Confirming and Disconfirming Theories About Ideomotor Compatibility in Dual-Task Performance: A Reply to Greenwald (2005)

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Because small dual-task costs with ideomotor-compatible tasks do not necessarily indicate the absence of a bottleneck, M.-C. Lien, R. S. McCann, E. Ruthruff, and R. W. Proctor (2005) considered additional sources of evidence regarding bottleneck bypass. This evidence argued against complete bottleneck bypass and, instead, supported an *engage-bottleneck-later* model in which early bottleneck substages are bypassed but late substages are not. A. G. Greenwald (2005), however, contended that M.-C. Lien et al. (2005) did not use the procedures needed to produce complete bottleneck bypass and that a complete bottleneck bypass hypothesis, combined with additional assumptions, could explain their data. The authors contend that this disagreement stems from Greenwald's focus on confirming predictions of complete bottleneck bypass (small dual-task costs) without disconfirming predictions of bottleneck presence. In particular, Greenwald neglects to consider the possibility that a latent bottleneck limitation could also produce small dual-task costs.

Dual-task performance limitations have been widely attributed to a processing bottleneck that prevents central stages from operating on more than one task at a time. In Lien, McCann, Ruthruff, and Proctor (2005), we found no evidence that ideomotor (IM)-compatible tasks completely bypassed this bottleneck. Greenwald (2005), however, argues that there are problems with our approach and that our conclusions are "limited in generalizability" (p. 221). In this reply, we point out that whereas Greenwald has attempted to confirm bottleneck bypass predictions (small dual-task costs), our goal was to discriminate between theories. Given our aims, our procedures were justified and our conclusions were appropriate.

Theory Discrimination Requires Disconfirmation

Greenwald (2003, 2005) has argued that IM-compatible tasks completely bypass the central bottleneck. This conclusion is based primarily on his finding that under certain conditions, dual-task costs are small when both tasks are IM compatible. He has referred to this finding as *perfect timesharing*, a term that blurs the dis-

tinction between the empirical finding and the theoretical conclusion. One problem with Greenwald's conclusion in favor of complete bottleneck bypass is that the obvious alternative hypothesis (that the bottleneck was still present) was not ruled out or even considered. We (Lien et al., 2005) have pointed out that the bottleneck model would also naturally predict small dual-task costs with IM-compatible tasks (or any other tasks that produce unusually short response times [RTs]; see also Anderson, Taatgen, & Byrne, 2005; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003). The reason is that the more quickly Task 1 is performed, the less Task 2 will be delayed. In fact, the central bottleneck model could even predict the virtual absence of dual-task costs, as shown in Figure 1, if Task 1 central stages are completed before the Task 2 central stages are ready to begin. We refer to such a bottleneck limitation that produces little or no observable dual-task cost in a particular condition as a *latent bottleneck*.

Given that small or even nonexistent dual-task costs are not necessarily diagnostic of bottleneck bypass for IM-compatible tasks, confirmation of this result (which has not even been obtained reliably) provides little discriminative value. We (Lien et al., 2005) therefore argued that a more sophisticated approach was necessary. We used several converging sources of evidence, such as the size of the psychological refractory period (PRP) effect relative to mean Task 1 response time (RT1), correlations between RT1 and Task 2 response time (RT2) within trials, and cross-task correspondence effects. We also conducted simulations to determine whether various bottleneck models could account for both qualitative and quantitative aspects of our data. Using this new approach, we found that a bottleneck model provided a close fit to many aspects of the data. At the same time, there were also clear indications that the bottleneck was not completely intact with
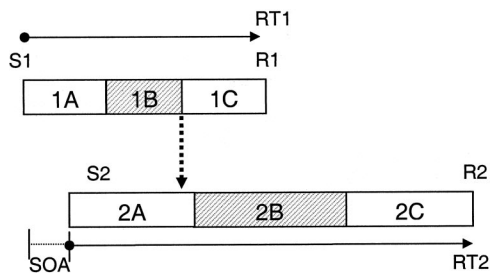
Figure 1. A latent central bottleneck model. When RT1 is sufficiently short, Task 1 central operations (1B) might finish before Task 2 central operations are ready to begin. If so, a central bottleneck would not delay Task 2 at a short stimulus onset asynchrony (SOA). 1A, 1B, and 1C are, respectively, the prebottleneck, bottleneck, and postbottleneck 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.

IM-compatible tasks (contrary to our previous view; Lien, Proctor, & Allen, 2002; Lien, Proctor, & Ruthruff, 2003). We concluded that, on the whole, the results favored an *engage-bottleneck-later* model in which early substages of the bottleneck were bypassed, leaving a bottleneck in later substages (e.g., motor code selection).

Is the Bottleneck "Universal" or "Inevitable"?

