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Still No Evidence for Perfect Timesharing With Two Ideomotor-Compatible Tasks: A Reply to Greenwald (2003)

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For 30 years, A. G. Greenwald and H. G. Shulman's (1973) psychological refractory period (PRP) study has been cited as evidence for perfect timesharing with ideomotor (IM)-compatible tasks. Recently, M.-C. Lien, R. W. Proctor, and P. A. Allen (2002) failed to replicate these results and concluded that IM compatibility is neither necessary nor sufficient to eliminate the PRP effect. A. G. Greenwald (2003) attributed Lien et al.'s nonreplication to the use of (a) a non-IM-compatible task, (b) varied trial spacing, and/or (c) inappropriate instructions. The authors of the present article argue that the first 2 factors are not critical and that instructions merely affect the criterion for speed versus accuracy. In each of Greenwald's experiments, dual-task costs were evident on response time or error rates. Furthermore, the small dual-task costs in his study are consistent with a bottleneck model. Thus, Greenwald (2003) does not provide evidence that IM-compatible tasks enable perfect timesharing.

The psychological refractory period (PRP) effect, the slowing of response time (RT) for the second of two tasks at short stimulus onset asynchronies (SOAs), has often been attributed to participants' inability to perform central operations (e.g., response selection) for two tasks at the same time (see Lien & Proctor, 2002; Pashler, 1984; Pashler & Johnston, 1998, for reviews). Many studies have examined whether the central bottleneck can be bypassed, which would greatly reduce or eliminate the PRP effect. Results have shown that the PRP effect is remarkably robust and sometimes remains even after extensive practice (e.g., Ruthruff, Johnston, & Van Selst, 2001; Van Selst, Ruthruff, & Johnston, 1999) or with highly compatible stimulus and response sets (e.g., Brebner, 1977; Smith, 1967). In one important exception, however, Greenwald and Shulman (1973) argued that central operations can be bypassed and the PRP effect eliminated (i.e., allowing perfect timesharing) with two ideomotor (IM)-compatible tasks. They defined IM compatibility as situations in which the "stimulus resembles sensory feedback from the response" (p. 70). According to their IM-compatibility theory, response codes for the IM-compatible tasks can be activated directly and thus bypass the limited-capacity central stage.

Lien, Proctor, and Allen (2002)

In the three decades since Greenwald and Shulman's (1973) study, their conclusion has been widely cited but rarely questioned. Lien et al. (2002), however, recently questioned Greenwald and Shulman's conclusion for three major reasons. First, Greenwald and Shulman's conclusion was oversimplified. When RTs were averaged over the two tasks, the PRP effect was relatively small. However, when the PRP effect was measured in the standard way (short-SOA Task 2 RT minus long-SOA Task 2 RT), as in most PRP studies, results from Greenwald and Shulman's two experiments were actually in conflict: A significant PRP effect of 89 ms was observed with two IM tasks in Experiment 1, but little or no PRP effect was observed in Experiment 2. Greenwald and Shulman identified the instructions that "most often the 2 signals on each trial would be simultaneous" (p. 73) as being the crucial methodological factor differentiating their two experiments. However, their final conclusion, that "the PRP effect is eliminated when both tasks are IM compatible" (p. 74), did not acknowledge the importance of particular instructions. Second, Lien et al. failed to replicate Greenwald and Shulman's results. All four of Lien et al.'s experiments showed a significant PRP effect with two IM-compatible tasks, even when the method of Greenwald and

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Shulman's Experiment 2 was directly replicated. Third, Greenwald and Shulman's IM-compatibility theory is inconsistent with the finding that the PRP effect is evident when only one of the two tasks is IM compatible. Greenwald and Shulman proposed that dual-task interference is primarily due to the overloading of central operations and that these central operations are bypassed for IM-compatible tasks. If so, the IM-compatibility theory seems to imply that the PRP effect should be absent whenever either task alone is IM compatible, even if the other is not. Contrary to this implication, Greenwald and Shulman's own experiments, as well as Lien et al.'s attempted replications, unambiguously showed a PRP effect when one task was IM compatible and the other was not.

