Psychonomic Bulletin & Review (2022) 29:501–511
https://doi.org/10.3758/s13423-021-01974-1

BRIEF REPORT

Bypassing the central bottleneck with easy tasks: Beyond ideomotor compatibility

Morgan Lyphout-Spitz[1] · François Maquestiaux[1,2] · Eric Ruthruff[3]

Accepted: 14 June 2021

Abstract

Maquestiaux, Lyphout-Spitz, Ruthruff, and Arexis (2020) demonstrated that ideomotor-compatible (IM) tasks (e.g., pressing the left key when an arrow points left) can operate automatically, entirely bypassing the central bottleneck that constrains dual-task performance. But is bottleneck bypassing a specific consequence of IM compatibility or is it due to task ease? To answer this question, we tested the automaticity of a task that was easy but not IM. The task was easy due to the high semantic compatibility between the stimulus and the response: saying "ping" when hearing "pong" and "pong" to "ping" in Experiment 1, saying "low" when hearing "high" and "high" to "low" in Experiment 2. We presented it as Task 2, along with a Task 1 that was not easy, due to the use of an arbitrary stimulus-response mapping. Single-task trials were randomly intermixed with dual-task trials and then used as baselines to assess dual-task costs and to simulate distributions of inter-response intervals (IRIs) predictive of bottleneck bypassing vs. bottlenecking. The results of both experiments provided converging evidence that the entire Task 2 bypassed the bottleneck on virtually all trials: very small dual-task costs, high percentages of response reversals, and a close match between the observed IRI distributions and that predicted by bottleneck bypassing. Neither ideomotor compatibility nor task speed (the semantic task was not particularly fast) explain these findings. We therefore propose that the key to bypassing the central bottleneck is the ease with which people can fully load the stimulus-response mapping into working memory.

Keywords Automatic processing · Central bottleneck · Dual-task interference · Ideomotor compatibility · Response selection

Introduction

People routinely experience difficulty performing two tasks at once. For instance, talking can interfere with driving (Strayer & Johnston, 2001) and cause accidents. To explain the ubiquity of dual-task interference, Pashler (1994) proposed a processing bottleneck that precludes concurrent central processing on two tasks. Central processes are those that come after perceiving the stimuli but before executing the response (e.g., response selection and decision-making). Many subsequent experiments have supported this account across a wide range of tasks. Recent research, however, has identified a rare exception: the bottleneck can be entirely bypassed with ideomotor-compatible (IM) tasks (e.g., Maquestiaux, Lyphout-Spitz, Ruthruff, & Arexis, 2020). Tasks are deemed IM when "*the stimulus resembles sensory feedback from the response*" (Greenwald & Shulman, 1973, p. 70). Examples would be pressing a left key to a left-pointing arrow or repeating aloud auditory words (shadowing). Why do such tasks bypass the bottleneck? Does it reflect a special property of IM tasks or task ease more generally, such as the ease of representing tasks within working memory? Here we addressed these questions by using a non-IM task that has high semantic compatibility.

Background

Pashler (1994) proposed that a central bottleneck prevents attention from being simultaneously allocated to the central operations of two distinct tasks. The key assumption is that central stages of the first task (e.g., selecting the response

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✉ Morgan Lyphout-Spitz
morgan.lyphout-spitz@edu.univ-fcomte.fr

[1] Laboratoire de recherches intégratives en neurosciences et psychologie cognitive (LINC, UR 481) and Maison des sciences de l'homme et de l'environnement (MSHE) Ledoux (UAR 3124), Université Bourgogne Franche-Comté, 1 rue Charles Nodier, 25000 Besançon, France

[2] Institut Universitaire de France, Besançon, France

[3] Department of Psychology, University of New Mexico, Albuquerque, NM, USA

associated with the current stimulus) recruit all available attention, thereby delaying the central stages of the second task (the horizontal dashed line in Fig. 1A).

Studies employing the psychological refractory period (PRP) procedure are generally consistent with a central bottleneck (Janczyk & Kunde, 2020; Koch, Poljac, Müller, & Kiesel, 2018; Maquestiaux, 2012; for a review of forms of parallel processing during the central bottleneck, see Fischer & Plessow, 2015). This dual-task procedure involves presenting two stimuli (S1 and S2) separated by a variable onset asynchrony (SOA), each requiring a speeded response (R1 and R2). Participants are typically instructed to respond to each task as fast as possible, with extra emphasis on Task-1 speed. These instructions confine interference on Task 2 only, thus simplifying the predictions of the competing models. Reliably, Task-1 reaction time (RT1) remains constant across SOAs, whereas Task-2 reaction time (RT2) increases by hundreds of milliseconds from the longest to the shortest SOA. This RT2 increase is called the PRP effect.

Bottleneck bypassing with an ideomotor-compatible task

Recently, Maquestiaux et al. (2020) revisited the issue of whether response selection on IM tasks is "automatical," meaning that they can operate in parallel with all the stages of another task, even the central stage. We henceforth refer to this simply as bypassing the central bottleneck, or just *bypassing*. Although previous studies demonstrated that IM tasks sometimes produce small dual-task costs (e.g., 18 ms in Greenwald & Shulman, 1973), this does not necessarily indicate bottleneck bypassing. The reason is that small dual-task costs are also consistent with the presence of a brief central bottleneck (Anderson, Taatgen, & Byrne, 2005; Lien, McCann, Ruthruff, & Proctor, 2005; Lien, Proctor, & Allen, 2002; Lien, Proctor, & Ruthruff, 2003), especially when both tasks are IM-compatible (e.g., Halvorson, Ebner, & Hazeltine, 2013). Indeed, when the central stages of both tasks are short, which is likely in the case of IM tasks, bypassing and bottlenecking predict the same thing: small dual-task costs.

