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Learning to Bypass the Central Bottleneck: Declining Automaticity With Advancing Age

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Does advancing age reduce the ability to bypass the central bottleneck through task automatization? To answer this question, the authors asked 12 older adults and 20 young adults to first learn to perform an auditory–vocal task (low vs. high pitch) in 6 single-task sessions. Their dual-task performance was then assessed with a psychological refractory period paradigm, in which the highly practiced auditory–vocal task was presented as Task 2, along with an unpracticed visual–manual Task 1. Converging evidence indicated qualitative differences in dual-task performance with age: Whereas the vast majority of young adults bypassed the bottleneck, at most 1 of the 12 older adults was able to do so. Older adults are either reluctant to bypass the bottleneck (as a matter of strategy) or have lost the ability to automatize task performance.

Keywords: cognitive aging, dual-task interference, automatization, practice

In dual-task situations, older adults often suffer from large dual-task costs relative to young adults (for reviews, see Allen, Ruthruff, & Lien, 2007; Hartley, 1992; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). It is therefore important for cognitive aging researchers to identity the sources of such declines in performance with age. Another important issue is to determine whether and how age differences can be eliminated or at least attenuated. In the current study, we sought to make progress on both issues by comparing young and older adults' dual-task performance using a tractable dual-task procedure and high practice levels. We were particularly interested in whether the ability to automatize entire tasks declines with age, an issue that thus far has been largely ignored.

Laboratory studies have generally shown that older adults can improve their dual-task performance with practice (e.g., Baron & Mattila, 1989; Greenwood & Panasuraman, 1991; Kramer, Larish, & Strayer, 1995; McDowd, 1986; Salthouse & Somberg, 1982; Sit & Fisk, 1999; for a notable exception, see Rogers, Bertus, & Gilbert, 1994). In all of the studies cited, at least one task that was performed continuously and that required multiple operations was paired with another task (either discrete or continuous). For instance, Kramer et al. (1995) trained young and older adults on a monitoring task (e.g., resetting a moving gauge when it reached a critical point) and an alphabet–arithmetic task (e.g., solve $K - 3 = ?$). Such complex dual-task procedures give the individuals a great deal of control over when they perform each task. Even when combinations of simple discrimination tasks were used, the temporal overlap between the two tasks was not precisely examined (Bherer et al., 2005, 2008). Consequently, it is difficult or even impossible to determine precisely which operations of one task are carried out simultaneously with operations of the other task. The resulting measures of dual-task performance are aggregate and, as such, render it nearly impossible to delineate specific sources of age differences and practice effects (see also Allen et al., 2007; Hartley & Little, 1999).

A simpler and more analytically tractable dual-task paradigm is the psychological refractory period (PRP) procedure. In this pro-

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cedure, two distinct stimuli (S1 and S2), whose onsets are separated by a variable stimulus onset asynchrony (SOA), require two distinct speeded responses (R1 and R2). The SOAs range from short (creating high temporal overlap between the processing of Task 1 and Task 2) to long (little or no temporal overlap). Instructions often encourage participants to respond as quickly and accurately as possible to each task while emphasizing the speed of Task-1 responses. Placing clear priority on Task 1 usually causes interference to affect Task 2 almost exclusively, which greatly simplifies model predictions. The typical finding is that mean Task-2 reaction time (RT2) is several hundreds of milliseconds (300+ ms) longer at short SOAs than at long SOAs. This RT2 lengthening is called the PRP effect (for reviews, see Lien & Proctor, 2002; Meyer & Kieras, 1997b; Pashler, 1994b).

Several recent studies have used the PRP procedure to compare young and older adults' dual-task performance. In general, they found that the size of the PRP effect increases with advancing age (Allen, Ruthruff, Elicker, & Lien, in press; Allen, Smith, Vires-Collins, & Sperry, 1998; Glass et al., 2000; Hartley, 2001; Hartley & Little, 1999; Hein & Schubert, 2004; Maquestiaux, Hartley, & Bertsch, 2004; although some exceptions have been observed with lexical tasks; Allen et al., 2002; but see Lien et al., 2006).

Theories of the PRP Effect

Welford (1952) suggested that the PRP effect occurs because of a cognitive limitation that prevents more than one central mental operation from being carried out at once. The exact definition of a "central" stage has been difficult to pin down but is generally conceived as the "thoughtlike" processes involved in deciding how to deal with the current stimulus (e.g., response selection). Figure 1 illustrates this proposal, known as the central bottleneck model. Between stimulus onset and the associated motor response, three successive processing stages intervene: the precentral stage (A), central stage (B), and postcentral stage (C). It is assumed that precentral (e.g., stimulus identification) and postcentral (e.g., response execution) stages of one task can be carried out in parallel with any stage of the other task. The central stages, however, are assumed to require access to a mechanism that can handle only one central operation at a time (i.e., single-channel).

At short SOAs, the Task-2 central stage is postponed until Task-1 central processing is completed, creating a bottleneck delay in Task-2 processing sequence (represented by the horizontal dashed line in Figure 1). At long SOAs, however, the Task-2 processing sequence is not interrupted because the Task-2 central stage is not needed until after the completion of Task-1 central stage (i.e., there is no temporal overlap in the demand for the Task-1 and Task-2 central stages).

The PRP equation, which expresses the PRP effect in terms of the durations of the component stages of Task 1 and Task 2 (see Pashler & Johnston, 1989; Ruthruff, Johnston, & Van Selst, 2001), is as follows:

$$\text{PRP effect} = 1A + 1B - 2A - \text{SOA}_{\text{short}} \qquad (1)$$

According to Equation 1, any manipulation that increases the duration of Task-1 processing up to the central stage (i.e., 1A and/or 1B) should carry over fully, delaying Task-2 processing at short SOAs (where the bottleneck delay is present) but not at long SOAs (where the bottleneck delay is absent). This prediction, termed the Task-1 carryover prediction, has been consistently verified (for a review, see Pashler, 1994b).

Because $RT1 = 1A + 1B + 1C$, it follows that $1A + 1B = RT1 - 1C$. Thus, Equation 1 can be rewritten as follows:

$$\text{PRP effect} = RT1 - 1C - 2A - \text{SOA}_{\text{short}} \qquad (2)$$

According to Equation 2 (as well as Equation 1), the duration of RT1 influences the size of the PRP effect; a long mean RT1 should result in a large PRP effect, whereas a short mean RT1 should result in a small PRP effect. Consequently, a linear relationship between the PRP effect and RT1 with a slope of roughly 1 should be observed across individuals, assuming that they differ primarily in the duration of central operations (which seems like a reasonable first approximation). If the bottleneck could be bypassed, however, then one might expect very little relationship between the PRP effect and RT1 across individuals (i.e., a slope approaching 0).

Other accounts of the PRP phenomenon have also been proposed. Meyer and Kieras (1997a, 1997b) postulated that the central bottleneck arises from strategic and voluntary postponement of

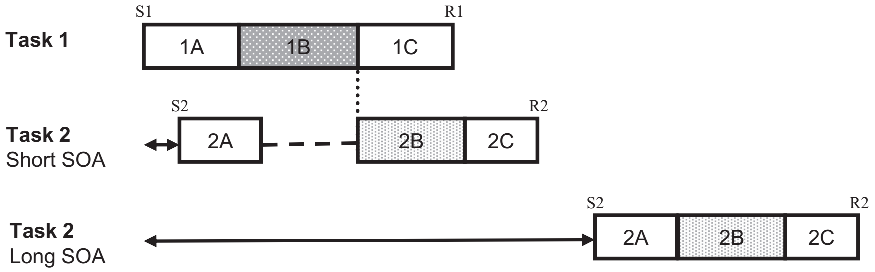

Figure 1. Central bottleneck model. R1 and R2 correspond to the Task-1 and Task-2 speeded responses to the stimuli S1 and S2 in the case in which S1 and S2 onsets are separated either by a short or a long stimulus onset asynchrony (SOA). The processing of each task can be decomposed into three stages labeled precentral stage (A), central stage (B), and postcentral stage (C). Stages A and C of one task can be carried out in parallel with all stages of the other task. However, Stage B can proceed on one task at a time, resulting in a bottleneck delay on Task 2 at the short SOA (represented by the horizontal dashed line) but not at long SOA. The Task-2 slowing from the long SOA to the short SOA is called the psychological refractory period (PRP) effect.

Task-2 central operations (i.e., adoption of a cautious task-coordination strategy). Miller, Ulrich, and Rolke (2009) provided evidence consistent with the hypothesis that the central bottleneck results from performance optimization. However, the validity of this hypothesis has not yet been established. Central capacity-sharing models of PRP interference have also been developed and can mimic some of the predictions of the central bottleneck model (in which the allocation of attention to tasks is strictly all or none, a special case of capacity sharing; Navon & Miller, 2002; Tombu & Jolicoeur, 2003; but see also Ruthruff, Pashler, & Hazeltine, 2003).

Can the Central Bottleneck Be Bypassed Through Extensive Practice?