Greenwald (2003)

Recently, Greenwald (2003) reiterated his position that perfect timesharing does occur with two IM-compatible tasks. He suggested that Lien et al.'s (2002) nonreplication of Greenwald and Shulman (1973) might have been due to one or more of three differences in procedure. He also conducted two new experiments that he interpreted as evidence for one of the procedural differences being crucial for enabling perfect timesharing. Below, we first describe the three procedural differences cited by Greenwald and explain why it is unlikely that they played a critical role in Lien et al.'s nonreplication. We then discuss the results of Greenwald's two new experiments and argue that they still do not provide strong evidence for "perfect timesharing" with two IM-compatible tasks.

Three Procedural Differences Between Greenwald and Shulman (1973) and Lien et al. (2002)

Greenwald (2003) contended that three procedural details might explain the deviations from perfect timesharing observed in Lien et al.'s (2002) experiments. First, he argued that Lien et al.'s task—a left–right movement of a joystick to a left–right arrow—may not have been IM compatible. Because participants grasped the joystick handle with their dominant hand and placed their other hand on the base of the joystick to stabilize it, Greenwald argued, "the nondominant hand's role in this coordination opposed the IM-compatible direction-plus-position cue" (p. 860). We argue, however, that response selection for the joystick movement in Lien et al.'s study involved selecting a left–right action made by the dominant hand; the nondominant hand merely prevented any movement of the apparatus. Studies of stimulus–response compatibility effects have consistently found that responses are coded in terms of response goals (e.g., move the joystick left or right), which are defined by task instructions, rather than in terms of effectors, such as hands (e.g., Guiard, 1983; Hommel, 1993). Thus, regardless of whether or how the two hands were coordinated in Lien et al.'s study, the response goal was simply to move the joystick in the direction that corresponded to the arrow direction–position. Moreover, when Lien, McCann, Ruthruff, and Proctor (2003) used an immoveable joystick, so that only the dominant hand response was involved, a substantial PRP effect with two IM-compatible tasks was still found. Hence, Lien et al.'s (2002) nonreplication was not due to their participants' stabilizing the joystick with the nondominant hand.

Second, Greenwald (2003) claimed that, "unlike those of other studies that have obtained perfect timesharing, [. . . Lien, Proctor, & Allen's] procedure did not use regularly spaced trials" (p. 860), which "may have prevented their subjects from preparing optimally for the timeshared task combinations" (p. 861). However, we see no reason why it is necessary to use a fixed time between stimulus presentations. In fact, a negative consequence of this procedure is that a relatively slow response on one trial will result in a relatively short preparation interval for the next trial. Arguably, it makes more sense to use a constant response–stimulus interval (RSI) so that preparation time will be constant. Indeed, the latter procedure has been adopted in the overwhelming majority of modern cognitive psychology experiments, including Lien et al. (2002), in which a constant RSI of 2 s was used.[1]

Third, Greenwald (2003) objected that the instructions used by Lien et al. (2002) were different from those of Greenwald and Shulman (1973). Greenwald and Shulman contended that the crucial factor distinguishing their Experiment 2 from their Experiment 1 was the instructions "The *S*s [subjects] were informed that most often the 2 signals on each trial would be simultaneous and were not given any expectation that one signal might reliably precede the other" (p. 73). Lien et al. were aware of this point and thus attempted to duplicate Greenwald and Shulman's instructions as closely as possible. Nevertheless, Greenwald suggested that Lien et al. omitted a crucial instruction that was not mentioned in Greenwald and Shulman's methods: "To the best of the present author's recollection, however, [. . . Greenwald & Shulman's] instructions for Experiment 2 not only stressed the simultaneous occurrence of the stimuli but also encouraged subjects to respond both rapidly and simultaneously to the simultaneous stimuli" (p. 860). Given that these instructions were not mentioned in the original article, Lien et al. can hardly be held accountable for failing to replicate them. Moreover, we argue that Greenwald's new experiments, summarized below, do not provide strong evidence that these instructions produced perfect timesharing.

