA dual-task condition. Within each set of blocks, the single-task blocks preceded the dual-task blocks, and within each of these pairs, the orders were randomized independently in each set of four blocks. Unlike Greenwald (2003), errors on either task in our experiment resulted in subjects seeing visual feedback indicating that an error on that task had been made.

Results

Trials with RT1/RT2 less than 100 ms (< 0.1% of responses) were excluded from analysis, as were those trials on which no response was recorded for one task or the other within 1,500 ms, since the response box collected the responses which were less than 1,500 ms (0.7% of the trials). ANOVAs were conducted on the above data sets, with SOA and block variables as within-subject factors. The mean data are summarized in Table 3 and Fig. 5.

Single-task RT and PE

Block had a significant effect on RT in both tasks, $Fs(3, 33) = 4.94$ and 20.69, $Ps < 0.01$, MSEs = 512 and 2,920. RT decreased across blocks in the visual–manual task (Ms = 310, 284, 282, and 271 ms, respectively) and in the auditory–vocal task (Ms = 519, 460, 385, and 376 ms, respectively).

Table 3 Mean response time (RT) in milliseconds and percent error (PE) as a function of task (T1 or T2), condition (single task, dual task, or combined dual task), SOA (0 or 1,000 ms), and block for Experiment 3

	Speed-stress condition			
	Block 1	Block 2	Block 3	Block 4
Single task				
T1 RT	310	284	282	271
PE	(0.96)	(1.56)	(2.12)	(0.57)
T2 RT	519	460	385	376
PE	(0.00)	(0.00)	(0.00)	(0.00)
Visual–manual task (T1) for dual task				
0-ms SOA RT	371	298	286	277
PE	(1.30)	(2.21)	(4.31)	(3.66)
1,000-ms SOA RT	350	303	320	301
PE	(0.13)	(1.05)	(1.18)	(1.18)
Auditory–vocal task (T2) for dual task				
0-ms SOA RT	570	431	421	411
PE	(2.02)	(3.30)	(1.45)	(1.83)
1,000-ms SOA RT	461	360	347	327
PE	(2.62)	(1.32)	(1.97)	(3.01)
Combined dual task				
0-ms SOA RT	469	365	355	345
PE	(1.69)	(2.77)	(2.91)	(2.69)
1,000-ms SOA RT	404	330	333	315
PE	(1.51)	(1.26)	(1.79)	(2.10)

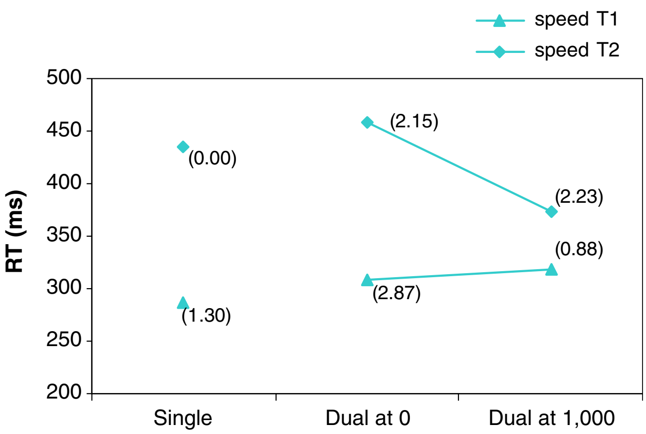

Fig. 5 Experiment 3: Mean response time (*RT*) for T1 and T2 for the single task, dual task at 0-ms SOA (*Dual at 0*), and dual task at 1,000-ms SOA (*Dual at 1,000*), with percentage error in *parentheses*

Dual-task RT1 and PE1

The main effect of SOA was not significant for RT or PE, Fs(1, 11) = 0.98 and 2.72, Ps ≥ 0.16, with mean RT tending to be slightly shorter at 0-ms SOA (M = 306 ms) than 1,000-ms SOA (M = 319 ms), but with PE being higher (2.91 and 0.79%, respectively). The main effect of block was significant for RT1, $F(3, 33) = 14.20$, $P < 0.0001$, MSE = 1,761, and almost so for PE1, $F(3, 33) = 3.50$, $P = 0.026$ uncorrected and 0.076 with the Huynh-Feldt correction, MSE = 0.001. RT1 was longest in the first block and shortest in the last (Ms = 360, 300, 303, and 289 ms for blocks 1, 2, 3, and 4, respectively), but PE1 showed the opposite trend of being smallest in block 1 and largest in the last two blocks (Ms = 0.13, 0.93, 1.06, and 1.05%). For RT1, block interacted with SOA, $F(3, 33) = 4.00$, $P = 0.042$, MSE = 883, indicating that this block effect was larger at 0-ms SOA (Ms = 369, 297, 285, and 276 ms) than at 1,000-ms SOA (Ms = 350, 302, 320, and 301 ms).