Several recent studies have examined whether practice can eliminate the central bottleneck. That is, can the central stages of the two tasks be performed "automatically," at the same time? A consistent finding is that when Task 1 and Task 2 do not share the same output systems (i.e., vocal and manual), young adults can substantially reduce—although usually not eliminate—dual-task costs with practice. Small residual dual-task costs have often been interpreted as evidence that Task-1 and Task-2 central operations were performed at the same time, bypassing the central bottleneck (e.g., Hazeltine, Teague, & Ivry, 2002; Schumacher et al., 2001).

Ruthruff, Johnson, Van Selst, Whitsell, and Remington (2003) pointed out that an absence of detectable interference does not necessarily indicate the absence of a central bottleneck (see also Anderson, Taatgen, & Byrne, 2005; Byrne & Anderson, 2001; Lien, Ruthruff, & Johnston, 2006). When the tasks are performed very quickly, as is typically the case after practice, a central bottleneck limitation can be in force yet produce no observable interference. Specifically, the Central Stage 1B is completed before the Central Stage 2B is even needed. In this case, performance of the two central stages is not demanded at the same time. Ruthruff, Johnson, et al. (2003) provided evidence of such a *latent* bottleneck after practice in a case study focusing on one participant (out of six) from Van Selst, Ruthruff, and Johnston (1999).

Ruthruff, Van Selst, Johnston, and Remington (2006, Experiment 2) also found very small dual-task costs after practice, using a PRP paradigm. Most important, they found converging lines of evidence that some participants (four out of 18) actually bypassed the central bottleneck entirely (the *bypassers*), whereas the vast majority of the participant (14 out of 18) clearly did not (the *bottleneckers*). Evidence of bottleneck bypassing was found even in conditions in which only Task 2 had previously been practiced. Such a result suggests that the highly practiced Task-2 central stage could operate without central attentional resources (i.e., Task 2 had been automatized). The authors argued against a latent bottleneck interpretation of their results because RTs of the unpracticed Task 1 were relatively long (from 528 to 609 ms), which normally would produce large PRP effects on Task 2 (see Equation 2).

A limitation of Experiment 2 of Ruthruff, Van Selst, et al. (2006), however, is that bypassing was observed in only a few participants. Consequently, this result raises the question of whether bottleneck bypassing is a genuine and general phenomenon or just reflects luck in selecting a few exceptional participants. To address this issue, Maquestiaux, Laguë-Beauvais, Ruthruff, and Bherer (2008, Experiment 1) modified several aspects of the procedure used by Ruthruff, Van Selst, et al. (2006, Experiment 2). They focused exclusively on single-task training with the auditory Task 2, because this condition maximizes the ability to distinguish between bottlenecking and bottleneck bypassing. The reason is that this condition produces very long mean RT1 values (because Task 1 is unpracticed when paired with the previously practiced Task 2), which would normally produce large PRP effects if a bottleneck was present (see Equations 1 and 2). Another modification was to make the auditory Task 2 more likely to be automatized (to operate with fewer central attentional resources) by reducing the number of stimuli (tones) from four to two and by modestly increasing the number of single-task training trials (5,040 trials instead of 4,480). A third modification was to increase the sample size (i.e., 20 young participants instead of six), so that the prevalence of bottleneck bypassing could be better established. These measures appear to have been very successful: Maquestiaux et al. (2008) reported several converging indicators of bottleneck bypassing in the vast majority of participants (17 out of 20). Specifically, for the bypassers, the mean PRP effect on Task 2 was only 166 ms despite the long duration of Task 1 (641 ms); response reversals were very frequent at the shortest SOA (66.1%), and the effects of increasing the duration of Task-1 processing stages up to and including the central stage (by 173 ms) did not carry over fully onto RT2 at short SOAs (the percentage of carryover was only 34.1%).

Maquestiaux et al. (2008, Experiment 1) presented two additional lines of evidence that participants genuinely bypassed the bottleneck, rather than simply reversing the central processing order (i.e., Task-2 central stage being performed before Task-1 central stage). First, the possibility of a central bottleneck with a reversed central processing order predicts that, at intermediate SOAs on which responses were reversed on about 50% of the trials, there should be a bimodal distribution of interresponse intervals (one mode for each possible central processing order). Contrary to this prediction, the distributions were unimodal; simulations showed that the observed interresponse interval distributions closely matched what one would expect from independent performance of the two tasks. Second, a reversed central processing order predicts a PRP effect on Task 1 instead of on Task 2. To estimate the predicted amount of PRP effect on Task 1, Maquestiaux et al. carried out simulations based on the PRP:RT1 functions from related PRP experiments (i.e., Maquestiaux et al., 2008, Experiment 2; Van Selst et al., 1999). Whereas the predicted PRP effects on Task 1 were large (~70 ms), the actual data showed no PRP effect (−17 ms). Thus, the results contradicted the hypothesis of a reversed central processing order. In short, this study indicated that under the conditions studied, a very high percentage of young adults (i.e., 17 out of 20) can bypass the central bottleneck.

Goals of the Current Study

In most of the previous studies comparing PRP interference between young and older adults, very low practice levels have been used. Under these experimental conditions, every participant was expected to face a central processing bottleneck, and the main question was whether there would be quantitative differences in the amount of dual-task interference. Investigators in a few studies have examined age differences after practice, but again using paradigms in which both young and older adults were expected to be subject to the central bottleneck (and the data confirmed this expectation). The focus of these studies was on possible quantitative differences in the amount of dual-task interference. For instance, in Maquestiaux, Hartley, and Bertsch (2004, Experiment 1), six young adults and six older adults performed seven training sessions, each consisting of 320 dual-task trials of a PRP procedure pairing an auditory–vocal Task 1 with a visual–manual Task 2. Results indicated that PRP reduction across practice was smaller in older adults (32%) than in young adults (69%) and that the PRP interference was attributable to a processing bottleneck throughout learning. Results in other studies have shown more comparable reductions in the PRP effect with practice, when less complex pairs of tasks were used (e.g., see Allen et al., in press; Maquestiaux et al., 2004, Experiments 2 and 3). Again, none of the researchers in these studies observed any evidence of bottleneck bypassing in either age group, nor did they expect to find such evidence.

At present, no study has yet specifically addressed the important question of whether advancing age reduces the ability to bypass the central bottleneck (i.e., a qualitative change in dual-task processing with age). Therefore, we tackled this issue in the present study, taking advantage of procedures from previous studies that have successfully shown bottleneck bypassing in young adults (e.g., Maquestiaux et al., 2008; Ruthruff, Van Selst, et al., 2006). Specifically, 12 older adults participated in a PRP experiment strictly identical to Experiment 1 of Maquestiaux et al (2008), which was carried out with 20 young adults. In the present study, we utilized the data from the young adults in Maquestiaux et al. as a baseline to compare the new data from 12 older adults in the identical procedure.

In our paradigm, the basic approach is to first intensively train participants on one of the tasks in single-task sessions and then see whether participants performing this task can bypass the bottleneck in a dual-task session. Specifically, the participants first performed 5,040 practice trials, spread over 6 days, of a speeded tone–pitch classification task (low tone vs. high tone) requiring a vocal response (low vs. high). Then, they performed three dual-task sessions in which the highly practiced auditory–vocal task (now Task 2) was paired with an unpracticed visual–manual Task 1 requiring a speeded manual key press (four possible key presses) to an alphanumeric character (eight possible stimuli). The stimulus–response (S-R) compatibility of Task 1 was manipulated within-subjects and within-blocks in order to assess the Task-1 carryover prediction of the central bottleneck.

On the one hand, one might expect older adults to successfully bypass the bottleneck after practice, just as young adults do. Authors of a few previous studies have hinted that age differences in dual-task performance are minimized when the responses for the two tasks are in different modalities (Hartley, 2001; see also Hartley & Maquestiaux, 2007), as is the case in the present experiment. Consequently, this experiment should provide ideal conditions for older adults to show bottleneck bypassing. On the other hand, it is possible that, with advancing age, cognitive mechanisms become more inflexible. That is, individuals might gradually lose the ability to automatize new tasks and bypass the central bottleneck.

Testing for the Presence of a Processing Bottleneck

If the bottleneck remains following extensive practice, with Task-2 central stages postponed until Task-1 central stages are complete, then PRP effects should be large (>300 ms). Note that given Equations 1 and 2, Task-2 practice by itself should not reduce the PRP effect. Note also that given these same equations and the assumption that individuals differ almost exclusively in the duration of central processes, there should be a linear PRP:RT1 function with a slope of 1 across participants. In addition, the Task-1 carryover prediction should be verified. Finally, central processing should occur in a sequential order, with the Task-1 response followed by the Task-2 response, with only very rare response reversals.

In contrast, if Task-2 practice allows bottleneck bypassing due to automatization, then the PRP effect should be small (<300 ms), uninfluenced by the duration of Task 1 (i.e., a relatively weak relationship between the PRP effect and RT1 across participants), and there should be little or no carryover of Task-1 S-R compatibility effects onto RT2 at short SOAs. Also, participants should frequently respond to the tasks in an order opposite to their presentation order (i.e., R2 before R1) and more so at short SOAs than at long SOAs. Note that because Task 2 is easier and more highly practiced, participants performing Task 2 would usually win a parallel race with those performing Task 1 at short SOAs.