Greenwald's (2003) New Experiments

To further support his IM-compatibility theory, Greenwald (2003) presented two new experiments, each of which used two IM-compatible tasks. Experiment 1 included single-task blocks, 0-ms SOA dual-task blocks, and 1,000-ms SOA dual-task blocks with fixed trial spacings (2 s for single-task blocks and 0-ms SOA dual-task blocks; 3 s for 1,000-ms SOA dual-task blocks). To demonstrate the importance of instructions, he compared the Greenwald and Shulman (GS) condition, which stressed speed and simultaneous responding (i.e., "YOU ARE TO MAKE TWO RESPONSES AT THE SAME TIME," p. 862), with the Lien, Proctor, and Allen (LPA) condition, which emphasized speed and accuracy equally (i.e., "respond to each task as quickly and accu-

[1] In Lien et al. (2002), the accuracy of participants' vocal responses for each trial was entered into a computer by the experimenter as quickly as possible. The feedback message for the two tasks was then presented for 1 s, followed 1 s later by the stimulus for the next trial.

Table 1
Mean Response Times (in Milliseconds; Error Proportions in Parentheses) for Task 1, Task 2, and Their Averages in Greenwald's (2003) Experiment 1 as Functions of Block Type and Instruction Condition

	GS condition				LPA condition			
Task	0-ms SOA dual task	1,000-ms SOA dual task	Single task	PRP effect	0-ms SOA dual task	1,000-ms SOA dual task	Single task	PRP effect
Task 1	291	290	269		350	340	309	
	(3.57)	(1.17)	(2.85)		(0.88)	(1.29)	(2.30)	
Task 2	410	416	398	−6	534	491	504	43*
	(13.41)	(10.31)	(8.99)	(3.10)	(10.96)	(10.17)	(8.64)	(0.79)
Average	351	353	333	−2	442	416	406	27*
	(8.49)	(5.75)	(5.92)	(2.74*)	(4.60)	(5.74)	(5.47)	(−1.14)

Note. GS = Greenwald & Shulman (1973); LPA = Lien, Proctor, & Allen (2002); SOA = stimulus onset asynchrony; PRP = psychological refractory period.
* $p \leq .05$.

rately as you can").[2] We summarize his results in Table 1.[3] In both instruction conditions, RTs were slower in the 0-ms SOA dual-task blocks than in the single-task blocks. Comparing performance in the 0-ms and 1,000-ms SOA dual-task blocks, however, Greenwald claimed that results from the GS condition replicated Greenwald and Shulman's (1973) earlier finding of "perfect timesharing" and that results from the LPA condition replicated Lien et al.'s (2002) finding of a substantial PRP effect.

Greenwald (2003) further argued that neither the pure single-task blocks nor the 1,000-ms SOA dual-task blocks in Experiment 1 constituted appropriate control conditions for measuring dual-task interference. He contended that the extra response preparation for the dual-task trials compared with that for the single-task trials "constitutes a burden that will increase latencies" and that the switching from Task 1 to Task 2 in the 1000-ms SOA dual-task blocks would "produce slowed responding on the second task" (p. 866; for an opposite view, see Lien, Schweickert, & Proctor, 2003). In Experiment 2, therefore, he used a mixed-task control condition, in which the two kinds of single-task trials (Task 1 alone or Task 2 alone) were mixed randomly within blocks. In this control condition, each relevant stimulus was accompanied by an irrelevant "accessory" stimulus in the other modality (a click accompanied the visual Task 1, and three asterisks accompanied the auditory Task 2). Experiment 2 adopted (approximately) the GS instructions of Experiment 1 and included conditions in which two non-IM-compatible tasks were used. For the two IM-compatible tasks condition, RTs were faster in the 0-ms SOA dual-task blocks (which Greenwald called "timeshared blocks") than in the mixed-task control blocks. For the two non-IM-compatible tasks condition, however, RTs were slower in the 0-ms SOA dual-task blocks than in the mixed-task control blocks. Greenwald concluded that these results confirmed perfect timesharing with two IM-compatible tasks.

