Psychology and Aging
2011, Vol. 26, No. 1, 181–187

0882-7974/11/$12.00 DOI: 10.1037/a0021497

BRIEF REPORT

A Demonstration of Dual-Task Performance Without Interference in Some Older Adults

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Highly efficient dual-task processing is demonstrated when reaction time to each of two tasks does not differ between the dual-task situation and the single-task situation. This has been demonstrated reliably in younger adults; nevertheless, the two extant studies of extensive dual-task training did not find evidence for it in any elderly adult. The origins of age-related differences after training were explored in a study in which the stimuli for the two tasks were perfectly redundant although two distinct responses were required. The dual-task situation thus greatly reduced the demands of stimulus categorization while still requiring two response selections and two response executions. After only limited training 8 of 8 younger adults and 5 of 8 older adults showed performance consistent with highly efficient processing. Three older adults failed to show this even after 12 training sessions. The results implicate stimulus categorization more than response selection as an important locus of inefficient dual-task processing, particularly for older adults.

Keywords: cognitive aging, dual-task performance, practice, response selection, stimulus categorization

As early as 1887, Paulhan (1887) questioned whether people could efficiently carry out two tasks at the same time. Based on his own introspections from experiments he carried out on himself, he speculated that it might be possible when the two tasks required distinct operations. More than a century of subsequent research has disconfirmed his speculation. Over a wide domain of tasks and task combinations, people fail to carry out two tasks at the same time. Certain central operations for one task appear to be delayed until the central operations for the other task are completed, resulting in serial processing of the central stages of the two tasks, called the *central bottleneck*. One question that has been of fundamental theoretical importance is whether people are able to carry out the central stages of the two tasks at the same time, even if they normally do not. A definitive answer to this question would decide between two fundamentally different accounts of the central processing of two simultaneous or overlapping tasks. One account, the *central bottleneck model*, holds that there is an unavoidable structural limitation of the cognitive architecture such that central operations can be carried out on only one task at a time and that this bottleneck cannot be removed (see e.g., Pashler, 1994; Welford, 1952). Another account, the *Executive Process/Interactive-Control* (EPIC) model, holds that the central bottleneck is functional rather than structural and is under the strategic control of the individual; a bottleneck may be put in place to delay processing of the second task, but it need not be in which case the central stages of the two tasks can proceed in parallel (Meyer & Kieras, 1997a, 1997b). If simultaneous central processing of two tasks can be demonstrated, it would appear that the central bottleneck model must be wrong (i.e., must not hold in all situations) and some version of the EPIC model must be closer to the truth.

The initial step in addressing this theoretical contretemps is to demonstrate highly efficient dual-task processing, defined as task performance in the dual-task situation that is equivalent to performance of the same task performed alone. Meyer and Kieras (1999) proposed that highly efficient dual-task processing "occurs when five prerequisite conditions prevail in combination: (a) participants are encouraged to give the tasks equal priority; (b) participants are expected to perform each task quickly; (c) there are no constraints on temporal relations or serial order among responses; (d) different tasks use different perceptual and motor processors; and (e) participants receive enough practice to compile complete production rule sets for performing each task." (p. 54). Meyer, Kieras, Schumacher, Fencsik, and Glass (2001) extended this list to include providing participants with regular feedback about performance and with monetary incentives. Several studies in younger adults

This article was published Online First February 7, 2011.

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We are grateful for the assistance of Katherine Frazier, Patricia Krimmer, Alexandra Maritano, Erica Palmquist, Selvi Paulraj, Netta Shaked, and Sarah Sorice. This research was supported by Grant AG15-19195 from the US National Institute on Aging.