Method

Twelve older adults performed nine sessions spread over 9 different testing days (three sessions per week), using exactly the same procedure as the 20 young adults in Maquestiaux et al. (2008, Experiment 1). The first phase consisted of six training sessions with the auditory Task 2 only; the second phase consisted of three dual-task sessions.

Participants

Twelve older adults (mean age = 63.3 years, *SD* = 3.0 years, range = 59–68 years; 9 women, 3 men) were recruited from the Montréal area. The 20 young adults (mean age = 24.6 years, *SD* = 2.5 years, range = 20–31 years; 10 women, 10 men) from Maquestiaux et al. (2008, Experiment 1) were recruited from the Université du Québec à Montréal and the Institut Universitaire de Gériatrie de Montréal. Participants were paid 10 Canadian dollars per session for their participation. All participants were generally well educated, with older adults reporting slightly fewer years of education (M = 15.2 years, *SD* = 3.3 years) than young adults (M = 17.6 years, *SD* = 1.6 years), $t(30) = 2.85$, $p < .01$. On a 5-point health rating scale (5 = *excellent health*), older and young adults gave mean self-ratings of 4.1 (*SD* = 1.0) and 4.6 (*SD* = 0.5), respectively, $t(30) = 1.76$, $p = .09$. Participants were screened for normal or corrected-to-normal vision and hearing via self-report. None of them reported any difficulties in discriminating the auditory and visual stimuli presented in the experiment. They also had no history of neurological diseases and did not take any medication that might have affected cognition. The Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) indicated no impaired cognitive abilities among the older participants (M = 29.2, *SD* = 1.0, range = 28–30). We also conducted psychometric tests to better characterize the participants on different cognitive functions: working memory (Letter–Number Sequence; Wechsler, 1981), attentional span (Digit Span; Wechsler, 1981), speed of processing (Symbol Search and Digit Symbol Substitution Test; Wechsler, 1981), abstraction (Matrix Reasoning and Similarities; Wechsler, 1981), and attention and executive functions (Trail Making A and B; Reitan & Wolfson, 1985; Verbal Fluidity; Spring & Benton, 1997; and the modified Stroop test; Bohnen, Jolles, & Twijnstra, 1992). The Stroop test was a modified version with an additional fourth task in which participants were asked to switch between identifying the color of the ink and reading the word aloud. Descriptive statistics for general characteristics and scores for each test according to both age groups are shown in Table 1, along with *p* value of independent samples *t* tests comparing the means of young and older adults on each general characteristic (except on age) and test (except on MMSE).

Stimuli

Visual Task 1. The Task-1 stimulus was a single alphanumeric character drawn from the set 1, 2, 3, 4, A, B, C, D, presented in Times New Roman font. The characters subtended approximately 1.49° vertically × 1.04° horizontally at a typical viewing distance of 46 cm. The background was white, and the alphanumeric characters were black.

Auditory Task 2. Task 2 was to identify the pitch of a tone presented for 150 ms over headphones. The tone pitch was either 400 Hz (low) or 1,800 Hz (high).

Apparatus

Stimulus presentation and timing were controlled by a PC-compatible computer equipped with Chant Speechkit Version 4 (Chant, Inc. San Francisco, CA) for detecting speech onset and a Voice Connexion system (Microsoft Speech SDK Version 5.1; Microsoft Corp., Redmond, Washington) for automatically recognizing speech.

Procedure

Participants responded to the character by pressing the *F*, *T*, *Y*, or *J* key on a qwerty keyboard, using the fingers of the right hand. For half of the participants, the numbers were mapped compatibly (1, 2, 3, 4) onto the four response keys from left to right, whereas the letters were mapped in a scrambled order (C, A, D, B) onto the same four keys. For the other half of the participants, the letters were mapped in alphabetic order (A, B, C, D), but numbers were mapped in a scrambled order (3, 1, 4, 2). Participants responded to the pitch of the tone with a vocal response, either "haut" (French for "high") or "bas" (French for "low"). Participants spoke into a microphone attached to the headphones.

During Phase 1, all participants performed six single-task training sessions on the auditory–vocal task, which would later become Task 2 in Phase 2. Each training session was broken into 14 blocks of 60 trials (total of 840 trials), separated by 2-min breaks. During each break, the computer provided feedback on the average speed and average accuracy for the previous block. Participants were instructed to respond as quickly and accurately as possible and to consistently improve their performance from one block to the next.

Table 1
Descriptive Statistics of Characteristics and Tests Measuring Cognitive Function in Young and Older Participants

	Young adults ($n = 20$)			Older adults ($n = 12$)		
General characteristics	*M*	*SD*	Range	*M*	*SD*	Range
Mean age	24.6	2.5	20–31	63.3	3	59–68
Years of education	17.6	1.6	14–20	15.2^{**}	3.3	11–20
5-point health rating scale	4.6	.5	4–5	4.1 *ns*	1	2–5
Tests						
MMSE (maximum score = 30)				29.2	1	28–30
Working memory—Letter–Number Sequence (scaled scores)	11.7	1.7	9–14	13.3^{*}	1.9	10–16
Attentional span—Digit Span (scaled scores)	10.5	2.6	6–15	10.6 *ns*	3.3	6–18
Speed of processing						
Symbol Search (scaled scores)	11.7	3.3	6–19	10.9 *ns*	2.1	7–14
Digit Symbol Substitution Test (scaled scores)	11.2	3.1	7–18	12.6 *ns*	4	6–19
Abstraction						
Matrix Reasoning (scaled scores)	14.6	2.3	10–18	10.3^{***}	3.5	5–18
Similarities (scaled scores)	12.2	24	8–17	12.1 *ns*	2.3	8–17
Attention and executive functions						
Trail Making						
A (time in seconds)	28.3	8.5	15–43	31.9 *ns*	7.5	24–43
B (time in seconds)	57.8	16.1	37–90	71 *ns*	26	42–125
Modified Stroop						
Time on first plate	38.3	6.7	30–55	37.7 *ns*	5	30–46
Time on second plate	58.3	11	43–88	61.7 *ns*	7	46–73
Time on third plate	89.6	24.1	54–156	108.7^{*}	16.6	77–132
Time on fourth plate	100.0	21	66–146	129.4^{**}	26.3	79–166
Verbal fluidity (number of words)	41.5	16.4	15–65	45.2 *ns*	9.4	31–63

Note. MMSE = Mini-Mental State Examination; *ns* = nonsignificant.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

During Phase 2, all participants performed three dual-task (PRP) test sessions, pairing an unpracticed visual Task 1 with the already highly practiced auditory Task 2. Because participants had to learn a new task and a new paradigm, the first test session was considered practice and therefore was not included in the analyses. Each dual-task session consisted of 20 warm-up dual-task trials followed by 384 experimental dual-task trials. The experimental trials were a random ordering of eight repetitions of the 48 trial types produced by a complete factorial cross of SOA (15, 65, 150, 250, 550, and 1,000 ms), Task-1 S-R compatibility (compatible or incompatible), and Task-1 response finger (first through fourth). All variables were manipulated within blocks, thus eliminating differences in strategy between conditions. The dual-task sessions were broken into eight blocks of 48 trials, separated by 2-min breaks. During each break, the computer provided feedback on the average speed of participants performing Task 1 and the accuracy of participants performing both Task 1 and Task 2 for the previous block. Participants were given typical PRP instructions: Respond as quickly and accurately as possible to each task while emphasizing the speed of Task-1 responses. There were no explicit verbal instructions regarding response order or response grouping.

In both phases of the experiment, each trial began with the presentation of a black asterisk for 500 ms in the center of a white screen. Then, a random foreperiod of 100–250 ms (in steps of 50 ms) was introduced. In the dual-task condition, the Task-1 character appeared in the screen center followed by the Task-2 tone after one of six randomly selected SOAs (15, 65, 150, 250, 550, or 1,000 ms). The Task-1 character remained until a response was registered or 2,500 ms had elapsed. In the Task-2 training condition, only the tone was presented. The timing of the Task-2 tone in this single-task condition was yoked to that of the dual-task condition: Following the random foreperiod, there was an additional delay equivalent to the SOA in dual-task trials.

After each trial, a message displayed for 600 ms informed participants whether they made an erroneous or correct response on the two tasks in the dual-task condition (Phase 2) or on Task 2 in the single-task condition (Phase 1). Also, if the participant responded to a stimulus within 100 ms of its onset, a “trop rapide” (French for “too early”) message was displayed for 600 ms. If the participant failed to respond to a stimulus within 2,500 ms of its onset, a “trop lent” (French for “too slow”) message was displayed for 600 ms. The intertrial interval was 1,000 ms.