We argue, for reasons discussed below, that these two experiments still do not provide strong evidence for perfect timesharing with two IM-compatible tasks. First, although Greenwald (2003) suggested that proper instructions are the key to enabling perfect timesharing, we argue that changing instructions merely shifts speed–accuracy criteria. Second, although the PRP effect was absent for RTs in the GS condition of Experiment 1, a PRP effect was present for error rates. Finally, we argue that relatively small PRP effects do not necessarily indicate that the central bottleneck has been bypassed.

Are instructions the key that unlocks the door to perfect timesharing? Greenwald (2003) suggested that specific instructions are necessary to enable perfect timesharing. We argue, however, that the instructional differences between the GS and LPA conditions might merely have shifted speed–accuracy criteria. In the 0-ms SOA dual-task blocks, for instance, Task 1 RT was faster in the GS condition (291 ms) than in the LPA condition (350 ms), but the error rate was 4 times higher in the GS condition (3.57%) than in the LPA condition (0.88%). Similarly, Task 2 RT was faster in

[2] The full instructions for both the GS and LPA conditions in Greenwald's (2003) Experiment 1 were as follows. In the LPA condition,

> the following instructions were presented in introductory instructions for the experiment: "During this experiment sometimes tasks will be presented simultaneously. Your job is to respond to each task as quickly and accurately as you can. Do not wait for the other task to appear. Remember that speed and accuracy are important." A reminder that "speed and accuracy are equally important" was provided before each block of trials for all single-task and dual-task conditions (p. 862).

In the GS condition,

> first, the preliminary instructions were "Throughout this experiment, it is important for you to respond as rapidly as you possibly can while maintaining a high rate of accuracy." Second, prior to each block of trials, subjects were reminded to respond "very rapidly." And, third, in the dual-task ISI = 0 [SOA = 0 ms] condition, the instructions prior to each block additionally reminded subjects "YOU ARE TO MAKE TWO RESPONSES AT THE SAME TIME" (p. 862).

[3] We thank Anthony G. Greenwald for supplying these data.

the GS condition (410 ms) than in the LPA condition (534 ms), but the error rate was much higher in the GS condition (13.41%) than in the LPA condition (10.96%).[4]

The likely presence of a speed–accuracy criterion shift between the GS and LPA conditions at the 0-ms SOA dual-task blocks has two implications. First, if there is a bottleneck, then the speedup in RTs should reduce the PRP effect (see below for detailed discussion of this point). Thus, the corresponding reduction of the PRP effect in the GS condition is not surprising. Second, when speed is emphasized, participants may attempt to maintain a constant speed across blocks, causing any differences in difficulty between blocks to show up primarily in error rates. This situation is the opposite of what is normally assumed for the traditional RT paradigm, in which it is assumed that participants try to maintain a constant error rate across conditions and that the effects of processing difficulty will show up primarily in RTs (see Pachella, 1974; Wickelgren, 1977).

Was the PRP effect eliminated? In Greenwald's (2003) Experiment 1, the GS instructions in the 0-ms SOA dual-task blocks emphasized speed and simultaneous responding, which might have led participants to understand that accuracy was not important. Furthermore, only one of the two responses was collected on each trial in the 0-ms SOA dual-task blocks (due to software restrictions; see Greenwald's Footnote 4), and then the feedback message *ERROR* was based only on that response. Thus, when participants made an error on one task, they often did not receive the error message. The frequent absence of error feedback, combined with the strong speed emphasis, might have led participants to respond quickly at the cost of accuracy. Note that this software restriction did not affect the 1,000-ms SOA blocks, in which feedback was based on both responses in a trial. In addition, the GS instructions emphasized simultaneous responding for the two tasks in the 0-ms but not in the 1,000-ms SOA dual-task blocks; these instructions might have further increased the emphasis on speed. These arguments suggest that the participants' bias toward response speed was higher in the 0-ms SOA dual-task blocks than in the 1,000-ms SOA dual-task blocks.