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have now found evidence consistent with highly efficient dual-task processing (Hazeltine, Teague, & Ivry, 2002; Schumacher et al., 2001) or with bypass of the central bottleneck (see Hazeltine, Ruthruff, & Remington, 2006; Maquestiaux, Laguë-Beauvais, Ruthruff, & Bherer, 2008; Ruthruff, Hazeltine, & Remington, 2006; Ruthruff, Van Selst, Johnston, & Remington, 2006)[1] in young adults. Each of these studies has incorporated very extensive practice of one or both tasks and in addition several have used procedures with simple tasks, with simultaneous onset of the stimuli for the two tasks, as well as with incentives for highly efficient dual-task processing and regular feedback about meeting that goal. The issue would appear to be settled but is not because theoretical accounts have been proposed in which a bottleneck could still be in place but undetectable even when highly efficient dual-task processing has been demonstrated. We will return to this possibility in the discussion.

Adult age differences in most measures of dual-task processing are small and limited but probably reliable (for reviews, see Allen, Ruthruff, & Lien, 2007, and Hartley, 1992; for a meta-analysis see Verhaeghen, Steitz, Sliwinski, & Cerrella, 2003). Two studies have probed for evidence of highly efficient dual-task processing or central bottleneck bypass in older adults using procedures that have been shown to produce such evidence in a substantial fraction of younger adults. Göthe, Oberauer, and Kliegl (2007) used a procedure that had previously produced evidence of highly efficient processing in younger adults (Oberauer & Kliegl, 2004). They gave 16 to 24 sessions of practice with two tasks, each of which involved updates of working memory, one for a number, one for a letter. In this procedure speeded responses were not required, thus avoiding the possibility raised by Tombu and Jolicœur (2004) that incentives to speed responses elicit more effort in dual-task trials than in single-task trials. On each trial, participants performed a series of memory updates before indicating the final result. At each update, the stimulus indicated how one or both of two items held in working memory should be updated. The participant pressed a key when that updating was complete and she or he was ready for the next memory update instruction. Oberauer and Kliegl demonstrated highly efficient processing of the two tasks by showing that processing times in dual-task situations were not significantly different from the longer of the two single tasks in the same situation. Five of six younger adults tested met the criterion of highly efficient processing after 24 practice sessions. Göthe et al. (2007) tested six additional younger adults as well as 12 older adults, using the same protocol. Nine of the total 12 younger adults, but none of the older adults showed evidence for highly efficient processing.

Maquestiaux, Laguë-Beauvais, Ruthruff, Hartley, and Bherer (2010) adopted a procedure in which 17 of 20 younger adults had previously shown evidence that the central bottleneck was bypassed (Maquestiaux et al., 2008). This procedure was an optimized version of a procedure first used by Ruthruff, Van Selst, et al. (2006, Experiment 2), in which 4 of 18 younger adults showed evidence for bypass of the central bottleneck after extensive practice. This procedure involved a complex visual-manual (VM) first task, mapping four digits and four letters onto the same four keys, and an easier auditory-vocal (AV) second task, vocally identifying whether the pitch of a tone was high or low. They used stimulus-onset asynchronies (SOAs) varying from 15 to 1,000 ms but, following theoretical arguments and empirical evidence that only improved performance on the second task is critical for observing parallel execution of central processes in the two tasks (see also Lien, Ruthruff, & Johnston, 2006), they gave extensive training (5,040 trials) on the AV second task alone and then paired it with the unpracticed VM first task. When Maquestiaux et al. (2010) applied this procedure to 12 older adults, in contrast to the results with younger adults, at most one older adult showed evidence consistent with central bottleneck bypass. It is important to note that Maquestiaux et al. (2008) and Maquestiaux et al. (2010) were not looking for and did not test for highly efficient dual-task processing, using our definition (see Footnote 1). Applying our standard, 6 of 20 younger adults and none of 12 older adults demonstrated dual-task performance with no significant interference (see Maquestiaux et al., 2010, Figure 4).

To summarize, studies with extensive practice on tasks shown to have produced evidence of highly efficient dual-task performance or central bottleneck bypass in many younger adults have not found such evidence in older adults. The available evidence, although limited, is unambiguous: Older adults overwhelmingly cannot or do not choose to adopt modes of processing that allow apparently simultaneous processing of two tasks without interference whereas many young adults can and do adopt such processing strategies.