To overcome this theoretical impasse, Maquestiaux et al. (2020) presented an IM task as Task 2 in a PRP experiment, along with a "slow" Task 1 that produced long RT1s due to a long central stage. With this pairing, the candidate models make highly distinctive predictions regarding the amount of dual-task cost on Task 2: negligible in case of bottleneck bypassing but large in case of bottlenecking (because Task-2 central processing is delayed; see Fig. 1A). Using a slow Task 1 also permits two additional indicators: the rate of response reversals and the RT1:RT2 correlations. Bottleneck bypassing predicts frequent response reversals (R2 then R1) at short SOAs because Task 2 would routinely win the race against the slow Task 1. It predicts weak RT1:RT2 correlations at all SOAs because the tasks are performed more or less independently. Meanwhile, bottlenecking predicts rare response reversals because Task 1 is attended before Task 2. It predicts higher RT1:RT2 correlations at short SOAs because random variation across trials in Task-1 pre-bottleneck and/or bottleneck stages should carry over onto Task 2 following the bottleneck delay.

In Maquestiaux et al. (2020), the IM Task 2 required indicating the direction of an arrow (pointing to the left or to the right) with a spatially compatible keypress (left index or right index keypress). The control group performed a non-IM, shape discrimination for Task 2 (circle vs. triangle). Task-1 and Task-2 stimuli were separated by a variable SOA of 15, 65, 250, or 1,500 ms. Intermixed within these dual-task trials were single-task trials, which offer an appropriate baseline against which to assess dual-task interference. PRP studies have traditionally measured dual-task costs using the long SOAs as a baseline; however, long SOAs allow participants to finish Task 1 then use any available time to selectively

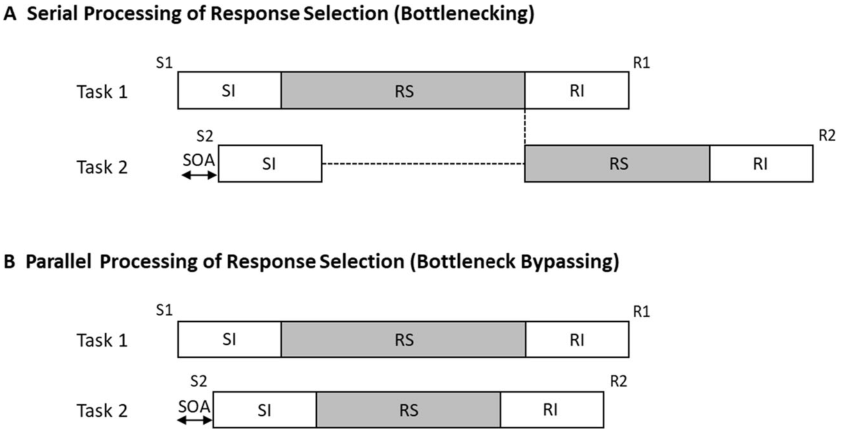

Fig. 1 Two distinct central processing modes when pairing a Task 1 that produces long reaction times (due to the long duration of its central stage) and a Task 2, using the Psychological Refractory Period (PRP) procedure. *SOA*: stimulus onset asynchrony, *SI:* stimulus identification, *RS*: response selection, *RI:* response initiation

prepare for only Task 2 (something not possible at short SOAs and not possible on single-task trials).

The indicators were plainly consistent with bottleneck bypassing when Task 2 was IM: a negligible dual-task cost on Task 2 (3 ms), very frequent response reversals at the shortest SOA (79%), and weak RT1:RT2 correlations (.28). But the indicators were consistent with bottlenecking when Task 2 was non-IM: a large dual-task cost on Task 2 (194 ms), infrequent response reversals (21%), and strong RT1:RT2 correlations (.48).

Maquestiaux et al. (2020) also simulated the entire distribution of inter-response intervals (IRIs) predicted by the bottleneck-bypassing hypothesis. These simulations paired every single-task RT on Task 1 with every single-task RT on Task 2 (for more details, see the *Results* section below). At the shortest SOA, Maquestiaux et al. reported a close match between the observed and simulated IRI distributions, indicating bottleneck bypassing.

The Current Study

Because IM tasks have been found to entirely bypass all processing bottlenecks, and other tasks have not, one might assume that the key to bypassing is IM compatibility. That is, response selection is automatic specifically because the stimulus is essentially the same as the response, requiring no attention to navigate between them. However, another possibility is that IM tasks are simply at one extreme end of a continuum of task difficulty. For example, perhaps the real key to bypassing is simply the ease of loading both tasks into working memory simultaneously.

With regard to this question, Halvorson and Hazeltine's study (2015) is highly intriguing: they obtained small dual-task costs with tasks that are undoubtedly non-IM, such as saying "dog" when hearing "cat" or pressing the key opposite to the pictured hand. This finding goes against a large number of previous studies reporting robust dual-task costs with non-IM tasks. However, equating these small dual-task costs with bottleneck bypassing is problematic because Halvorson and Hazeltine did not specifically set out to assess bypassing. In addition, their use of only a 0-ms SOA for tasks with very different mean RTs (e.g., 365 vs. 518 ms) raises the concern that the central operations of the two tasks were often asynchronous (Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003). Therefore, the finding of small dual-task costs is a tantalizing clue, but does not provide unambiguous evidence of bottleneck bypassing.

Here we evaluated whether a non-IM yet easy task can operate automatically, thereby entirely bypassing the central bottleneck. In Experiment 1, Task 2 required saying "ping" when hearing "pong" and "pong" to "ping". In Experiment 2, Task 2 required saying "high" to "low" and "low" to "high" (actual words in French were "haut" and "bas"). These pairings are not IM because merely echoing the stimulus would lead to an error rate of 100%. Yet, they still rely on a strong semantic association, thus making the tasks very easy (e.g., easy to prepare). Using the PRP procedure, our approach involved presenting this task as Task 2, along with a visual-manual Task 1 that produced long RTs (due to a long central stage).