Analyses

For the auditory–vocal task training sessions, we conducted separate analyses of variance (ANOVAs) on mean auditory RT (to become RT2 in the dual-task phase) and auditory–vocal task error rate, using age group as a between-subjects variable and session (1, 2, 3, 4, 5, and 6) as a within-subject variable. In the dual-task phase (Sessions 8–9), we conducted separate ANOVAs on mean RT1, RT2, response reversal rate (the percentage of trials in which the Task-2 response was emitted before the Task-1 response), Task-1 error rate, and Task-2 error rate, using age group as a between-subjects variable and the factors of SOA and Task-1 S-R compatibility (compatible vs. incompatible) as within-subjects variables. To decompose the significant main effects, we performed post hoc comparisons using the Bonferroni procedure. Only single-task trials with correct responses and latencies between 100 and 2,500 ms were included in the RT analysis. Only dual-task trials with correct responses and latencies between 100 and 2,500 ms on both Task 1 and Task 2 were included in the RT analysis. In older adults, application of the RT cutoffs led to the removal of 2.96% and 3.74% of the trials in the single-task and dual-task conditions, respectively. In young adults, identical RT cutoffs led to the removal of 6.87% and 6.39% of the trials in the single-task and dual-task conditions, respectively. These rejected trials were primarily from the vocal task, due to noise that was picked up inadvertently (resulting in an RT < 100 ms) or failure to detect the initial vocal response (resulting in an RT $> 2{,}500$ ms). These voice–key problems occurred somewhat more often in young adults than in older adults.

Results

Looking ahead, the overall data showed important differences in the ability to bypass the central bottleneck with age. In contrast to the majority of young adults, older adults’ data were consistent with the presence of a central bottleneck. Note that, however, a closer follow-up examination of individual older participants (described in detail within the Appendix) indicated that one of them actually bypassed the bottleneck.

Training Phase

Figure 2 shows the decline in mean auditory–vocal task RT (to become Task 2 in the dual-task phase) for both age groups across the six training sessions. Auditory RT was larger overall for older ($M = 570$ ms, $SD = 154$ ms) than for young ($M = 365$ ms, $SD = 67$ ms) adults, $F(1, 29) = 30.41$, $p < .001$ (partial $\eta^2 = .51$). Auditory–vocal task training significantly shortened auditory RT from Session 1 ($M = 540$ ms, $SD = 148$ ms) to Session 6 ($M = 391$ ms, $SD = 146$ ms), $F(5, 145) = 39.36$, $p < .001$ (partial $\eta^2 = .58$), and this main effect was not qualified by an interaction with age group, $F(5, 145) = 1.66$, $p = .15$ (partial $\eta^2 = .05$). However, we note that, numerically, auditory RT shortening across training was smaller for older adults (114 ms) from Session 1 ($M = 644$ ms, $SD = 170$ ms) to Session 6 ($M = 530$ ms, $SD = 144$ ms) than for young adults (171 ms) from Session 1 ($M = 478$ ms, $SD = 90$ ms) to Session 6 ($M = 308$ ms, $SD = 57$ ms).

Because auditory RT in Session 1 was much larger for older adults than for young adults (644 ms vs. 478 ms, respectively), we

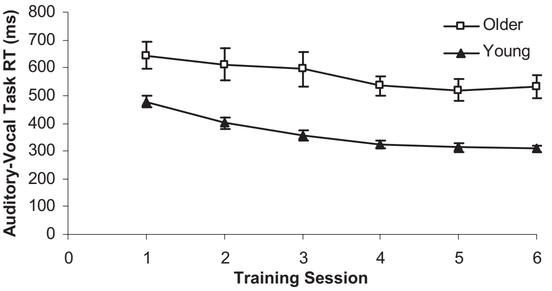

Figure 2. Mean auditory–vocal task response time (RT) as a function of training sessions in young and older adults. Bars show standard errors (calculated based on between-subject variance in the mean for that condition).

performed an analysis taking into account the initial point from which each age group started. Specifically, an independent samples *t* test was carried out on the change in auditory RT from Session 1 to Session 6 as a percentage of the auditory RT in Session 1. The percentage of auditory RT shortening for older adults (18%) was half that for young adults (36%), and the difference was statistically significant, $t(30) = 4.18$, $p < .01$.

The average auditory–vocal task error rate did not differ between young ($M = 4.97\%$, $SD = 3.17\%$) and older ($M = 4.92\%$, $SD = 2.88\%$) adults, $F(1, 29) < 1$ (partial $\eta^2 = .09$). It remained stable across training sessions, $F(5, 145) < 1$ (partial $\eta^2 = .04$). There was no significant interaction between age group and session, $F(5, 145) < 1$ (partial $\eta^2 = .02$).

Test Sessions

Visual Task 1 RTs. Figure 3 shows mean RT1 (bottom panel) and RT2 (top panel), averaged across the last two test sessions (i.e., Sessions 8 and 9), as a function of SOA in young and older adults. Mean RT1 was 271 ms longer for older ($M = 917$ ms, $SD = 142$ ms) than for young ($M = 646$ ms, $SD = 105$ ms) adults, $F(1, 30) = 37.72$, $p < .001$ (partial $\eta^2 = .56$). There was a main effect of SOA on RT1, $F(5, 150) = 10.28$, $p < .001$ (partial $\eta^2 = .25$), which was qualified by age group, $F(5, 150) = 3.12$, $p < .05$ (partial $\eta^2 = .09$). Separate ANOVAs conducted for each age group indicated main effects of SOA on RT1 for young adults, $F(5, 95) = 2.67$, $p = .026$ (partial $\eta^2 = .12$), and for older adults, $F(5, 55) = 6.69$, $p < .001$ (partial $\eta^2 = .38$). In young adults, mean RT1 was slightly shorter (by 30 ms) at the 250 ms SOA ($M = 635$ ms, $SD = 108$ ms) than at the 1,000 ms SOA ($M = 665$ ms, $SD = 130$ ms). In older adults, mean RT1 was 70 ms shorter at the four shortest SOAs ($M = 902$ ms) than at the 1,000 ms SOA ($M = 972$ ms, $SD = 175$ ms). One might speculate that the auditory Task-2 stimulus increases the sense of urgency to get Task 1 out of the way, especially at the shortest SOAs.

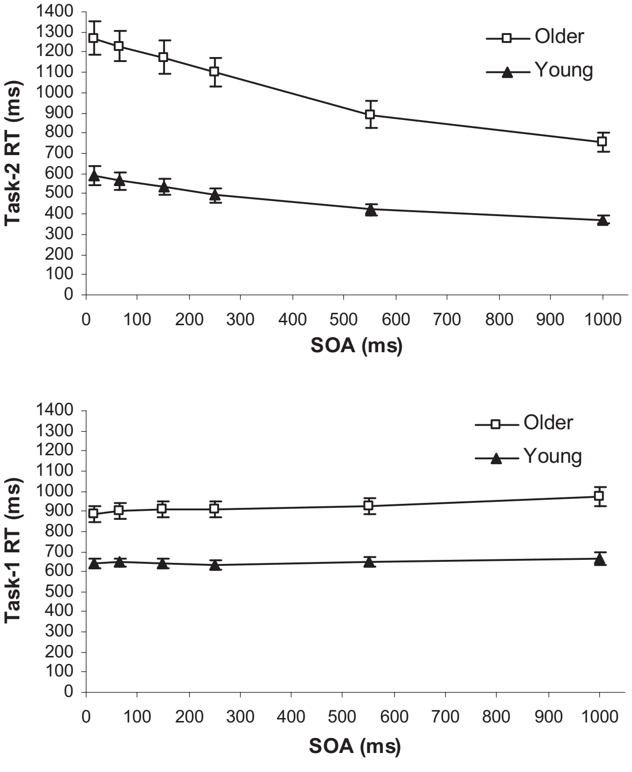

Figure 3. Mean Task-1 and Task-2 response times (RTs) as a function of stimulus onset asynchrony (SOA) in young and older adults. Bars show standard errors.

Mean RT1 was longer in the incompatible ($M = 855$ ms, $SD = 208$ ms) than in the compatible ($M = 645$ ms, $SD = 160$ ms) condition, $F(1, 30) = 180.21$, $p < .001$ (partial $\eta^2 = .86$). The Task-1 S-R compatibility effect (computed as the difference between RT1 in the incompatible condition and the compatible condition) was larger for older adults (274 ms) than for young adults (172 ms), $F(1, 30) = 9.51$, $p < .01$ (partial $\eta^2 = .24$). Also, there was a significant interaction between Task-1 S-R compatibility and SOA, $F(5, 150) = 2.27$, $p < .05$ (partial $\eta^2 = .07$). Separate ANOVAs conducted for each mapping condition indicated that the RT1 shortening with decreasing SOAs was slightly more pronounced in the incompatible condition, $F(5, 150) = 8.34$, $p < .001$ (partial $\eta^2 = .22$), than in the compatible condition, $F(5, 150) = 6.72$, $p < .001$ (partial $\eta^2 = .18$). A sense of urgency to complete Task 1, triggered by the onset of the auditory Task-2 stimulus at the shortest SOA, might have an amplified effect when Task 1 was the slowest (i.e., in the incompatible condition). The interaction between Task-1 S-R compatibility and SOA was not qualified by age group, $F(5, 150) = 1.99$, $p = .08$ (partial $\eta^2 = .06$).

PRP effect on the Auditory Task 2. The PRP effect was computed as the difference between RT2 at the shortest SOA (15 ms) and the longest SOA (1,000 ms). Figure 3 (top panel) shows that the size of the PRP effect was larger for older adults (PRP effect = 516 ms) than for young adults (PRP effect = 216 ms), $t(30) = 5.42$, $p < .001$. Note that at the longest SOA (1,000 ms), participants, especially older adults, often failed to finish Task 1 before Task 2 started.[1] Consequently, the observed PRP effect likely underestimates the actual bottleneck delay experienced by older adults at short SOAs. The age difference of 300 ms in PRP interference (albeit possibly underestimated) was only slightly larger than the difference of 271 ms in mean RT1 between these two age groups.