What is the source of difficulty for older adults? What is it that most younger adults are capable of doing that virtually no older adults in fact do? Prior research shows that it must involve the central stages of processing, that is those operations that intervene between the early perceptual registration of the stimuli and the late execution of the motor response (Maquestiaux, Hartley, & Bertsch, 2004; Maquestiaux et al., 2010). Although that central stage is frequently treated as synonymous with response selection, it is clear that those central operations must include at least two components for each task, categorizing the perceptually identified stimulus and then selecting the appropriate response for that category. The source of the difficulty for older adults could lie in either *stimulus categorization* or *response selection* or both. To address this issue, we developed a dual-task procedure that should greatly reduce the demands of the stimulus categorization process. We adapted the procedure with which Hazeltine et al. (2002) had found highly efficient dual-task processing in younger adults. Task 1 required a verbal identification of one of three tones as high, medium, or low; Task 2 required a manual response to identify a visual stimulus as being to the left of fixation, at fixation, or to the right of fixation. The important change was that we made the stimuli for the two tasks perfectly redundant, so that a high tone always corresponded to a stimulus on the left, a medium tone to a stimulus in the center, and a low tone to a stimulus on the right. The result is that there were effectively only three stimuli; however, each stimulus required two distinct responses. As soon as either the visual or the auditory stimulus has been processed the stimulus ensemble can be categorized. Nevertheless, it is still necessary to map that category onto two different responses. If one

[1] These researchers who found evidence for bottleneck bypass did not typically report tests for highly efficient dual-task processing, but instead examined measures such as response reversal rate, inter-response intervals, and carry-over of Task 1 difficulty effects onto Task 2 reaction time (in designs with varied SOAs).

problem for the older adults tested by Maquestiaux et al. (2010) was the inability of older adults to carry out two tasks each with a requirement for stimulus categorization processes, that hindrance would be removed in the present procedure and at least some older adults should give evidence of highly efficient dual-task processing. If the problem was the inability to make two response selections at the same time, older adults should continue to show inefficient dual-task processing.

We took a number of the steps advocated by Meyer and Kieras (1999) and by Meyer et al. (2001) to encourage highly efficient processing. Following Hazeltine et al. (2002), we used simple tasks that arguably mapped naturally onto the responses: The tone stimulus required a vocal response; the visual stimulus required a spatially compatible key press. Such task pairings likely reduced peripheral—input or output—interference as well as the duration of response selection and execution stages. The stimuli for the two tasks were presented simultaneously and participants were instructed to emphasize both tasks equally. We provided economic incentives for meeting the criteria of simultaneous dual-task processing, as we describe below. We also provided feedback after each trial. The participant's RT for that trial was displayed together with the target time that the participant was trying to achieve. For each task, the average on correct trials from the unmixed single-task blocks during a session became the target time for the next session that was displayed to the participant on each trial. At the end of the session the average dual-task RT and the average single-task RT (from unmixed single-task blocks), which became the new target time, were displayed. Finally, we provided the possibility for extensive practice with as many as eight sessions of 420 trials each.

Method

Participants

Eight younger and eight older adults were recruited by word of mouth. The younger adults (4 women) averaged 20.5 years of age (SD = 1.1 years) and 14.3 years of education (SD = 0.9 years). The mean rating of health at present, using a 10-point scale (10 = excellent), was 8.4 (SD = 0.8). Average measured far visual acuity was 20/19.0 (SD = 4.5). The older adults (4 women) averaged 77.5 years of age (SD = 4.4 years) and 16.4 years of education (SD = 3.5 years), gave average health ratings of 8.6 (SD = 1.6), and had mean visual acuity of 20/26.2 (SD = 7.9). After the tasks and study were explained, participants were promised $100 either for completion of eight training sessions or for meeting the performance criteria, if that occurred sooner.