To probe for bottleneck bypassing, we relied upon three converging indicators: dual-task cost on Task 2, response reversal rate, and simulations of IRI distributions.

Experiment 1

Method

Figure 2 depicts the tasks and procedure.

Participants Twenty-four undergraduate psychology students from the University of Franche-Comté (*M* = 19.6 years old, *SD* = 1.8 years; 21 women) participated in exchange for partial course credit. The sample size of 24 was fixed in advance and chosen so we would have as much statistical power as the most comparable study (i.e., *N* = 24 in Maquestiaux et al., 2020).

Apparatus and stimuli The experiment was programmed with E-Prime and run on a laptop computer using an AZERTY keyboard, coupled with headphones and a PST Serial Response Box. Voice onset was detected by the voice key integrated within the box; the experimenter manually entered the participant's vocal response using the box.

The visual Task-1 stimulus was a colored circle – purple, blue, green, or yellow – displayed in the screen center. The circle diameter was 2 cm. The auditory Task-2 stimulus was the spoken word "ping" or "pong," lasting 250 ms.

Design and procedure For Task 1, participants pressed the E key with their left index finger when the circle was purple or green, and the P key with their right index finger when it was blue or yellow. For Task 2, they responded to the spoken word "ping" by saying "pong" and vice versa.

Participants started with 96 familiarization trials on Task 1 and then 96 familiarization trials on Task 2. They then performed 16 familiarization dual-task trials followed by 288 experimental trials consisting of a random mixture of PRP trials (192 trials) and single-task trials (48 for Task 1, 48 for Task 2). The combination of the four Task-1 stimuli and the two Task-2 stimuli with each of the four SOAs (15, 65, 250,

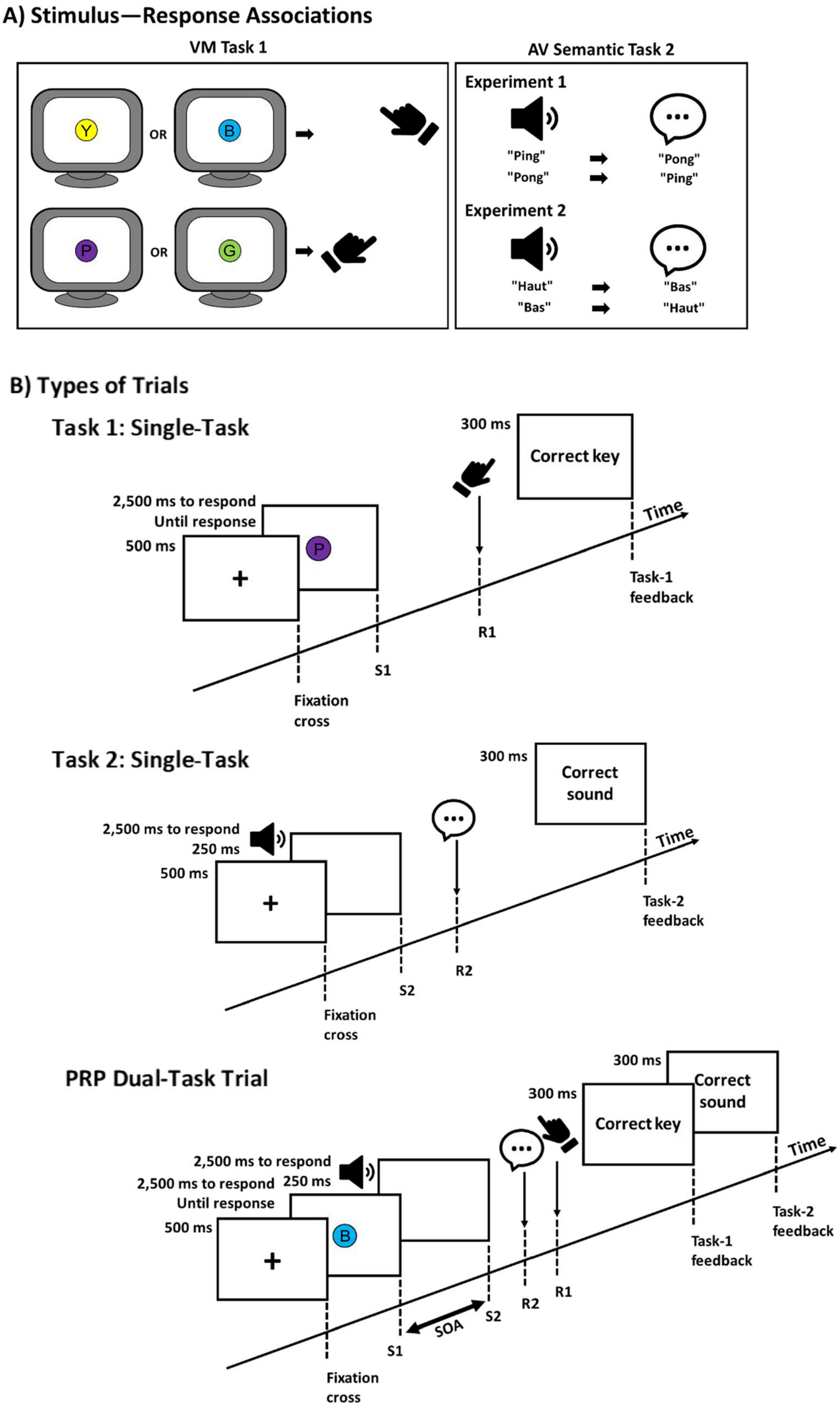

Fig. 2 Stimulus-response associations (**A**) and types of trials (**B**) in Experiments 1 and 2. In the example psychological refractory period (PRP) dual-task trial, response order was reversed: Task-2 response (R2) was emitted before Task-1 response (R1). *S1:* Task-1 stimulus, *S2:* Task-2 stimulus, *SOA*: stimulus onset asynchrony. The letter within each circle, not displayed during the experiment, indicates its color, with Y for yellow, B for blue, P for purple, and G for green