Although we (Lien et al., 2005) found no evidence of complete bottleneck bypass with IM-compatible tasks, we never stated that complete bypass was theoretically impossible or could never be demonstrated empirically. Nevertheless, Greenwald (2005) ascribes to us the extreme and untenable position of "bottleneck universality" (p. 224). He also states that we concluded that "simultaneous [IM]-compatible choice tasks cannot be perfectly timeshared" (p. 221) and that "a response selection bottleneck is inevitable" (pp. 221, 224).

In fact, the words *universality* and *inevitable* simply do not appear anywhere in our article, and neither does the phrase "cannot be perfectly timeshared." On the contrary, we explicitly stated that complete bypass might be possible if IM compatibility were combined with other factors (such as practice or certain incentives) and that it was important to continue searching for these conditions. Furthermore, we described in detail one case of apparent bottleneck bypass with a saccadic eye-movement task (Pashler, Carrier, & Hoffman, 1993). Also note that one of us has recently reported finding a case of bottleneck bypass after extensive practice (Ruthruff, Van Selst, Johnston, & Remington, in press).

Procedures for Disconfirming a Central Bottleneck

Contrary to Greenwald (2005), we argue that the bottleneck model is quite "disconfirmable." There are several results that would indicate complete bottleneck bypass: (a) small PRP effects combined with a long RT1, (b) responses to Task 2 well before Task 1, and (c) weak RT1–RT2 dependency within trials. In fact, these results have been obtained in three previous studies (Johnston & Delgado, 1993; Pashler et al., 1993; Ruthruff et al., in press), leading those authors to conclude that the bottleneck had

been bypassed. We designed our experiments with IM-compatible tasks so that it would be possible to obtain these results and thus disconfirm the bottleneck model. Note, however, that even when both tasks were IM compatible, none of these signs of bottleneck bypass were present in our experiments (Lien et al., 2005).

Ironically, the procedures that Greenwald (2003, 2005) has recommended for studying IM compatibility actually make it extremely difficult to demonstrate bottleneck bypass. First, he insists that both tasks must be IM compatible, ensuring that the RTs to both tasks will be short. Because RT1 will be short, the bottleneck could become latent, thus making essentially the same prediction as the complete bottleneck bypass model—small dual-task costs. Greenwald also recommends providing very strong speed stress, which would further reduce RT1 and eliminate any differences between the predictions of the two models. Instructions to respond simultaneously, recommended by Greenwald, are also problematic,[1] because they could cause very strong correlations between RT1 and RT2 (eliminating use of such correlations as indicators of bottleneck presence vs. absence). In summary, Greenwald has created a hypothesis about the set of conditions required for bottleneck bypass that cannot be confirmed or disconfirmed easily.

Greenwald (2005) also argues that "perfect timesharing" requires blocking stimulus onset asynchronies (SOAs) so that participants can optimally prepare for Task 2 following Task 1 stimulus onset. To support this argument, he cites single-task studies showing foreperiod effects with simple RT tasks. These citations are not directly relevant, however, because we used a dual-task design, not a single-task design, and we used choice-RT tasks, not simple-RT tasks. These differences are very important. First, temporal expectancy is known to have a much stronger effect on simple RT than on choice RT (e.g., Van Selst & Jolicœur, 1997). In support of this point, note that Greenwald's (2005) control experiment, which mixed the SOAs between a warning signal and an IM-compatible choice-RT task, produced only about a 15-ms difference in RT2 between the short and long SOAs (see his Figure 1B).[2] Second, in dual-task paradigms (but not in single-task paradigms), the Task 2 stimulus generally appears while participants are still performing Task 1 (i.e., at short SOAs). Thus, it is highly questionable that, as Greenwald suggests, participants begin preparing for Task 2 after Task 1 stimulus onset (see De Jong, 1995; Lien, Schweickert, & Proctor, 2003; Luria & Meiran, 2003).

To evaluate the importance of blocking SOAs, it is important to focus on studies with choice-RT tasks and dual-task conditions. In one such study, Bertelson (1967) found that mixing versus blocking SOAs had little influence on the PRP effect. According to Greenwald (2005), it was inappropriate for us to cite this finding

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[1] In Greenwald (2003, Experiment 1), speed-stress instructions did not eliminate the PRP effect but, rather, shifted it from RT to error rates (see Lien, Proctor, & Ruthruff, 2003, for a detailed discussion). Even that shift may have been a consequence of improper error feedback caused by software limitations in Greenwald's (2003) study (see his Footnote 4), for we have found the PRP effect to remain present in RT data even with Greenwald's speed-stress instructions (Shin, Cho, Lien, & Proctor, 2005).