Tasks

The experimental procedures were controlled by programs written in E-Prime (Version 1.0, Schneider, Eschman, & Zuccolotto, 2002) and running on Intel Pentium computers. Manual responses were made with button presses on a response box (Serial Response Box Model 200a, Psychology Software Tools); vocal responses triggered a voice-operated relay in the response box via a microphone near the lips attached to a collar resting loosely around the participant's neck.

AV task. Each AV trial began with a dark screen displaying three gray dots vertically centered and horizontally arranged for 1,000 ms. At an approximate viewing distance of 46 cm, each dot subtended .80° of visual angle; the dots were separated by 1.40°, center to center. A tone, either 220, 880, or 3520 Hz, was then presented over speakers for a duration of 200 ms. The participant was instructed to respond as quickly and accurately as possible by saying "low," "medium," or "high" to the low, medium, and high-pitched tone, respectively. Latency was determined from the onset of the tone until a vocal response was sensed; 3,000 ms was allowed for a response. If a response was detected, a feedback display appeared for 1,500 ms giving the RT on that trial, the average RT to that point, and the target RT. After the feedback display, the participant was probed to identify the verbal response that had been given by pressing a key on the computer keyboard with their left hand. If no response was detected, the message "No voice response detected" was displayed for 750 ms. The next screen provided feedback about the correctness of the response for 1,000 ms. Participants were asked about difficulty in discriminating the tones; none reported any.

VM task. Each VM trial also began with a dark screen displaying three gray dots for 1,000 ms. One of the dots was then replaced with a white, filled square, 1.40° in extent; the other two gray dots were replaced with white dots of the same size in the same locations. Latency was determined from the onset of the square until the participant identified the location as left, center, or right by pressing the left, center, or right button using the index, middle or ring fingers of the right hand on the response box; 3,000 ms was allowed for a response. The square was displayed until a response was detected or 3,000 ms had elapsed. Feedback was then displayed giving the correctness of the response and RT feedback as for the AV task.

Dual task. Each dual-task trial began with the three gray dots presented for 1,000 ms. At that time one of the following three tone-square pairs was presented simultaneously: low tone and left white square, medium tone and central white square, or high tone and right white square. The other two display locations were replaced with white dots. Participants gave a vocal response to the tone and a manual response to the square, as in the separate tasks; 3,000 ms was allowed for both responses. Feedback was then presented for 1,500 ms giving the correctness and RT information for the square response and RT information for the tone response and whether the tone response was sensed or not. The participant then identified the vocal response that had been given with a left-hand key press, and received feedback for 750 ms about the correctness of the response.

Procedure

There was one practice session followed by two to eight training sessions. The practice session comprised three blocks: two pure single-task blocks (50 trials of the AV task only, 50 trials of the VM task only) and one mixed single-task block (100 trials with a random mix of 50 AV and 50 VM trials). The intertrial interval throughout was 1,000 ms. Each block was introduced with an explanation of what kinds of trials would occur during that block. The average RTs for correct trials in the AV and VM tasks from the pure single-task blocks were presented at the end of the practice session, and became the target times for the first of the training sessions. The nature of the upcoming training was then

Table 1
Descriptive Statistics for Single-Task and Dual-Task Reaction Times (ms) by Younger and Older Adults in the Auditory-Vocal Task and the Visual-Manual Task

	Auditory-Vocal task			Visual-Manual task		
Age group	Single *M*	Single *SE*	Dual *M*	Single *M*	Single *SE*	Dual *M*
Younger						
M	542	21	548	411	13	410
SD	104	6	109	38	9	61
Older						
M	1,170	39	1,094	1,028	38	1,083
SD	516	18	548	486	15	558

described. The goal of having dual-task RT nearly equal to the target single-task RT was emphasized and the regular feedback about actual and target RTs was explained. It was also emphasized, however, that accuracy should not be sacrificed for speed.