PRP effect versus RT1 for individuals. Figure 4 plots the mean PRP effect during the test sessions as a function of mean RT1 for all older participants (top panel) and all young participants (bottom panel). In each panel, the best-fitting regression line relating the PRP effect and RT1 is represented by a dashed line. Assuming an intact central bottleneck, the PRP effect should depend critically on the duration of RT1 (see Equations 1 and 2). For older adults, RT1 correlated strongly with the size of the PRP effect (slope = .585), $r(10) = .597$, $p < .05$, consistent with an intact bottleneck. But, for young adults, RT1 was not significantly

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[1] At the 1,000-ms SOA, older adults' mean RT1 was particularly long ($M = 972$ ms, $SD = 136$ ms), so that the Task-1 response was emitted after the onset of the Task-2 stimulus on 41.6% of trials. In contrast, young adults' mean RT1 ($M = 665$ ms, $SD = 130$ ms) was 335 ms shorter than the value of the longest SOA, and the Task-1 response was emitted after the onset of the Task-2 stimulus on only 10.9% of the trials.

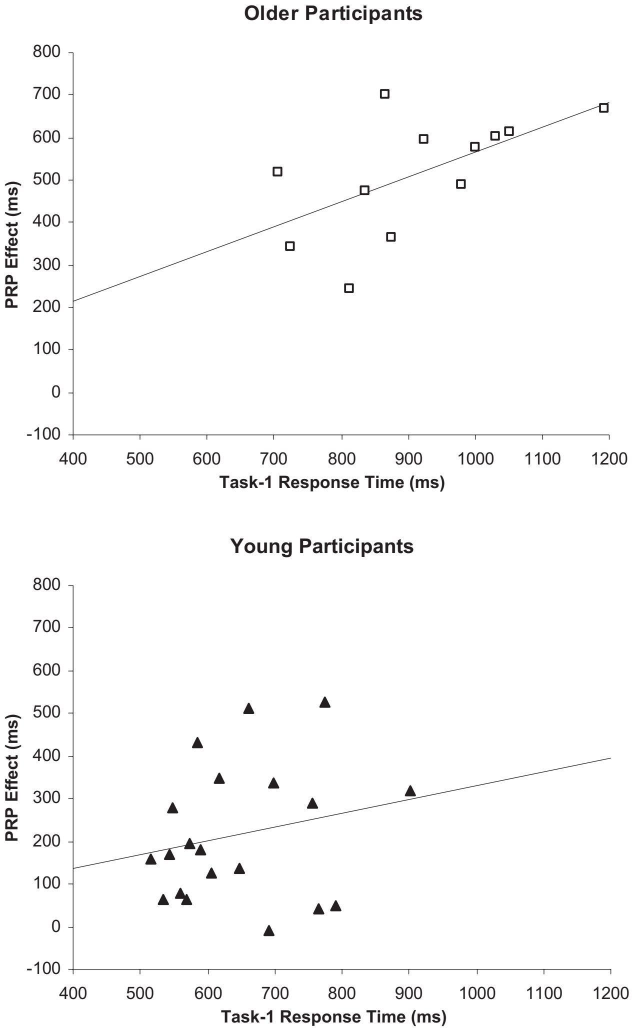

Figure 4. Psychological refractory period (PRP) effect as a function of Task-1 response time (RT1) for each older participant (top panel) and young participant (bottom panel). The central bottleneck model predicts a linear function relating RT1 and the size of the PRP effect with a slope of roughly 1.0. $\mathrm{PRP}'_{\mathrm{older}} = .585\ (\mathrm{RT1}) - 19.907$; $r^2 = .357$. $\mathrm{PRP}'_{\mathrm{young}} = .324\ (\mathrm{RT1}) + 5.717$; $r^2 = .046$.

correlated with the size of the PRP effect (slope = .324), $r(18) = .210$, $p = .38$, consistent with bottleneck bypassing. Note, however, that the difference between the two correlation coefficients (young vs. older) did not reach statistical significance ($p = .254$, compared using the Fisher r-to-z transformation, two-tailed), perhaps due to insufficiently large sample sizes.

Task 1

Carryover prediction. Figure 5 shows how Task-1 S-R compatibility influenced RT1 (horizontal dashed line) and RT2 (symbol) at each SOA for older adults (top panel) and for young adults (bottom panel). The bottleneck model predicts that increasing the duration of Task-1 processing stages up to and including the central stage should carry over fully onto RT2 at short SOAs but not at long SOAs. We tested this prediction using the Task-1 S-R compatibility manipulation. The significant interaction between Task-1 S-R compatibility and SOA, $F(5, 150) = 21.65$, $p < .001$ (partial $\eta^2 = .42$), was qualified by a three-way interaction with age group, $F(5, 150) = 7.53$, $p < .001$ (partial $\eta^2 = .20$). In young adults, the effect of Task-1 S-R compatibility on RT1 (172 ms) carried over onto RT2 more at the four shortest SOAs (73 ms) than at the 1,000 ms (23 ms), $F(5, 95) = 8.42$, $p < .001$ (partial $\eta^2 = .31$). However, the percentage of carryover at the four shortest SOAs onto RT2 was only 42.4% of its effect upon RT1, which is significantly smaller than the 100% of carryover predicted by the central bottleneck model, $t(19) = 7.44$, $p < .001$. In older adults, the effect of Task-1 S-R compatibility on RT1 (274 ms) carried over onto RT2 more at short SOAs (239 ms) than at the 1,000 ms SOA (67 ms), $F(5, 55) = 10.70$, $p < .001$ (partial $\eta^2 = .49$). At the four shortest SOAs, the percentage of carryover was 87.2%, which did not differ from the predicted 100% carryover, $t(11) = 1.71$, $p = .11$.

Response reversal rate. The imperative stimulus on Task 1 always preceded the imperative stimulus on Task 2 and instructions emphasized Task-1 processing speed. When applying the central bottleneck model, we would then assume that Task-1 central processing would precede Task-2 central processing. In this case, responses should be emitted in the same sequential order—Task-1 response followed by Task-2 response—whatever the SOA, resulting in a response reversal rate close to 0% (as is almost always the case in PRP studies, assuming that participants do not group responses very often). Figure 6 shows the mean response reversal rate as a function of SOA and Task-1 S-R compatibility in young adults (represented by triangles) and older adults (represented by squares). Consistent with the standard bottleneck model, the overall response reversal rate was very small for older adults (3.8%) but was significantly higher for young adults (27.6%), $F(1, 30) = 16.93$, $p < .001$ (partial $\eta^2 = .36$). The main effect of SOA, $F(5, 150) = 29.646$, $p < .001$ (partial $\eta^2 = .50$), was qualified by an interaction with age group, $F(5, 150) = 18.59$, $p < .001$ (partial $\eta^2 = .38$). Consistent with the bottleneck model, the low response reversal rate of older adults was not influenced by SOA, $F(5, 55) = 1.41$, $p = .24$ (partial $\eta^2 = .11$). In contrast, the response reversal rate of young adults was large (46.2%) at the three shortest SOAs but negligible at the 1,000-ms SOA (0.7%), $F(5, 95) = 45.51$, $p < .001$ (partial $\eta^2 = .70$). The high rate of response reversals for young adults at the shortest SOAs indicates bottleneck bypassing.

In addition, the interaction between SOA and age group was qualified by Task-1 S-R compatibility, $F(5, 150) = 4.85$, $p < .001$ (partial $\eta^2 = .14$). Consistent with bottlenecking, Task-1 S-R compatibility did not influence the response order in older adults (i.e., Task-1 response followed by Task-2 response), $F(1, 11) = 3.07$, $p = .11$ (partial $\eta^2 = .22$), and this interaction did not further interact with SOA, $F(5, 55) = 1.25$, $p = .30$ (partial $\eta^2 = .10$). In sharp contrast, young adults emitted R2 before R1 more often in the incompatible condition ($M = 33.1\%$, $SD = 20.5\%$) than in the compatible condition ($M = 22.0\%$, $SD = 14.7\%$), $F(1, 19) = 41.38$, $p < .001$ (partial $\eta^2 = .66$), particularly when SOAs were short, $F(5, 95) = 12.30$, $p < .001$ (partial $\eta^2 = .39$). These findings are consistent with bottleneck bypassing in young adults: An incompatible Task 1 gives Task 2 a better chance to win the parallel race, as does a short SOA.