and 1,500 ms) resulted in 32 distinct trial types, each of which was repeated six times within a session to obtain the 192 dual-task trials. The 288 experimental trials were broken into nine blocks of 32 trials. During each 2-min break between blocks, the computer provided performance feedback regarding the preceding block: Task-1 speed and accuracy, and Task-2 accuracy. Participants were asked to copy these scores on a grid to ensure awareness of their performance and to promote efforts at improvement. They were informed that either one or two stimuli would occur on each trial. They were also instructed to respond as fast and accurately as possible and were given the typical PRP instructions emphasizing Task-1 speed. Note that the instructions did not constrain response order, and both orders – R1 then R2 and R2 then R1 – were allowed and included in analyses.

Every trial began with a black fixation cross displayed for 500 ms in the screen center. For Task-1 single-task trials, the colored circle was then presented and remained until response or 2,500 ms had elapsed. For Task-2 single-task trials, the word was played and participants had up to 2,500 ms to respond before timing out. Then, a 300-ms visual message indicated whether the response was correct. For dual-task trials, the circle was presented, followed after the SOA by the auditory word. Then, two successive 300-ms messages indicated whether the Task-1 and Task-2 responses were correct. If no response to a task was detected, an additional 200-ms message stated that fact. The intertrial interval was 800 ms.

Results

We removed trials for which the RT was below 100 ms or above 2,500 ms on Task 1 (single-task: 0.17%; dual-task: 0.17%) or Task 2 (single-task: 2.17%; dual-task: 1.95%). Error trials were also removed from RT analyses. Figure 3 shows the resulting mean RTs. See also Table 1 for descriptive statistics.

Reaction times and error rates

Task 1 The main effect of SOA was significant, $F(3, 69) = 4.99$, $p < .01$, $\eta_p^2 = 0.18$. Post hoc comparisons using the Bonferroni procedure showed a 44-ms RT1 increase from the longest SOA to the two intermediate SOAs, with no other significant comparisons. Mean Task-1 error rate was relatively uninfluenced by SOA, $F(3, 69) = 1.53$, $p = .21$, $\eta_p^2 = 0.06$.

Semantic Task 2 RT2 slightly increased from the longest SOA to the shortest SOA, $F(3, 69) = 3.33$, $p < .05$, $\eta_p^2 = 0.13$, yielding a mean PRP effect of only 25 ms. Mean Task-2 error rate was uninfluenced by SOA, $F(3, 69) = 2.00$, $p = .12$, $\eta_p^2 = 0.08$.

Probing for bottleneck bypassing

Dual-task costs Dual-task costs were calculated as the RT difference between the shortest SOA and the mixed single-task trials. The mean dual-task cost was significant but only 34 ms on Task 2, $t(23) = 3.26$, $p < .01$, $d_z = 0.67$, and only 18 ms on Task 1, $t(23) = 1.44$, $p = .16$, $d_z = 0.30$. Such small dual-task costs are consistent with bottleneck bypassing.

Response reversal rates Response reversals should be frequent at short SOAs in case of bottleneck bypassing (because Task 2 would often win the race against the slow Task 1), but relatively rare in case of bottlenecking. Consistent with bottleneck bypassing, the rate of response reversals was much higher at short SOAs (e.g., 52.4% at the shortest SOA) than at the longest SOA (0.1%), $F(3, 69) = 118.34$, $p < .001$, $\eta_p^2 = 0.84$.

Simulations of IRI distributions We used the mixed single-task trials on Task 1 and Task 2 to simulate the IRI distributions that should occur on dual-task trials, at each SOA, for bottleneck bypassing as well as for bottlenecking. The question is whether the observed IRIs more closely match the predictions from bypassing or bottlenecking.

Bypassing For each participant, we first paired each of the 48 mixed single-task trials on Task 1 with each of the 48 mixed single-task trials on Task 2, resulting in 2,304 simulated dual-task trials. To simulate complete bottleneck bypassing, we then calculated the predicted IRI for each trial at a given SOA as follows: IRI = SOA + RT2 – RT1. These simulated data were then filtered exactly as with the real dual-task data, by removing outliers and error trials.

Bottlenecking We also predicted the distribution of IRIs that would be observed if the tasks were performed serially, i.e., in the case of bottlenecking. Our simulation was based on the finding that the mean PRP effect is roughly equal to mean RT1 – SOA – 300 ms (Van Selst, Ruthruff, & Johnston, 1999). Applying this at the level of individual trials, we estimated the bottleneck delay as RT1 – SOA – 300 ms (note that this value could not go below zero). We simply added this bottleneck delay to the observed single-task RT2 for that simulated trial to obtain the predicted dual-task RT2.

Findings Figure 4 (left panels) shows, for each SOA, the observed IRI distribution along with the predicted IRI distributions. When task overlap was very high (i.e., at the 15-ms and