Given the likelihood of a speed–accuracy trade-off between blocks, both RT and error data should be considered in determining whether the PRP effect has been eliminated with two IM-compatible tasks. Although there was no PRP effect on RTs in the GS condition of Experiment 1, the Task 1 error rate was 3 times higher in the 0-ms SOA dual-task blocks (3.57%) than in the 1,000-ms SOA dual-task blocks (1.17%). Similarly, Task 2 error rate was much higher in the 0-ms SOA dual-task blocks (13.41%) than in the 1,000-ms SOA dual-task blocks (10.31%). Even with Greenwald and Shulman's (1973) measurement of the PRP effect, averaged across Task 1 and Task 2, the PRP effect on error rate was statistically significant in the GS condition. Greenwald (2003) downplayed these effects by noting that they were smaller and nonsignificant early in the experiment. Nevertheless, the error rate was higher in the 0-ms SOA dual-task blocks than in the 1,000-ms SOA dual-task blocks for all four phases of the experiment (see Greenwald's Table 1).

A PRP effect on error rates might also have occurred in Experiment 2 of Greenwald (2003). Because of the lack of detailed error data, however, we are not able to evaluate this possibility. Furthermore, in contrast to Greenwald's view, we argue that his mixed-task blocks did not provide an appropriate control condition for measuring dual-task interference. In his mixed-task blocks, there was uncertainty prior to each trial about what task would need to be performed. Also, because stimuli were presented in both modalities in the mixed-task blocks, participants had to determine which stimulus was relevant and which one was irrelevant, and inhibition of the irrelevant stimulus might have been needed. Meanwhile, there was no task uncertainty in the dual-task blocks and no need to inhibit an irrelevant stimulus. These advantages might have cancelled out a real disadvantage of having to perform two tasks at the same time. In fact, a comparison of the dual-task and the single-task blocks reveals significant dual-task interference for the visual–manual IM-compatible task in Experiment 2. Consequently, neither experiment in Greenwald's study provides unambiguous support for perfect timesharing with two IM-compatible tasks.

Was the central bottleneck bypassed? Do the small dual-task costs observed by Greenwald (2003) support the key assumption of IM-compatibility theory "that IM-compatible tasks could bypass a limited-capacity response selection process [central bottleneck]" (p. 859; see also Greenwald & Shulman, 1973)? It has previously been noted that small dual-task costs can, under some circumstances, be obtained even when the central bottleneck still exists (e.g., Byrne & Anderson, 2001; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003). According to the central bottleneck model, the predicted PRP effect at the 0-ms SOA is given by $1A + 1B - 2A$[5] (where 1A and 1B refer to the perceptual and central processing stage, respectively, of Task 1, and 2A refers to the perceptual processing stage of Task 2; Van Selst et al., 1999). Thus, there are two conditions leading to little or no PRP effect: (a) short stage durations for 1A and 1B and (b) a long stage duration for 2A. Short stage durations for 1A and 1B are likely to occur when Task 1 is easy (e.g., with IM-compatible tasks), as reflected in short RTs. Previous studies have provided evidence that when Task 1 is sufficiently short, the central bottleneck can become "latent," producing little or no interference (Ruthruff et al., 2003; Van Selst et al., 1999). In addition, a small PRP effect is likely to occur when stimulus identification for Task 2 is time-consuming, resulting in a relatively long duration for Stage 2A.