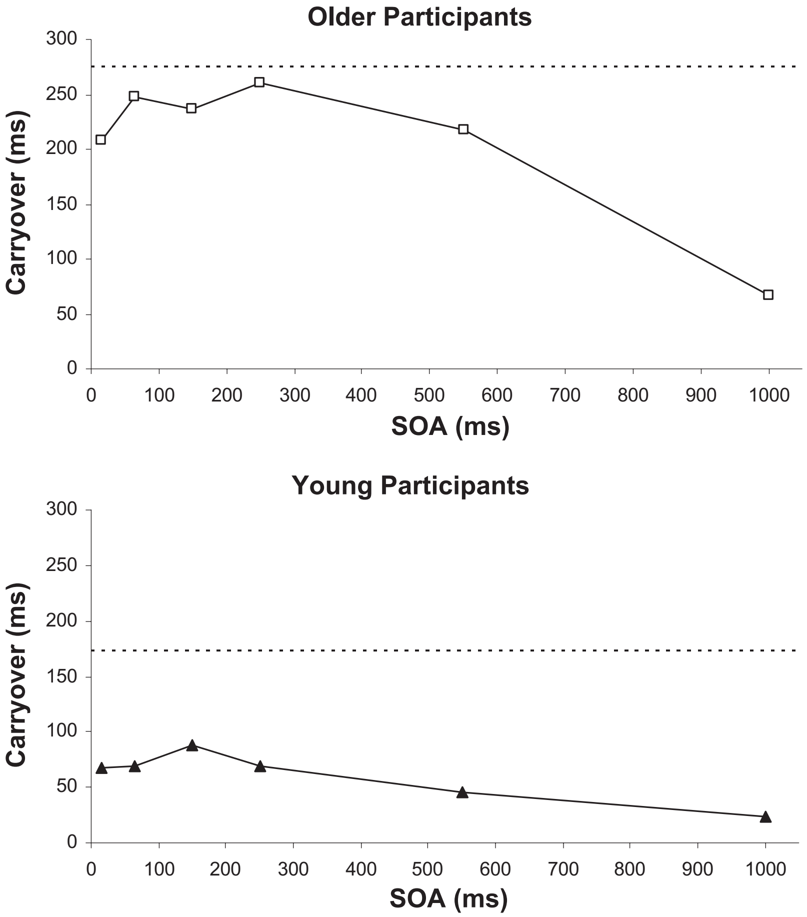

Figure 5. Effect of Task 1 stimulus–response (S-R) compatibility on Task 2 response time (RT2) at each stimulus onset asynchrony (SOA) for older participants (top panel) and young participants (bottom panel). The mean effect of Task 1 S-R compatibility on Task 1 response time is represented by the horizontal dashed line.

Task-1 and Task-2 Error Rates

Visual Task 1. In dual-task test sessions, young adults committed more errors on Task 1 (M = 6.2%, SD = 3.0%) than did older adults (M = 2.7%, SD = 1.1%), $F(1, 30) = 14.35$, $p < .001$ (partial $\eta^2 = .32$). Task-1 error rates gradually increased from the longest SOA (M = 3.8%, SD = 2.5%) to the shortest SOA (M = 6.2%, SD = 4.6%), (5, 150) = 3.51, $p < .01$ (partial $\eta^2 = .10$), and this effect was similar in both age groups, $F(5, 150) = 1.89$, $p = .10$ (partial $\eta^2 = .06$). Task-1 error rates were higher in the incompatible condition (M = 7.0%, SD = 4.5%) than in the compatible condition (M = 2.8%, SD = 2.0), $F(1, 30) = 39.92$, $p < .001$ (partial $\eta^2 = .57$), and this main effect was qualified by an interaction with age group, $F(1, 30) = 10.25$, $p < .01$ (partial $\eta^2 = .25$). Specifically, the difference of Task-1 error rates between the incompatible and the compatible conditions was smaller for older adults (3.6% vs. 1.8%), $F(1, 11) = 7.86$, $p < .05$ (partial $\eta^2 = .42$), than for young adults (8.9% vs. 3.3%), $F(1, 19) = 46.07$, $p < .001$ (partial $\eta^2 = .71$). Neither the Task-1 S-R compatibility × SOA interaction, $F(5, 150) = 1.03$, $p = .40$ (partial $\eta^2 = .03$), nor the Age Group × Task-1 S-R compatibility × SOA interaction, $F(5, 150) < 1$ (partial $\eta^2 = .02$), was significant.

Auditory Task 2. In dual-task test sessions, Task-2 error rate did not differ between young (M = 4.5%, SD = 4.0%) and older (M = 5.1%, SD = 3.6%) adults, $F(1, 30) < 1$ (partial $\eta^2 = .01$). Neither the main effect of SOA, $F(5, 150) = 1.37$, $p = .24$ (partial

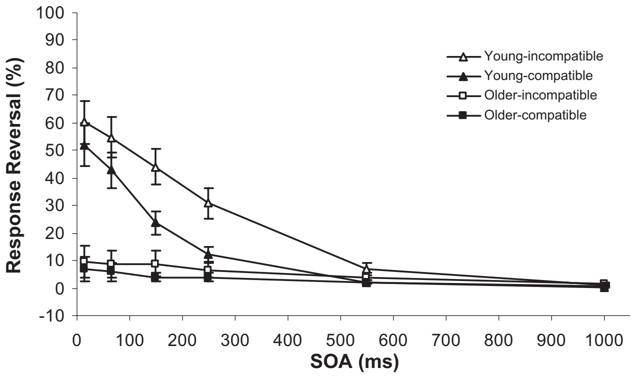

Figure 6. Effect of Task-1 stimulus–response (S-R) compatibility (compatible or incompatible condition) on the percentage of response reversal at each stimulus onset asynchrony (SOA) in young adults (represented by triangles) and older adults (represented by squares). Bars show standard errors.

η^2 = .04), nor the main effect of Task-1 S-R compatibility, $F(1, 30) < 1$ (partial η^2 = .003), was significant. Neither Age Group × SOA, $F(5, 150)$ = 1.77, p = .12 (partial η^2 = .06), nor Age Group × Task-1 S-R compatibility, $F(1, 30)$ = 1.46, p = .23 (partial η^2 = .05), was significant. There was a significant interaction between SOA and Task-1 S-R compatibility, $F(5, 150)$ = 2.57, p = .03 (partial η^2 = .08). Task-2 error rate was not influenced by SOA in the incompatible condition, $F(5, 150)$ = 1.35, p = .24 (partial η^2 = .04), but was slightly smaller at the 550 ms SOA (M = 3.5%, SD = 4.1%) relative to each of the other five SOAs (where the mean Task-2 error rate ranged from 4.7% to 5.4%) in the compatible condition, $F(5, 150)$ = 2.30, p = .048 (partial η^2 = .07). There was no significant interaction among age group, SOA, and Task-1 S-R mapping, $F(5, 150) < 1$ (partial η^2 = .01).

Discussion

The primary goal of this research was to determine whether older adults show a preserved ability to bypass the central processing bottleneck. We used the same PRP design employed by Maquestiaux et al. (2008, Experiment 1), in which the large majority of young adults (17 out of 20) showed converging evidence of bottleneck bypassing.

Bypassing the Central Bottleneck Is Rare in Older Adults

Results provided several converging indicators of qualitative differences in dual-task performance of older participants and young participants. First, auditory–vocal task training (to become Task 2 in the dual-task phase) shortened RT much less in older (reduction of 18%) than in young (reduction of 36%) adults. Second, PRP effects in the dual-task sessions were much larger for the older participants (M = 516 ms) than for the young participants (M = 216 ms). Third, the duration of RT1 correlated strongly with the size of the PRP effect among older adults (.597) but not among young adults (.210). Fourth, the 100% carryover of Task-1 S-R compatibility effects onto RT2 predicted by bottleneck was roughly confirmed for older adults (carryover of 87.2%) but clearly not for young adults (carryover of only 42.5%). Fifth, older participants only rarely reversed the response order (3.8% of trials), whereas young adults often did (27.6%), especially at the three shortest SOAs (46.2%). In sum, the present data provide evidence of bottlenecking in older adults, but bottleneck bypassing in the vast majority of the young adults.

An examination of each of the bottleneck model predictions described earlier for individual young adults revealed that 17 out of 20 had bypassed the bottleneck and three out of 20 did not (see Maquestiaux et al., 2008, for details). The same examination of each of the bottleneck model predictions applied to individual older adults, described within the Appendix, revealed only one bypasser. Table 2 summarizes the percentage of response reversals, mean RT, and mean error rate on both Task 1 and Task 2 across SOAs for each older participant. The older bypasser corresponds to Participant Number 10. Given only one bypasser out of 12 older adults, it makes sense that the aggregate older adult data closely approximated that predicted by a central bottleneck. Also note that the presence of one bypasser among the older adult sample can explain the minor deviations from the bottleneck model predictions in this sample (excluding this one person, the remaining data even more closely match the bottleneck model predictions).

The proportion of bottleneckers among the older adults (11 out of 12) was significantly greater than the proportion of bottleneckers among young adults (three out of 20), $\chi^2(1, N = 32) = 17.91$, $p < .001$. Put another way, the present results indicate a qualitative difference in how older and young adults perform in dual-task situations. In general, older adults are less likely than young adults to carry out central processing in the two tasks at the same time.

Why Is Bottleneck Bypassing Rare in Older Adults?

The current finding of a residual processing bottleneck in the overwhelming majority of older adults, but in only a small minority of young adults, is in line with Göthe, Oberauer, and Kliegl (2007). These authors found that all 12 older adults but only three of 12 young adults failed to perform two tasks requiring updates of working memory (a location and a number) in parallel following 16–24 practice sessions. Göthe et al. proposed a default setting of the executive system for preventing parallel processing of central cognitive operations, which can be easily overwritten after practice in young adults but not in older adults.