Each training session comprised 12 blocks of trials: Two single-task blocks of 25 trials with the AV task, two single-task blocks of 25 trials with the VM task, and eight blocks of 40 mixed single-task and dual-task trials each with 10 AV single-task trials, 10 VM single-task trials, and 20 dual-task trials. The intertrial interval was 1,000 ms. The order of the 12 blocks was determined randomly for each participant in each session. Each block began with an explanation of the kinds of trials that would occur during that block. Each training session began with a review of the target RTs and the goals to be achieved. At the end of each training session average RTs for correct trials in the AV and VM tasks from the pure single-task blocks were presented, and became the target times for the next training session.

Training sessions were continued until the mixed single-task RTs did not differ significantly from the dual-task RTs for the same task, for both of the tasks, or until eight sessions had been completed.[2] No more than two sessions were completed in a day, and at least 2 hr but not more than 72 hr separated sessions.

Results

The central concerns of the research were whether equivalent levels of performance could be achieved in single-task and dual-task situations for both tasks in younger and older adults. For the last session, the median RTs and the standard errors of the RTs were determined for both the AV and VM tasks from the mixed blocks for both the single-task and dual-task trials. Median RTs were used here (and throughout the analyses to be reported) to reduce the impact of extreme outliers but without trimming the data.[3] The means and standard deviations of the individual median RTs are given in Table 1. For each task z scores were calculated comparing the mixed dual-task RT to the mixed single-task RT, $(M_{\mathrm{DUAL}} - M_{\mathrm{SINGLE}})/SE_{\mathrm{SINGLE}}$. The last session was either the eighth session or the first session in which, for both tasks, dual-task performance did not differ significantly from (mixed) single-task performance, that is the z score for a task was less than or equal to 1.96, including if it was negative. All of the younger adults satisfied the criteria for both tasks within two sessions ($M = 1.75$ sessions) as did five of the eight older adults ($M = 1.40$ sessions). The resulting pairs of z scores form a state space as shown in Figure 1. If the difference between (mixed) single-task performance and dual-task performance was nonsignificant for both tasks, we operationally defined this as highly efficient dual-task processing; neither of the tasks was detectably postponed in the dual-task situation.[4] If the difference between (mixed) single-task and dual-task performance was nonsignificant for one task but significant for the other, we operationally defined this as indicating the operation of a central bottleneck; one of the tasks has been postponed. Within highly efficient dual-task processing we can distinguish a special subcase that we term *unitizing*. If performance on dual task was significantly better than (mixed) single task for one task but the difference was nonsignificant for the other task, then we operationally defined this as unitizing. Because the stimuli were perfectly redundant, the response could be selected once either of the two stimuli is categorized. This could result in the appearance of a significant reduction in the reaction time to the slower-categorized stimulus while reaction time to the other task should remain comparable to single-task performance. We note that unitizing could occur but not be operationally detectable because single-task and dual-task performance did not differ significantly for either task. The scatterplot for the observed performance on both tasks is shown in Figure 2 for younger adults and Figure 3 for older adults. Every younger adult fell into regions of the state space indicating highly efficient dual-task processing as did five of the eight older adults. One of the younger adults and two of the older adults demonstrated performance consistent with unitizing. Three of the older adults fell into areas consistent with the persistence of a central bottleneck. Their performance on the AV task was significantly better in the dual-task condition than in (mixed) single-task, but the performance on the VM task was significantly worse.

[2] Note that the target times given to the participant were the average RTs from the pure single-task blocks to provide a strong challenge. For the analyses, to examine the difference between single-task and dual-task performance without confounding differences in task preparation, we used the single-task trials from the mixed blocks as the comparison for dual-task trials because the mixed blocks required that both stimulus-response mappings for both tasks had to be prepared and the individual had to be ready to respond to both tasks on every trial. This provided a closer comparison than would pure, unmixed single-task trials, for which less preparation would suffice.

[3] Analyses of means produced qualitatively equivalent results.

[4] It is important to note that this is an operational definition. It is true that we are accepting the null hypothesis in using a nonsignificant difference between single- and dual-task trials as indicative of efficient processing. First, the test of the null hypothesis was very powerful, based on 160 observations. Second, and more important, our intent was to identify very efficient processing, but not to decide between truly parallel central processing and the operation of a latent or undetectable bottleneck.