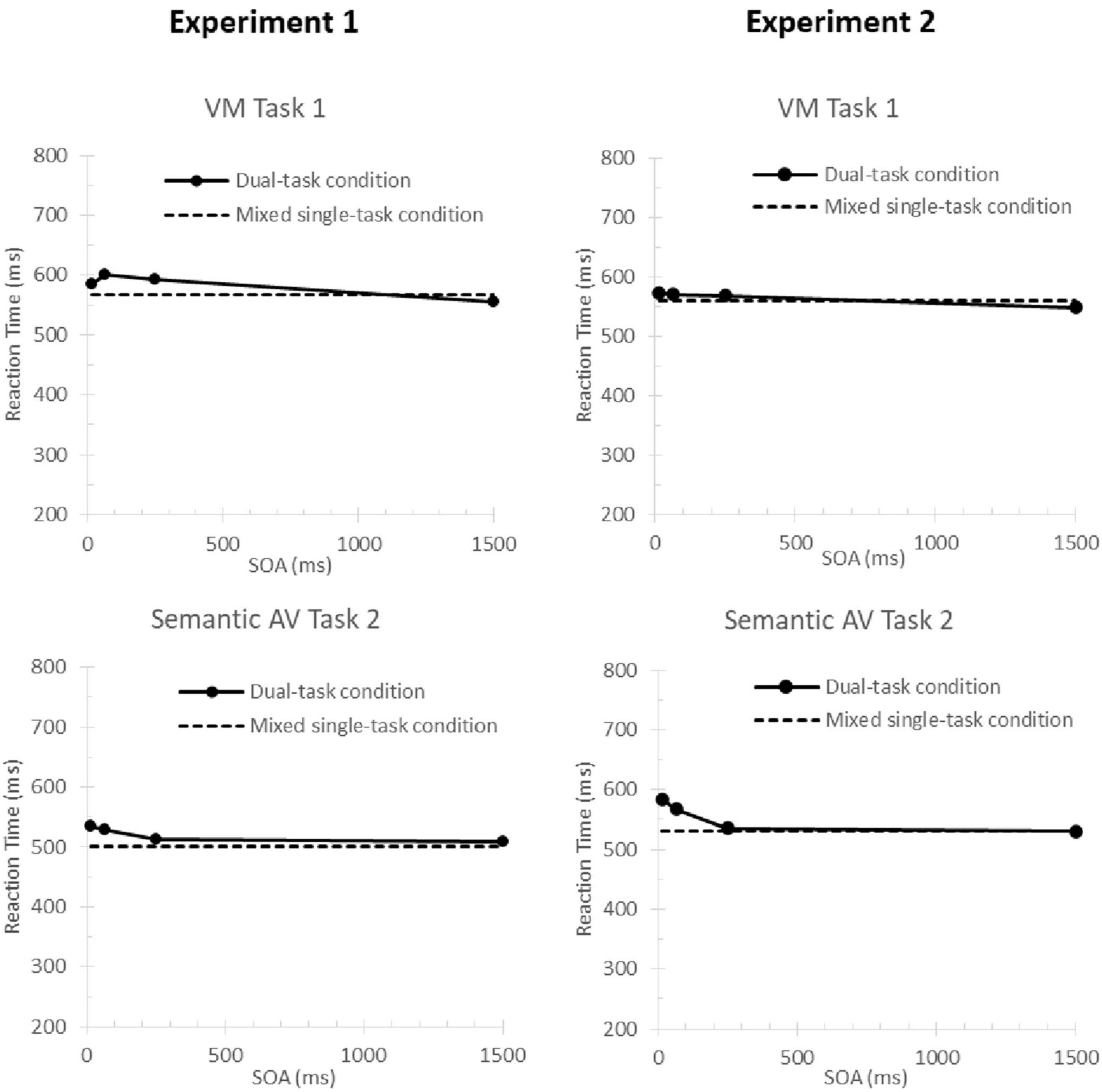

Fig. 3 Mean reaction time on Task 1 and Task 2 as a function of stimulus onset asynchrony (SOA) in Experiments 1 and 2. Dashed lines represent baseline performance in the mixed single-task condition

65-ms SOAs), the observed distributions were consistently quite well fitted by the distribution predicted by bottleneck bypassing. For instance, at the 15-ms SOA, the means did not statistically differ (-35 ms vs. -51 ms), $t(23) = 1.11$, $d_z = 0.23$. In contrast, the distributions predicted from bottlenecking provided very poor fits. For instance, at the 15-ms SOA, the difference between the observed and predicted means (-35 vs. 191 ms) was large, $t(23) = -12.13$, $p < .001$, $d_z = 2.48$. Note that, at long SOAs (i.e., at the 250-ms and 1,500-ms SOAs), bypassing and bottlenecking make similar predictions.

If participants tend to group responses together (e.g., Ulrich & Miller, 2008), there should be more IRIs near 0 ms than predicted by pure bypassing. This is indeed what happened at the 15-ms and 65-ms SOAs. The excess of trials near 0 ms could be explained by grouping on approximately 10% of

Table 1 Mean reaction time (RT), mean error rate (ER), and mean rate of response reversals (RR), As a Function of stimulus onset asynchrony (SOA) in Experiments 1 and 2.

Experiment 1 (Ping/Pong Task 2)					Experiment 1 (Haut/Bas Task 2)			
Measure	SOA (ms)				SOA (ms)			
	15	65	250	1,500	15	65	250	1,500
VM Task 1								
RT (ms)	585	601	594	554	573	570	569	548
ER1 (%)	3.55	2.86	2.25	3.48	3.66	3.91	3.30	4.22
AV Semantic Task 2								
RT2 (ms)	535	529	512	510	584	568	535	531
ER2 (%)	1.41	0.80	1.06	0.44	0.35	0.26	0.2	0.00

trials; this tendency was likely encouraged by the similarity of RTs on Task 1 and Task 2 (554 ms vs. 510 ms at the longest SOA).[1]

Discussion

In this PRP experiment, we wished to determine whether the central bottleneck can be bypassed with a Task 2 that is non-IM but very easy due to a strong semantic association. This semantic Task 2 involved saying "ping" when hearing "pong" and vice versa. The results showed converging evidence for bottleneck bypassing. First, the dual-task cost on Task 2 was very small: only 34 ms (PRP effect of 25 ms). Such a value is strikingly small given the mean long RT1 (584 ms); Van Selst et al. (1999), for example, reported a PRP effect of 352 ms with an unpracticed Task 1 that produced a similarly long mean RT1. Second, the rate of response reversals was much higher at short SOAs than at the longest SOA. Third, the observed IRI distributions at the short SOAs of 15 ms and 65 ms (i.e., when processing overlap between Task 1 and Task 2 was very high) were more closely matched by the predictions from bypassing than by the predictions from bottlenecking.