The present results are consistent with the general view of increased conservatism of executive control in old age, although we did find one older adult capable of bottleneck bypassing. It is conceivable that the 11 older bottleneckers also had the same potential to bypass the bottleneck as the one older bypasser and the 17 young bypassers. Perhaps they simply elected to adopt a conservative task–coordination strategy (see Glass et al., 2000). This conjecture is consistent with results from Touron and Hertzog (2004). These authors showed that despite the apparent ability to shift from a time-consuming visual-scanning strategy to a more automatic memory–retrieval strategy in a word-matching task, older adults were reluctant to do so.

There is, however, reason to doubt the hypothesis that the difference between the older bypasser and the 11 older bottleneckers was simply a matter of strategy (i.e., by choosing a riskier parallel task-execution strategy). A potential explanation is an exceptional ability to process the auditory–vocal task without central resources (i.e., task automatization) in this one older individual. Consistent with this conjecture, the shortening of the auditory–vocal task across the six single-task training sessions (representing 5,040 trials) was considerable for the one older bypasser (46.4%), but much smaller for the 11 older bottleneckers (15.3%). In the last training session, auditory–vocal task RT lowered to a value much smaller for the older bypasser (312 ms) than for the older bottleneckers (550 ms). Also, at the long SOAs in the dual-task sessions, baseline RT to the auditory–vocal task (as Task 2) was shorter by 350+ ms for the one older bypasser (415 ms) than for the older bottleneckers (M = 784 ms, range = 570–1,063 ms). These related pieces of evidence suggest that the older bypasser had an unusual ability to automatize the auditory–vocal task, relative to the older bottleneckers.

At present, we favor the hypothesis that despite 5,040 training trials, the older participants (except the one bypasser) had not achieved the level of auditory–vocal task automatization necessary for successful bottleneck bypassing. Consistent with this view,

Table 2

Mean Response Reversal Rates, Mean Reaction Times To Task 1 and Task 2, and Mean Error Rates to Task 1 and Task 2 as a Function of Stimulus Onset Asynchrony for Each of 12 Older Participant

Participant no./measure	Task 1–Task 2 SOA (ms)					
	15	65	150	250	550	1,000
1						
RR (in %)	0	3.4	2.6	1.7	0.9	0
RT1 (in ms)	982	1,035	1,052	1,016	1,011	1,090
ER1 (in %)	2.4	0.8	2.3	2.4	1.6	3.1
RT2 (in ms)	1,436	1,368	1,297	1,190	916	833
ER2 (in %)	2.6	3.3	3.3	3.3	5.8	4.1
2						
RR (in %)	0	0.9	0.9	0.8	0	0.9
RT1 (in ms)	941	920	1,002	938	1,016	1,190
ER1 (in %)	3.1	6.3	3.2	2.3	1.6	0.8
RT2 (in ms)	1,640	1,551	1,587	1,409	1,217	1,063
ER2 (in %)	1.0	0	0	0	0.8	2.5
3						
RR (in %)	2.6	0.9	3.7	0	1.8	0
RT1 (in ms)	1,036	1,007	1,045	1,056	1,038	1,134
ER1 (in %)	0.8	3.2	3.2	4.0	1.6	1.6
RT2 (in ms)	1,535	1,528	1,440	1,450	1,190	921
ER2 (in %)	0.8	5.9	5.9	8.3	5.7	6.7
4						
RR (in %)	0.8	0	0	0.8	0	0
RT1 (in ms)	700	732	712	702	707	683
ER1 (in %)	0.8	0	0.8	0	1.6	1.6
RT2 (in ms)	1,152	1,141	1,048	927	755	632
ER2 (in %)	0.8	0.8	0.8	0	0.8	0
5						
RR (in %)	1.8	2.7	6.4	4.3	2.0	0
RT1 (in ms)	862	913	859	872	852	895
ER1 (in %)	1.6	1.6	4.0	2.3	0.8	2.3
RT2 (in ms)	1,091	1,128	975	914	769	726
ER2 (in %)	5.0	6.6	6.6	7.1	1.0	6.7
6						
RR (in %)	0	1.0	1.9	2.8	3.2	2.4
RT1 (in ms)	909	908	1,011	999	1,022	1,038
ER1 (in %)	2.4	3.2	3.2	3.1	7.1	4.0
RT2 (in ms)	1,337	1,248	1,286	1,190	1,014	849
ER2 (in %)	9.6	8.3	8.3	8.3	13.4	10.4
7						
RR (in %)	0.9	0	0.9	0	0	0.9
RT1 (in ms)	845	879	860	839	919	861
ER1 (in %)	2.3	1.6	0	0.8	1.6	2.3
RT2 (in ms)	1,456	1,411	1,339	1,244	1,038	755
ER2 (in %)	5.8	7.4	7.4	4.0	3.4	8.2
8						
RR (in %)	2.2	2.6	0	2.9	0.9	2.0
RT1 (in ms)	1,156	1,204	1,170	1,197	1,212	1,211
ER1 (in %)	9.5	1.6	3.2	6.5	3.3	5.7
RT2 (in ms)	1,509	1,477	1,465	1,328	1,102	842
ER2 (in %)	6.5	7.7	7.7	5.3	5.7	7.6
9						
RR (in %)	2.0	1.0	0.9	1.9	1.0	2.2
RT1 (in ms)	873	872	880	940	933	1,054
ER1 (in %)	2.3	4.0	1.6	2.4	3.2	2.4
RT2 (in ms)	1,295	1,208	1,078	1,056	830	700
ER2 (in %)	15.8	11.5	11.5	12.9	12.2	6.6
10						
RR (in %)	60.2	44.2	32.4	23.7	12.4	2.7
RT1 (in ms)	829	811	825	816	791	806
ER1 (in %)	3.1	3.1	1.6	2.3	2.4	1.6
RT2 (in ms)	660	639	654	655	494	415
ER2 (in %)	8.6	9.5	9.5	5.5	5.6	7.4

(*table continues*)

Table 2 (*continued*)

Participant no./measure	Task 1–Task 2 SOA (ms) 15	65	150	250	550	1,000
11						
RR (in %)	1.7	4.3	1.7	2.6	0.9	0
RT1 (in ms)	705	723	712	714	749	748
ER1 (in %)	6.3	3.1	4.7	4.7	2.4	3.2
RT2 (in ms)	914	891	799	740	566	570
ER2 (in %)	0.8	0.8	0.8	1.6	2.5	3.3
12						
RR (in %)	4.2	4.3	3.3	0.8	0	0
RT1 (in ms)	790	800	810	815	849	954
ER1 (in %)	3.1	5.5	2.3	2.3	2.3	2.3
RT2 (in ms)	1,204	1,169	1,125	1,112	805	729
ER2 (in %)	2.4	2.3	2.3	3.9	0.8	3.3

Note. RR = mean response reversal rate; RT1 = mean reaction time to Task 1; RT2 = mean reaction time to Task 2; ER1 = mean error rate to Task 1; ER2 = mean error rate to Task 2.

auditory–vocal task training shortened RT by 36% in young adults but by only 18% in older adults. Of course, it is impossible to completely rule out the possibility that further single-task training would have led to further auditory–vocal task automatization and that more of the older adult participants would then have bypassed the bottleneck. Nonetheless, we are skeptical that any moderate additional amount of single-task training would have altered the present high proportion of bottleneckers among older adults (for a similar conclusion, see Göthe et al., 2007). First, there is no obvious reason why the relatively modest percentage of auditory–vocal task shortening (15.3% for the 11 older bottleneckers, 18% for all 12 older adults) following the first six single-task training sessions would accelerate with further single-task training sessions. Second, the indicators of bottlenecking were strong in older bottleneckers; that is, there was no hint that these participants were gradually beginning to bypass the bottleneck on a proportion of trials. In any case, we can safely conclude that with advancing age, the amount of practice required to achieve bottleneck bypassing is greatly increased, if it is possible at all.

Conclusions

In a PRP paradigm in which a highly practiced auditory–vocal Task 2 was paired with an unpracticed visual–manual Task 1, we found that almost none of our sample of older adults (11 out of 12) was able to evade the central processing bottleneck, despite thousands of practice trials on a simple task with only two choices. This finding is in sharp contrast with that of Maquestiaux et al. (2008, Experiment 1), who showed that nearly the entire sample of young participants (17 out of 20) was able to evade the bottleneck with practice. Therefore, the present results suggest that in older adults, either the capability to bypass the central bottleneck is present but less likely to be used, or it is lost. In either case, advancing age appears to be accompanied by a qualitative change in dual-task performance after practice.

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(*Appendix follows*)

Appendix

Evidence of One Bypasser Among Older Participants

Here, we discuss whether individual older participants did or did not bypass the bottleneck. We applied the same bottleneck model predictions described earlier but to individual data rather than to group data. That analysis revealed one candidate (out of 12) to have bypassed the bottleneck. The evidence for this breakdown is summarized. For a similar analysis of the young adults, see Maquestiaux et al. (2008, Experiment 1).