Dual-task RT2 and PE2

Respone time for T2 was 84 ms longer at 0-ms SOA (M = 457 ms) than at 1,000-ms SOA (M = 373 ms), $F(1, 11) = 15.93$, $P < 0.005$, MSE = 11,366, and it decreased across blocks (Ms = 517, 395, 384 and 368 ms for blocks 1, 2, 3, and 4, respectively), $F(3, 33) = 28.47$, $P < 0.0001$, MSE = 3,971. No interaction effect was found for RT2, $F < 1.0$. For PE2, only the F ratio for the interaction of SOA and block exceeded 1.0, $F(3, 33) = 2.31$, $P = 0.10$, MSE = 0.000511. Whereas PE2 was equal for 0- and 1,000-ms SOA in the first block, it was numerically higher for 0-ms SOA in the other three blocks.

Averaged RT and PE

For the average RT analysis, both main effects of SOA and block were significant. RT was 37 ms slower at 0-ms SOA (M = 383 ms) than at 1,000-ms SOA (M = 346 ms), $F(1, 11) = 5.94$, $P < 0.05$, MSE = 5,645, and RT decreased across blocks (Ms = 437, 348, 344, and 330 ms), $F(3, 33) = 23.98$, $P < 0.0001$, MSE = 2,555. The SOA and block interaction was not significant, $F(3, 33) = 1.724$, $P = 0.215$, MSE = 1673.52.

In the average PE analysis, no significant effects were found, though the block effect slightly approached the significance, Fs < 2.62, Ps > 0.114, MSE = 4.736. No two-way interaction effect was found, $F < 1.0$.

Discussion

Experiment 3 was conducted with a method that was even closer than those of Experiments 1 and 2 to the method used by Greenwald (2003) in the details of number of trial blocks, number of trials within each block, and pacing of the successive trials. Yet, again, the PRP effect on RT2 was clearly evident. Even though the exact instructions he used were employed in this experiment, we see no evidence for the elimination of the PRP effect on RT.

An analysis similar to that computed for Experiments 1 and 2 showed the function relating mean RT2 to RT1 bin at the 0-ms SOA to have a slope of 1.18, which is very close to that of 1.16 for the speed-stress condition in Experiment 1. The strong relationship between RT1 and RT2 at the 0-ms SOA is consistent with the hypothesis that the bottleneck limits the simultaneous processing of two ideomotor compatible tasks. The primary point remains that neither Greenwald's (2003) experiment nor the present experiments provide unambiguous support for the hypothesis that the PRP effect is eliminated with two ideomotor compatible tasks when speed-stress instructions are used.

General discussion

Absence of perfect timesharing

The lack of a PRP effect on RT with two ideomotor compatible tasks in Greenwald and Shulman's (1973) Experiment 2 has been widely cited in the dual-task literature as indicating that ideomotor compatible tasks bypass the limited capacity process of response selection. However, their results have not been replicated in several experiments (e.g., Lien et al., 2002), including their own Experiment 1. These prior findings indicate that use of two ideomotor compatible tasks is not sufficient to eliminate the PRP effect, and they leave open the question as to what conditions, if any, allow perfect timesharing for two such tasks. Greenwald (2003) reported that the PRP effect could be eliminated when ideomotor compatible tasks were combined with an admonition to respond quickly and simultaneously for the 0-ms SOA. Consequently, he proposed that a high state of preparatory activation is necessary for a stimulus to directly trigger its ideomotor-compatible response. However, although his experiment showed no PRP effect for RT2 with the speed-stress instructions, it did show a significant PRP effect in the PE2 data. This suggests that the anticipatory preparation produced by the speed-stress instructions reduced the amount of activation needed to attain a response threshold, causing the PRP effect to shift from being evident primarily in the RT measure to being more evident in the PE measure, consistent with sequential sampling models.