Our stimuli and responses were not only semantically associated but are also frequently paired together in the compound noun ping-pong. Indeed, single-task RTs were shorter for ping-pong (464 ms) than pong-ping (538 ms), $t(23) = -7.40$, $p < .001$, $d_z = -1.51$. If this factor is critical, then hearing "ping" and saying "pong" should be processed automatically (i.e., bottleneck bypassing) while the opposite association (which forms a nonword) should not (i.e., bottlenecking). Inconsistent with this prediction, both associations yielded similar dual-task costs (40 ms for ping-pong, 28 ms for pong-ping), $t(23) = 1.13$, $p = .27$, $d_z = 0.2$, and similar PRP effects (26 ms for ping-pong, 25 ms for pong-ping), $t(23) < 1$. Both associations also yielded high rates of response reversals at the shortest SOA (61.0% for ping-pong, 43.8% for pong-ping), $t(23) = 5.62$, $p < .001$, $d_z = 1.15$[2]. These data suggest that bottleneck bypassing does not depend on previous exposure to a particular order.

Experiment 2

The ping-pong task from Experiment 1 is not IM because merely echoing the stimulus would always produce an error. A peculiarity of this task, however, is that it involves onomatopoeia with nearly similar sounds ([pɪŋ] and [pɒŋ]). One could argue that it is nearly IM in that the response is similar to the stimulus. In Experiment 2, we wished to establish whether bottleneck bypassing could also be observed with a semantic task that is undoubtedly non-IM. To this end, we devised a semantic task composed of two antonyms: "haut" and "bas" (French for "high" / "low"). Because the stimuli and responses have highly distinctive sounds ([ˈo] and [bɑ]), they cannot be IM compatible. Furthermore, unlike the ping-pong task, the words "haut" and "bas" do not form a frequently used compound noun.

To probe for bottleneck bypassing on the semantic haut-bas Task 2, we used the exact same methodology (aside from the sounds) and indicators as in Experiment 1.

Method

Participants A new sample of 24 psychology students participated ($M = 20.1$ years old, $SD = 2.2$ years; 20 women).

Stimuli The auditory Task-2 stimuli were the spoken words "haut" or "bas."

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[1] The observed tendency to group responses hinders the analysis of RT1:RT2 correlations. Normally, bottleneck bypassing clearly predicts weak RT1:RT2 correlations because the tasks are performed independently. However, bypassing followed by response grouping would necessarily produce very high correlations. To address this issue, we first identified participants who grouped and participants who did not. For the short SOAs (15 ms and 65 ms), we estimated how often each participant produced IRIs suggestive of grouping (i.e., -25 ms to 25 ms) beyond that predicted from bypassing. We then carried out a median split on this excess, which was 0.08% for infrequent groupers and 13.9% for frequent groupers, $t(22) = 5.01$, $p < .001$, $d_z = 2.04$. Consistent with bypassing, the coefficient of correlation for non-groupers was weak overall (.27) and the main effect of SOA was not significant, $F(3, 33) < 1$, $\eta_p^2 = 0.08$; the correlations were .30, .27, .31, and .19 at the SOAs of 15 ms, 65 ms, 250 ms, and 1,500 ms, respectively. This is less than what Maquestiaux et al. (2020) reported for the case of bottlenecking with a non-IM task (~.57 at the short SOAs) but comparable to what they reported for the case of bypassing with an IM task (~.32). Meanwhile frequent groupers showed a sizable correlation at short SOAs (.43).

[2] This difference can be explained by the fact noted above that baseline single-task RT2 was much faster for ping-pong, $t(23) = -7.40$, $p < .001$, $d_z = -1.51$, increasing the opportunity for it to be produced before R1.