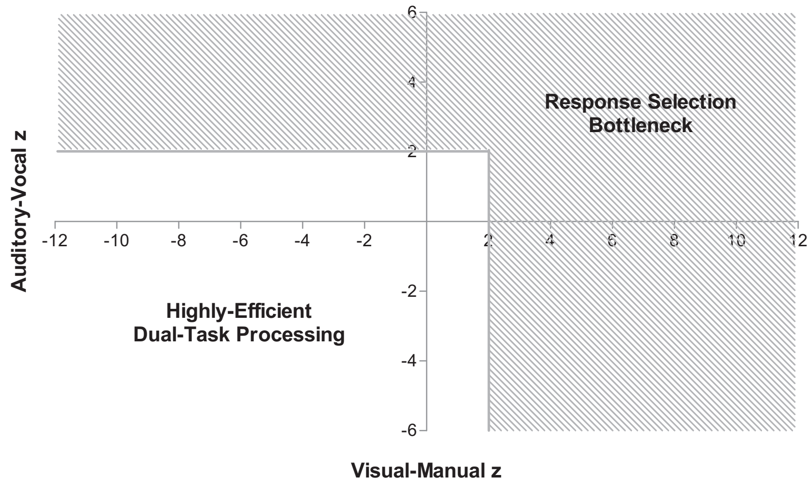

Figure 1. State space for performance on the two tasks. Vertical axis is z score for AV dual task compared to mixed single task; horizontal axis is z score for VM dual task compared to mixed single task. Shaded area shows pairs of z scores that indicate the presence of a central response selection bottleneck; unshaded area shows pairs of z scores that indicate highly efficient dual-task processing (including the special case of *unitization*, described in the text).

Analysis of variance on the proportion correct showed that performance was significantly better in the single-task condition than in the dual-task condition both for the AV task (Single Task: $M = 0.98$, $SE = .01$, Dual Task: $M = 0.95$, $SE = .01$; $F(1, 14) = 7.45$, $p = .016$, $\eta^2_P = .35$) and for the VM task (Single Task: $M = 0.98$, $SE = .01$, Dual Task: $M = 0.96$, $SE = .01$; $F(1, 14) = 6.20$, $p = .026$, $\eta^2_P = .31$). No other effects were significant.

To provide an additional opportunity for these three older individuals to demonstrate highly efficient processing, we invited them to return for four additional training sessions. In these additional sessions, the task was simplified. Now, only the low tone with left white square and the high tone with right white square ensembles were presented (the intermediate tone with central white square was deleted) thus reducing the number of unique stimulus ensembles from three to two. The sessions were otherwise identical to those in the initial training. None of the three individuals met the criteria for simultaneous processing within four sessions; each continued to show a significant slowing of the dual VM task relative to the mixed single task. The AV and VM *z* score pairs for the three individuals were (−0.80, 7.63), (−2.61, 2.53), and (−0.52, 20.72).

Discussion

The goal of the present research was to determine whether two distinct tasks could be performed simultaneously without interference, that is, whether performance of two tasks together could be