[2] Note that Greenwald (2005) did not include a condition in which SOAs were blocked. Therefore, one cannot evaluate whether blocking or intermixing SOAs had any influence on the PRP effect.

because "Bertelson pointed out that 'RT2 was slightly but systematically longer under the irregular [i.e., mixed-SOA] condition' (p. 56)" (p. 224). Bertelson's (1967) statement, however, was in reference to a main effect and not an interaction with SOA, as indicated by his very next phrase (which Greenwald neglects to quote): "RT2 was slightly but systematically longer under the irregular condition, *even during the PRP* [italics added]" (p. 56). Elsewhere, Bertelson was even more specific on this point, stating that "it seems clear that the influence of ISI [interstimulus interval, or in current terminology, *SOA*] on RT2 is the same under both [regular and irregular ISI] conditions" (p. 51), and "the occurrence of these delays can thus not be accounted for in terms of time uncertainty regarding arrival of the second signal, as the 'expectancy theory' tries to do" (p. 55).

Greenwald's (2005) primary justification for recommending these particular procedures (i.e., speed-stress instructions and blocking SOAs) is that they have been "established by previous research to be critical to obtaining perfect timesharing" (p. 221). Assuming that "perfect timesharing" implies bottleneck bypass, this claim is unsubstantiated. The studies Greenwald cites did show small PRP effects, but none of them actually ruled out the bottleneck model (only Hazeltine, Teague, & Ivry, 2002, even considered explicitly what a bottleneck model would predict). Once again, this oversight stems from Greenwald's emphasis on confirming predictions of the complete bottleneck bypass model (small dual-task costs) rather than considering whether alternative models were ruled out. It is interesting to note that, among the studies that actually did rule out a bottleneck model (Johnston & Delgado, 1993; Pashler et al., 1993; Ruthruff et al., in press), none adopted the procedures Greenwald claims to be necessary for bottleneck bypass. Rather, they used mixed SOAs and standard instructions, just as we did in Lien et al. (2005).

In summary, we see no evidence that any of the procedures Greenwald (2005) recommends are necessary, or even helpful, for bottleneck bypass. Furthermore, they greatly reduce the chances of obtaining results that could disconfirm bottleneck models. We believe that our procedures provide a much better opportunity to confirm or disconfirm bottleneck model predictions. Thus, our procedures are not only appropriate but also preferred.

Can the Bottleneck Bypass Hypothesis Explain Our Findings?

One of the reasons that we (Lien et al., 2005) favored a type of bottleneck model was the finding of strong RT1–RT2 relationship within trials at the shortest SOA. Our simulations showed that a bottleneck model with a single set of parameters precisely accounts for the magnitude of this relationship across four different experiments. Meanwhile, we noted that complete bottleneck bypass models provide no obvious reason to expect such a relationship. In his commentary, Greenwald (2005) suggests that the relationship might be a result of "subjects strategically sequencing the two tasks" (p. 224). Strategic sequencing creates a type of bottleneck (albeit a voluntary one), so it is not inconsistent with our conclusions but, apparently, is inconsistent with perfect timesharing. Greenwald also mentioned that the RT1–RT2 relationship could be due to "momentary fluctuations in attention or arousal" (p. 224). As we noted in Lien et al. (2005), it seems unlikely that such fluctuations could cause the strong dependency we observed

(RT2 was more than 100 ms longer when RT1 was long than when RT1 was short). Thus, although the bottleneck bypass hypothesis might explain our data with several questionable auxiliary assumptions, we concluded that this hypothesis is not nearly as attractive as the bottleneck model, which provides a principled, accurate quantitative account.

Concluding Remarks

Traditionally, investigators have inferred the presence or absence of a bottleneck solely on the basis of the presence or absence of dual-task costs. Continuing this tradition, Greenwald (2005) argues that previous studies with small dual-task costs have convincingly demonstrated bottleneck bypass and that their procedures should be closely followed. He even goes so far as to suggest that we are prepared to maintain the bottleneck hypothesis "in the face of all data" (Greenwald, 2005, p. 224), which presumably again refers to small dual-task costs. We (Lien et al., 2005), however, pointed out that before concluding that the bottleneck was absent in any situation, it is necessary first to consider the possibility that a bottleneck was present. After evaluating several alternative hypotheses using converging sources of evidence, we concluded not only that the bottleneck model was not ruled out in our experiments but also that it provided the most attractive account of our data.

In summary, there is still no solid evidence that IM compatibility is a sufficient condition for complete bottleneck bypass. However, we did find evidence that parallelism between tasks occurs deeper into the processing stream for IM- than for non-IM-compatible tasks, without actually eliminating the bottleneck. Furthermore, we continue to maintain (despite Greenwald's, 2005, inaccurate characterization of our beliefs) that complete bottleneck bypass might be possible under other conditions. It is important to search for these boundary conditions using a set of converging indicators capable of determining whether a bottleneck is present.

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