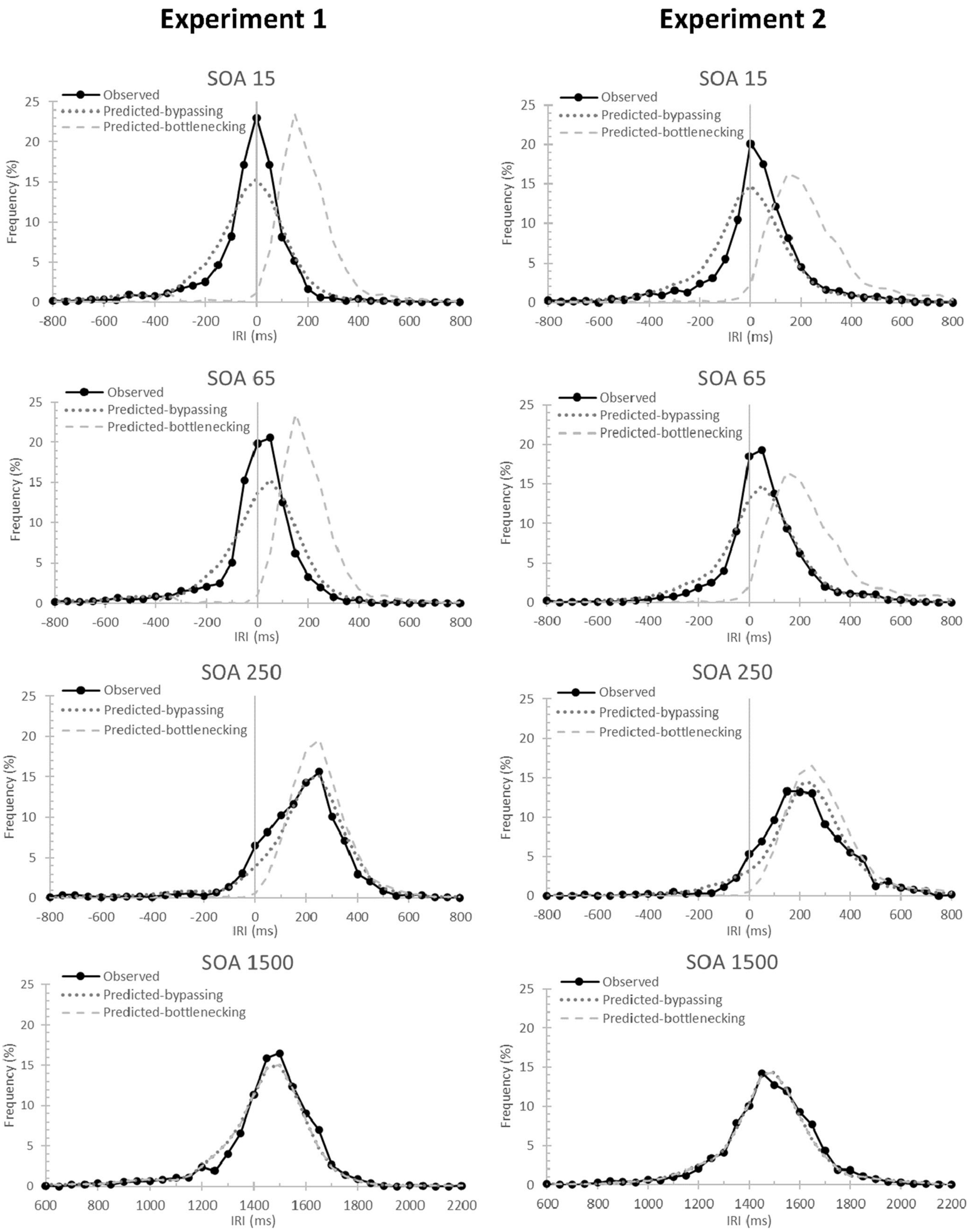

Fig. 4 Observed vs. predicted distributions of inter-response intervals (IRIs) at each stimulus onset asynchrony (SOA), for Experiment 1 and Experiment 2

Results

We removed trials for which RT was below 100 ms or above 2,500 ms on Task 1 (single-task: 0.09%; dual-task: 0.15%) or Task 2 (single-task: 0.43%, dual-task: 0.56%). Error trials were removed from RT analyses. The results are shown in Fig. 3 and Table 1.

Reaction times and error rates

Task 1 SOA did not influence RT1, $F(3,69) = 2.68$, $p < 1$, $\eta_p^2 = 0.10$, or Task-1 error rate, $F(3,69) < 1$.

Semantic Task 2 RT2 modestly increased from the longest SOA to the shortest SOA, $F(3,69) = 12.64$, $p < .001$, $\eta_p^2 = 0.36$, yielding a small mean PRP effect of only 53 ms. Mean Task-2 error rate was uninfluenced by SOA, $F(3,69) = 2.12$, $p = .11$, $\eta_p^2 = 0.08$.

Probing for bottleneck bypassing

Dual-task costs The mean dual-task cost was only 50 ms on Task 2, $t(23) = 6.70$, $p < .001$, $d_z = 1.37$, which is small given the long RT1, and only 11 ms on Task 1, $t(23) = 1.01$, $p = .32$, $d_z = 0.21$.

Response reversal rates Consistent with bottleneck bypassing, the rate of response reversals was higher at short SOAs (e.g., $M = 37.4\%$ at the shortest SOA) than at the longest SOA ($M = 0.0\%$), $F(3,69) = 50.55$, $p < .001$, $\eta_p^2 = 0.69$.

Simulations of IRI distributions The predicted IRI distributions of bottleneck bypassing and bottlenecking (simulated just as in Experiment 1) are shown for each SOA in Fig. 4 (right panels). At the two short SOAs, the observed distributions closely resemble the predicted distributions of bottleneck bypassing. For instance, at the 15-ms SOA, the difference between the observed and predicted means was only 36 ms (25 ms vs. -11 ms), $t(23) = 3.96$ $p < .001$, $d_z = 0.81$. In contrast, when comparing the observed distributions and the predicted distributions of bottlenecking at the two short SOAs, the differences were much larger. For instance, at the 15-ms SOA, the difference between the observed and predicted means was of 209 ms (25 ms vs. 234 ms), $t(23) = -9.51$, $p < .001$, $d_z = 1.94$.

As in Experiment 1 at the 15-ms SOA and the 65-ms SOA, the excess of trials centered near 0-ms suggests a tendency to group responses on approximately 5–10% of trials.[3]

Discussion

This experiment assessed the generality of the findings reported in Experiment 1. In particular, we relied on a semantic Task 2 (“haut” / “bas”) that is clearly non-IM (in contrast to the ping-pong Task 2 used in Experiment 1, which could be argued to be nearly IM). This resulted in a slight RT slowing of 33 ms relative to Experiment 1 (534 vs. 501 ms in mixed single-task trials), $t(46) = 1.09$, $p = .28$, $d_z = 0.32$. Nevertheless, the results again provided converging evidence for bottleneck bypassing: a small dual-task cost on Task 2 (50 ms; PRP effect of 53 ms) given the long mean RT1 (565 ms), a high rate of response reversals at the shortest SOA (37.4%), and a close match between the observed IRI distributions and the distributions predicted bottleneck bypassing. In sum, these findings replicate those from Experiment 1, and verify that the bypassing was not due to co-occurrence in language or to near IM compatibility (similar sounds).

General discussion

We wished to examine why bottleneck bypassing occurs with IM tasks; that is, does bypassing depend specifically on IM compatibility or, in contrast, does it merely depend on task easiness? We addressed this question in two PRP experiments. Specifically, we assessed whether a semantically easy but non-IM Task 2 – the ping-pong task in Experiment 1, the haut-bas task in Experiment 2 – could operate automatically, thereby entirely bypassing the central bottleneck. In both experiments, we found converging evidence of bottleneck bypassing: very small dual-task cost on the semantic Task 2, high rate of response reversals at the shortest SOA, and simulation analyses consistent with parallel central processing.