Because identifying the conditions, if any, under which perfect timesharing occurs has important implications for the nature of response selection, it is necessary to evaluate Greenwald's (2003) conclusion that speed-stress instructions are required to elicit perfect timesharing. The goal of the present study was to perform such an evaluation by manipulating instructions in a similar manner as Greenwald. The intent was to provide confirming or disconfirming evidence as to whether the PRP effect is in fact eliminated for two ideomotor compatible tasks with speed-stress instructions and whether any such elimination can be attributed unambiguously to perfect timesharing.

In all experiments, Task 1 required manual responses to left and right pointing arrows presented in left and right locations, respectively, and Task 2 required vocal naming responses to auditory letters. For Experiments 1 and 3, the Task 1 manual responses were keypresses, as in Greenwald's (2003) study, whereas for Experiment 2, the manual responses were unimanual switch movements, as in Greenwald and Shulman's (1973) study. Although speed-stress instructions reduced RT1 and RT2, and increased the error rate, as in Greenwald's (2003) Experiment 1, the instructional variable had no significant influence on the PRP effect for RT2 in any of the experiments. The PRP effect was 72 ms in Experiment 1 with the instructions used by Lien et al. (2002) and 52 and 84 ms in Experiments 1 and 3, respectively, with the speed-stress instructions added by Greenwald (2003). For Experiment 2, which used switch movement responses, the PRP effect was 59 and 42 ms with speed-and-accuracy and speed-stress instructions. Thus, even though the speed-stress instructions were effective at causing subjects to respond faster, the instructions produced at most a small reduction in the PRP effect on RT2; they certainly did not eliminate the PRP effect. Furthermore, the relation between RT1 and RT2 at the 0-ms SOA (predicted by bottleneck models) was at least as strong under speed-stress instructions as under speed-and-accuracy instructions.

Our experiments showed only a small tendency for a shift of the PRP effect from RT2 to PE2 under speed-stress instructions. Because they were designed to be similar to Greenwald's (2003) experiment but without the response-recording limitations of his apparatus, it is likely that the shift evident in Greenwald's (2003) experiment was mainly a consequence of those limitations. In his study, the vocal responses were recorded with automated voice-recognition software that often did not register responses accurately. This problem resulted in 15.1% of the vocal responses being unclassifiable (p. 862) and many correct responses being registered as errors (p. 863). Moreover, because Greenwald's software was capable of registering only one response per trial for the 0-ms SOA blocks, half of the error data at that SOA were missing. This meant that the estimates of error rates were noisy. It also meant that many errors in these 0-ms SOA blocks went undetected and did not trigger feedback to the subject. This implicit de-emphasis on accurate responding in these blocks, relative to the long SOA blocks, may have been responsible for the PRP effect shifting to the PE data in Greenwald's study.

Is the averaging method appropriate for measuring the PRP effect?

Greenwald and Shulman (1973) found that RT1 increased as SOA increased. They therefore suggested that, "Ss [subjects] might have been trading off processing capacity between the 2 tasks such that, as ISIs increased, Task 2 received relatively more capacity and Task 1 less." (p. 73). Consequently, Greenwald and Shulman proposed that the best indicator of the PRP effect is the average RT for the two tasks on each trial, rather than RT2 alone. When their Experiment 1 data, which showed a 75-ms PRP effect on RT2, were analyzed in this manner, the PRP effect was reduced to 18 ms. Greenwald and Shulman indicated, "These combined results more closely resembled the predicted effects, with the PRP effect being nearly absent when both tasks were IM compatible" (p. 73).