Both of the conditions (short 1A and 1B; long 2A) that enable the bottleneck to produce a small PRP effect seem to be present in the GS condition of Greenwald (2003). As a concrete example, the bottleneck model could explain the small PRP effect as follows. In the 1,000-ms SOA dual-task blocks, the visual–manual task was presented as Task 1 and the auditory–vocal task as Task 2. Given

[4] Greenwald (2003) noted that his automated voice-recognition software made two kinds of errors. First, "the vocal response received an unidentifiable code on 15.1% of vocal-response trials" (p. 862). These "unidentified responses were treated as correct in the analyses that were reported" (personal communication, A. G. Greenwald, March 27, 2003). Second, he noted that many of the errors reported by the voice-recognition software were actually correct responses. Because of these issues, it is difficult to determine the actual error rate for this task.

[5] The PRP equation is based on the assumption that a bottleneck occurs on every trial at the 0-ms SOA but never at the long SOA.

that RTs were much shorter for the visual–manual task (291 ms) than the auditory–vocal task (410 ms) in the 0-ms SOA dual-task blocks, it is reasonable to assume that participants performed central operations for two tasks in the same order as they did in the 1,000-ms SOA dual-task blocks. Suppose, as also seems reasonable, that the average combined duration of Stages 1A and 1B is about 180 ms (leaving 111 ms for response execution). Further, suppose that the duration of Stage 2A is about 200 ms. This estimate seems reasonable, given that it took 200 ms to fully present the auditory sound ("A" or "B") and that mean Task 2 RT was 410 ms. Under these durations, Stage 1B would tend to finish before Stage 2A; thus, the bottleneck stages would usually not conflict and little PRP effect should be expected. Although one could argue about the exact values of the relevant stage durations, it is clear that under certain plausible conditions, little PRP effect would occur. Given that a plausible bottleneck model can account for Greenwald's data, one cannot conclude that the bottleneck was bypassed or, in Greenwald's (2003) words, "evade[d] or minimize[d]" (p. 859) with two IM-compatible tasks.

Conclusions

We argue that two of the three procedural differences (non-IM-compatible task and variable trial spacing) suggested by Greenwald (2003) are unlikely to have been responsible for Lien et al.'s (2002) nonreplication. In fact, Greenwald's Experiment 1 used two IM-compatible tasks and fixed trial spacing, yet it confirmed Lien et al.'s finding of a PRP effect with the LPA instructions. This finding also provides converging evidence that the use of two IM-compatible tasks is not sufficient to eliminate the PRP effect. Even Greenwald agrees that perfect timesharing does not occur unless the instructions stress speed and simultaneous responding. We agree that instructions matter, but only because they cause a shift in the criterion for speed versus accuracy. Furthermore, we argue that the small PRP effects in Greenwald's study do not necessarily indicate that the central bottleneck was bypassed with two IM-compatible tasks. We describe how a simple and plausible central bottleneck model can easily explain small PRP effects when Task 1 RT is unusually short.

Some insight into the present debate is provided by Greenwald, Pratkanis, Leippe, and Baumgardner's (1986) arguments against theory-based research strategies as contrasted with result-centered research strategies. They argued that "confirmation bias is an expectable product of theory-centered research strategies," noting that "researchers display confirmation bias when they persevere by revising procedures until obtaining a theory-predicted result" (p. 216). According to Greenwald et al., "this strategy produces findings that are overgeneralized in avoidable ways" (p. 216) because theorists overlook the experimental modifications needed to produce the theory-predicted result. Consequently, they noted, "although the conclusions from such research need to be qualified by reference to the tried-and-abandoned procedures, those conclusions are often stated only in the more general terms of the guiding theory" (p. 220). We contend that overgeneralization with respect to stating conclusions in the general terms of IM-compatibility theory occurred with respect to Greenwald and Shulman's (1973) original findings. Such overgeneralization will continue to occur if the central message of Greenwald's (2003) study, as implied in the *Conclusion* of his article, is that the perfect timesharing prediction of IM-compatibility theory has been confirmed. IM compatibility is only a subset of the conditions that reduce dual-task interference, quite possibly for reasons very different from those suggested by IM-compatibility theory.

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3. [illegible]
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5. [illegible]
6. [illegible]
7. [illegible]

[illegible]