Can task speed account for automaticity?

Having demonstrated that easy, non-IM tasks can entirely bypass the central bottleneck, it becomes natural to wonder what exactly enables bottleneck bypassing. One plausible factor is the speed of the semantic Task 2. However, this task was not particularly fast in either Experiment 1 (501 ms in mixed single-task trials) or Experiment 2 (534 ms).

As a stricter test of the speed hypothesis, we examined the indicators of bottleneck bypassing as a function of participants’ baseline RT2. If speed truly is the key, then we should observe greater bypassing for participants who were the fastest on the semantic Task 2. To evaluate this prediction, we first carried out a median split on baseline RT2 (as measured in mixed single-task trials), separately for each experiment. After pooling across the two fast subgroups ($n = 12$ each) and the two slow subgroups ($n = 12$ each), we then compared the resulting fast and slow groups ($n = 24$ each)

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[3] As in Experiment 1, we separately analyzed participants who grouped and those who did not group. Consistent with bottleneck bypassing, the infrequent groupers showed a weak RT1:RT2 correlation (.22) and the main effect of SOA was not significant, $F(3,33) < 1$, $\eta_p^2 = 0.06$; the correlations were .20, .26, .27, and .16 at the SOAs of 15, 65, 250, and 1,500 ms, respectively.

on the indicators of bottleneck bypassing. Baseline RT2 was, of course, shorter for the fast subgroup than the slow subgroup: 439 versus 596 ms, $t(46) = -7.47$, $p < .001$, $d_z = -2.16$. Nevertheless, the fast and slow subgroups both produced small dual-task costs on Task 2 (only 32 and 52 ms), $t(46) < 1$, $d_z = -0.49$. Also, their rates of response reversals at the short SOAs (33.8 and 27.1%) did not differ, $t(46) = 1.49$, $p = .14$, $d_z = 0.43$. Because even the slowest participants bypassed routinely, speed does not appear to be the key enabler of bottleneck bypassing. Similarly, as noted in Experiment 1, the ping-pong association produced faster RTs than pong-ping, yet did not yield more evidence of automaticity.

In our view, processing speed must at least be correlated with automaticity and bypassing overall, but is neither necessary nor sufficient. It is not necessary because we found dual-task automaticity even for tasks and participants that were not particularly fast. Processing speed is also not sufficient. For instance, in our previous aging studies, we found that older adults were rarely bypassing even when younger adults with the same speed could do so routinely (Maquestiaux, Laguë-Beauvais, Ruthruff, Hartley, & Bherer, 2010; Maquestiaux, Didierjean, Ruthruff, Chauvel, & Hartley, 2013; Maquestiaux & Ruthruff, 2021; for a review, see Maquestiaux, 2016).

Is task preparation paramount?

If neither ideomotor compatibility per se nor task speed are the keys to enabling bottleneck bypassing, then what is? We conjecture that what matters the most is task preparation, specifically the ease with which people can load the S-R mapping into working memory (for evidence that the availability of working memory helps to reduce dual-task interference across practice, see Schubert & Strobach, 2018). Getting ready for the semantic task might be especially easy given the very strong association between the words "ping" and "pong" and between "haut" and "bas." Moreover, intermixing single-task trials on Task 2 with PRP dual-task trials may have further encouraged pre-loading of Task-2 S-R mapping into working memory. Note that, in classic PRP studies, which have no such single-task trials and always present Task 1 first, participants may tend to neglect advance preparation of Task 2. They might instead load up on Task 1 until finished, and then need to use central attention to boost Task-2 preparation.

This preparation account can also explain why the central bottleneck can be bypassed following extensive practice (Maquestiaux, Laguë-Beauvais, Ruthruff, & Bherer, 2008; Maquestiaux, Ruthruff, Defer, & Ibrahime, 2018): with practice, people learn to prepare more efficiently. Although this preparation account seems promising (see also Maquestiaux & Ruthruff, 2021), further research is needed to evaluate it more directly.

The spatial-verbal account proposed by Halvorson and Hazeltine (2015, 2019, for a similar proposal for highly practiced tasks, see Maquestiaux et al., 2018) offers an alternative account of our findings. According to this account, dual-task interference is minimal when the two task representations reside within distinct working-memory subsystems. As this is plausible for our tasks (e.g., the visuospatial sketchpad for the VM Task 1 and the phonological loop for the semantic AV Task 2), we cannot discard the spatial-verbal account. One difficulty in testing the spatial-verbal account, however, is that there is no accepted test of where task representations are held. It is unclear, for example, whether our participants did or did not use any verbal codes (e.g., "blue" and "green") when selecting manual responses to our colored stimuli. In any case, we can now safely conclude that ideomotor compatibility is not necessary for enabling bypassing.

Conclusions

The present study demonstrated a rare exception to the central bottleneck, made possible by using easy but non-IM tasks (i.e., semantic associates). This demonstration is based on two experiments, each using multiple SOAs and multiple converging indicators of bypassing: small dual-task cost on Task 2 (as well as on Task 1), high rates of response reversals, and high overlap between observed and predicted IRI distributions. These findings suggest IM tasks bypass the central bottleneck (Maquestiaux et al., 2020) not because of ideomotor compatibility per se but because of task easiness. Because our easy semantic tasks were not particularly fast, task speed is not sufficient to explain the findings. Instead, we conjecture that the key to enabling bottleneck bypassing is task preparation, in particular the ease with which people load the S-R mapping into working memory.

Author Note This research was supported by grants from the Bourgogne-Franche-Comté region and IUF.

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