PRP Effect

The putative *bottleneckers* had large PRP effects (range = 344–701 ms), whereas the one putative *bypasser* had a much smaller PRP effect of 245 ms (participant 10 in Table 2). One might expect a bypasser to produce little or no PRP effect. We attribute this nonzero PRP effect, in part, to a tendency of response grouping (as will be explained later). For a bypasser, an attempt to group responses (Pashler & Johnston, 1989) can be assumed to involve frequently withholding (delaying) the response to Task 2 while waiting for Task 1 to finish. Residual PRP effects could also result from competition between codes for the tasks simultaneously residing in working memory (see Hazeltine, Ruthruff, & Remington, 2006; Ruthruff, Hazeltine, & Remington, 2006). Another possibility (consistent with the findings in following sections) is that this older adult was subject to the processing bottleneck on a small proportion of trials (say, 25%).

Response Reversal Rate

Consistent with the bottleneck model prediction, the putative bottleneckers rarely reversed responses (1.5% overall). In contrast, the putative bypasser reversed responses on 60.2% of trials at the 15-ms SOA. To determine whether this response reversal rate is consistent with a parallel race between tasks, we conducted a simple simulation. Using RT1 and RT2 at long SOA trials, we estimated how often participants would have finished Task 1 after Task 2 if they performed the tasks in parallel (independently and with no interference) at an SOA of 15 ms. The predicted response reversal rate for the putative bypasser was 95.5%. This rate is roughly consistent with the observed rate (60.2%), when one considers the strong tendency to group responses (simultaneous responding would produce only 50% response reversals). For the putative bottleneckers, however, the simulation predicted a response reversal rate (69.5%) much higher than the observed rate (1.5%).

Interresponse Intervals (IRIs)

The distribution of IRIs at the short SOAs helps us to determine whether participants emitted Task-1 and Task-2 responses as a couplet on some trials (i.e., response grouping). Response grouping should result in a sharp peak of IRIs near 0 ms (see Miller & Ulrich, 2007). Figure 7 shows, for the putative bottleneckers (left panel) and the putative bypasser (right panel), the IRI distribution for each of the six SOAs. The percentage of response grouping (i.e., IRIs between −100 and +100 ms) was large for the putative bypasser (40.5% of all short-SOA trials) but small for the putative bottleneckers (6.5%). The central question here is whether the near-zero IRIs for the putative bypasser reflect grouping after bypassing or grouping after bottlenecking. Grouping after bottlenecking (Task-1 central operations before Task-2 central operations) implies that a participant withheld the Task-1 response, thus substantially elevating RT1 relative to the longest SOA (at which response grouping rarely occurred, according to the IRI distribution). The putative bypasser, however, produced only a negligible 16-ms lengthening of RT1 at short SOAs (15, 65, and 150 ms), relative to the longest SOA (see Table 2), ruling out bottleneck grouping. Grouping after bypassing would instead elevate RT2, consistent with the substantial PRP effect (245 ms) for this participant.

Task-1 Carryover Onto RT2

Consistent with the Task-1 carryover prediction of the central bottleneck model, the putative older bottleneckers produced 88.4% carryover at the short SOAs (15, 65, and 150 ms). For the putative older bypasser, assumed to perform Task-1 and Task-2 central operations simultaneously, there is no obvious reason for Task-1 S-R compatibility to strongly influence RT2. As predicted, the putative bypasser produced only 23.2% carryover at the shortest SOAs (15, 65, and 150 ms).

Was the Putative Bypasser a Bottlenecker Who Reversed the Central Processing Order?

Much of the evidence consistent with bottleneck bypassing for one older participant (i.e., small PRP effect, frequent response reversals, little Task-1 carryover) could be reconciled with bottlenecking if one simply assumed that the central processing order was reversed. Next, we evaluate two critical predictions derived from such a model.

First, an intact central bottleneck with frequent reversal of the central processing order should result in a bimodal IRI distribution (one mode for each central processing order) or a trimodal IRI distribution (a third mode near 0 ms in case of grouping). This is exactly what has been observed early in practice in designs in which positive and negative SOAs were mixed (see Pashler, 1994a; Ruthruff, Pashler, et al., 2003). In contrast, the putative bypasser produced a unimodal IRI distribution at short and intermediate SOAs (with an extra spike near 0 ms, presumably reflecting response grouping).

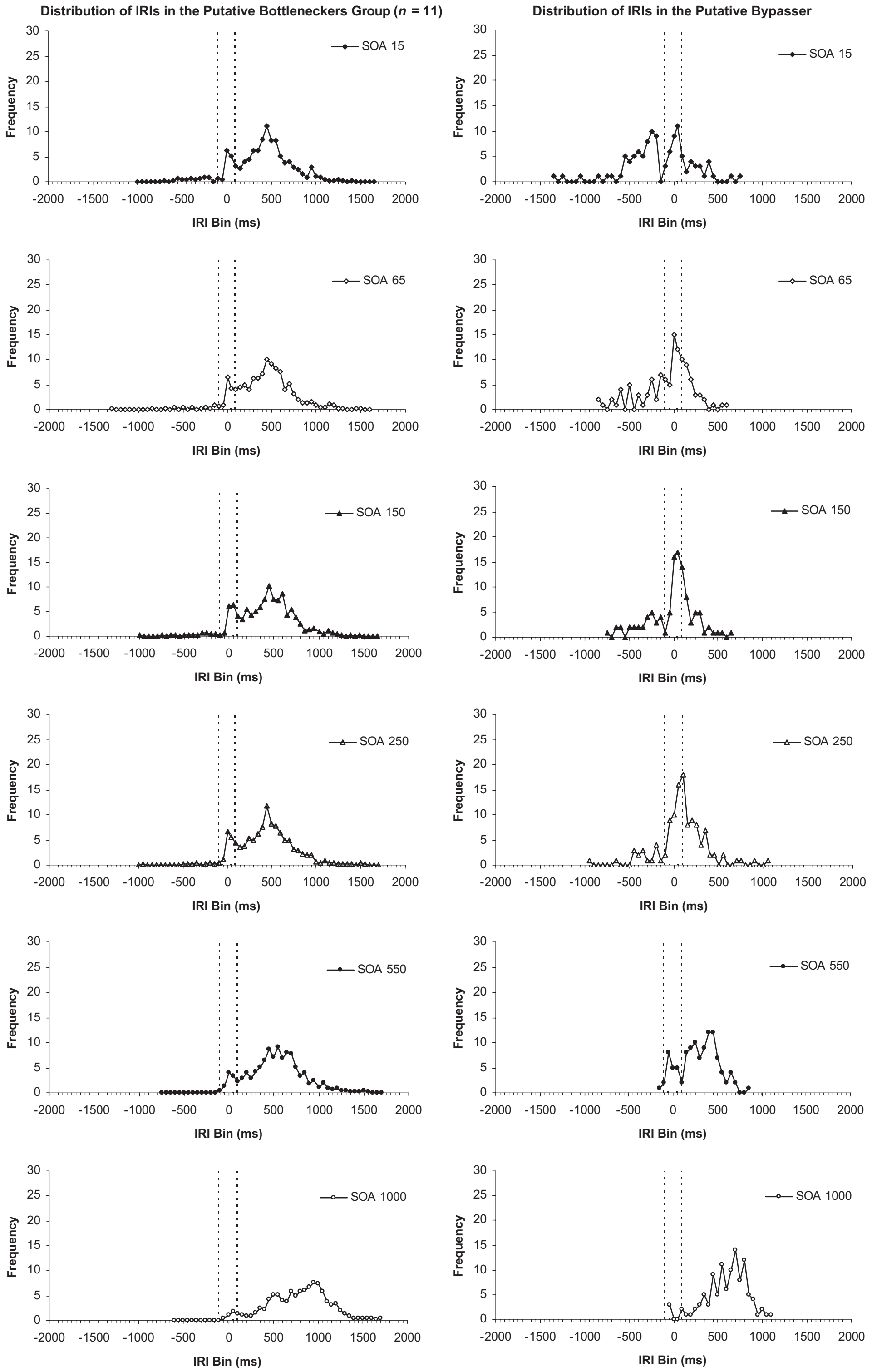

Figure 7. Histograms of interresponse intervals (IRIs) at each stimulus onset asynchrony (SOA) for the putative older bottleneckers group (left panels) and for the putative older bypasser (right panels). The range of IRIs between −100 to +100 ms, represented by the two vertical dashed lines, presumably indicates trials where response grouping occurred.

(*Appendix continues*)

Second, reversing the central processing order should cause a PRP effect on Task 1 (rather than on Task 2). This effect should be most pronounced at the short and intermediate SOAs, at which this individual often reversed the response order (see Table 2). In fact, a type of simulation discussed in Maquestiaux et al. (2008, Appendix) showed that the estimated PRP effect on Task 1 should be 271 ms at the 65-ms SOA, 144 ms at the 150-ms SOA, and 80 ms at the 250-ms SOA. These predicted values are far larger than the negligible amount of Task-1 slowing actually observed (5 ms at the 65-ms SOA, 19 ms at the 150-ms SOA, and 10 ms at the 250-ms SOA). Thus, a central bottleneck with a reversed central processing order seems implausible; instead, the data suggest bottleneck bypassing on the vast majority of trials.

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