The present experiments also produced a longer mean RT1 at the 1,000-ms SOA than at the 0-ms SOA. As in Greenwald and Shulman's (1973) analysis, the approximately 50-ms PRP effects evident in RT2 with the speed-stress instructions were reduced to nonsignificant values of 11 and 8 ms in Experiments 1 and 3, respectively. Following Greenwald and Shulman's logic, these data indicate perfect timesharing. However, three considerations caution against using this logic. First, because perfect timesharing implies that the two ideomotor compatible tasks do not require limited-capacity resources, an analysis assuming that T1 and T2 share limited-capacity resources is self-contradictory. Second, the increase in RT1 as SOA increases is inconsistent with expectations based on capacity-sharing models of the PRP effect. Such models, which assume graded capacity allocation between two tasks, predict the opposite pattern, a decrease in RT1 as SOA increases (see Navon & Miller, 2002; Tombu & Jolicœur, 2002, 2003). Third, even if capacity sharing between the two tasks occurred, it would only be a factor at the 0-ms SOA because, at the 1,000-ms SOA, T1 was typically completed well before S2 occurred.

If capacity sharing does not account for RT1 being longer at the 1,000-ms SOA than at the 0-ms SOA, what does? RT1 would be expected to increase with increasing SOA if subjects tended to group responses for the two tasks at all SOAs. However, response grouping would not seem to be a factor at long SOAs in the present study because SOA was blocked as in Greenwald's (2003) study; presumably, subjects knew not to group responses when the SOA would be 1,000 ms. Moreover, for the 1,000-ms SOA, R1 was almost always completed prior to onset of S2.

A more likely explanation is that subjects are more alert for performing the visual–manual T1 when the auditory stimulus is presented at the same time as the visual stimulus. Auditory stimuli are well known to have automatic alerting properties (e.g., Posner & Boies, 1971). With two-choice visual tasks, a neutral auditory warning signal not only reduces RT but also increases error rate (e.g., Posner, Klein, Summers, & Buggie, 1973), a pattern that tended to occur at the 0-ms SOA in the present study. Also, because the complete visual stimulus was available immediately and included highly compatible redundant features (physical location, in addition to the instructed feature, arrow direction), whereas the auditory stimulus unfolded over a 200-ms period and did not include a redundant feature, response selection for the visual task likely preceded that for the auditory task at the 0-ms SOA. If subjects were aware that this would be the case, they could adopt a strategy of selecting a response to the visual–manual task as quickly as possible so that they could then begin selecting a response to the auditory–vocal task more quickly. According to this view, which we believe to be the most plausible, the method of averaging RT1 and RT2 as the measure of the PRP effect is inappropriate and yields misleading conclusions.

Conclusion

The issues of what conditions, if any, allow two tasks to be perfectly timeshared have been debated for some time. Although it is tempting to think that two ideomotor compatible tasks, each of which requires a seemingly trivial form of response selection, might be time shared with no cost, the evidence has indicated otherwise. Greenwald (2003) argued that two ideomotor compatible tasks can be perfectly time shared, however, if instructions emphasize rapid and simultaneous responding for the two tasks. According to this view, the state of high advanced preparation induced by speed-stress instructions enables the stimulus to trigger its associated response directly. Although his data showed no PRP effect in the RT data, they did, however, show an effect in the error data. The three experiments we reported here show that, when proper accuracy feedback is provided, significant PRP effects can appear in the RT data even when rapid and simultaneous responding is encouraged. Thus, instructions do not seem to be the key to enabling bottleneck bypass with ideomotor compatible tasks.

All told, now, for experiments using visual–manual and auditory–vocal ideomotor compatible tasks such as those of Greenwald and Shulman (1973), there is one finding consistent with perfect timesharing (Greenwald & Shulman's, 1973, Experiment 2) and 12 findings inconsistent with perfect timesharing (Greenwald & Shulman's Experiment 1; Lien et al.'s, 2002, four experiments; both the speed-and-accuracy and speed-stress instructions of Greenwald's, 2003, Experiment 1; the present Experiment 3 and both the speed-and-accuracy and speed-stress conditions of the present Experiments 1 and 2). The condition under which two ideomotor compatible tasks of this type can be timeshared perfectly appears to be sharply restricted, indeed. On the whole, the evidence suggests that although the bottleneck may be somewhat later in the processing sequence (see Lien et al., 2005), ideomotor compatible tasks are subject to a response-selection bottleneck much like other tasks, even when instructions encourage a high state of preparation. Perhaps this bottleneck can be bypassed entirely when subjects receive extended practice, but it is not apparent at this time whether even with extended practice ideomotor compatible tasks can bypass the response-selection bottleneck and be perfectly timeshared (see, e.g., Tombu & Jolicœur, 2004).

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