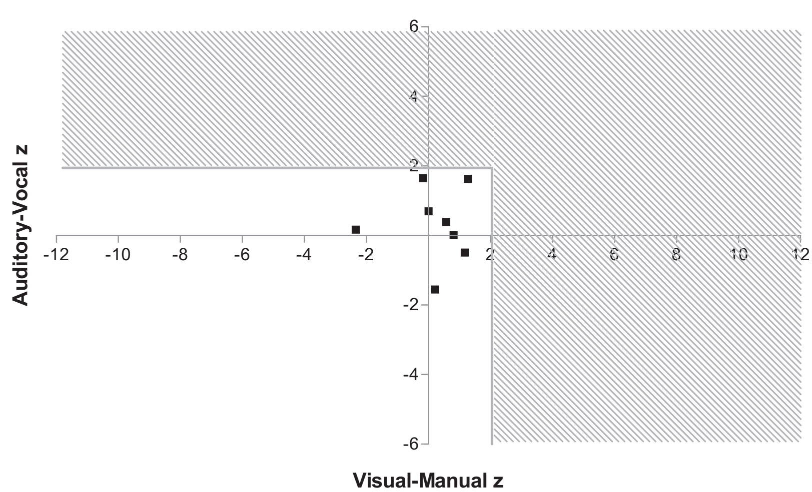

Figure 2. Scatterplot of observed z scores for the two tasks for younger adults. Shaded area shows pairs of z scores that indicate the presence of a central response selection bottleneck; unshaded area shows pairs of z scores that indicate highly efficient dual-task processing (including the special case of *unitization*, described in the text).

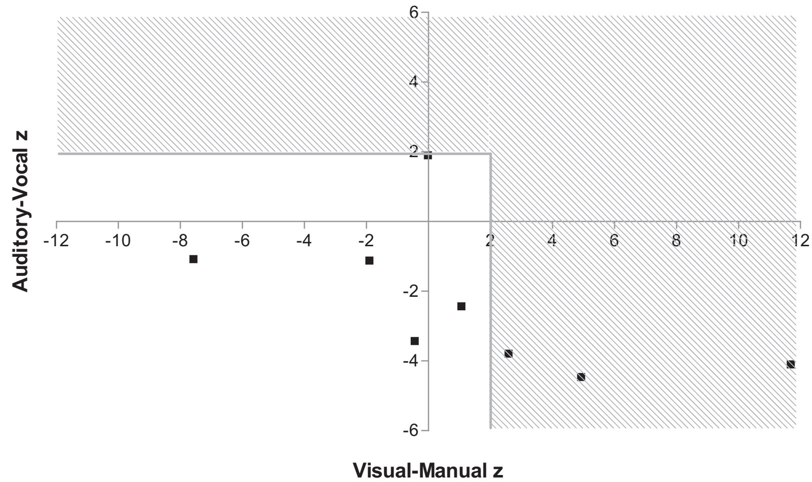

Figure 3. Scatterplot of observed z scores for the two tasks for older adults. Shaded area shows pairs of z scores that indicate the presence of a central response selection bottleneck; unshaded area shows pairs of z scores that indicate highly efficient dual-task processing (including the special case of *unitization*, described in the text).

as efficient as when either was performed in isolation, in both older and younger adults. In this experiment, participants were trained in a simultaneous-onset dual-task situation characterized by perfect redundancy between the stimuli for the two tasks, although two separate and distinct responses were still required. Compared to the central processes required in the conventional dual-task procedure, this procedure reduced the demands of stimulus categorization while leaving the demands for response selection unchanged. Under these circumstances, eight of eight younger adults and five of eight older adults showed performances consistent with highly efficient simultaneous processing of the two tasks and did so with relatively little training. Because prior efforts to show highly efficient dual-task performance (Göthe et al., 2007) or bottleneck bypass (Maquestiaux et al., 2004; Maquestiaux et al., 2010) in older adults have been unsuccessful, the present results suggest that, for at least some older adults, a principal impediment to efficient dual-task processing must be in the categorization of the stimulus, rather than in response selection per se. A majority of the older adults tested met the standard for highly efficient dual-task processing, meaning that they efficiently coordinated processes of response selection and execution. A minority of older adults still gave evidence of a postponement of one of the tasks even after 12 total sessions of training, suggesting either that they could not carry out response selection for the two tasks simultaneously or that they continued to carry out stimulus categorization for both tasks even when that was not necessary. From our results we speculate that the central bottleneck is better explained as a stimulus-categorization bottleneck than as a response-selection bottleneck.

Our procedure for determining the correctness of the vocal response was to have the participant identify the response with a key press after the task (or tasks) were completed. One reviewer noted that this has the effect of making it a triple-task procedure rather than a dual-task procedure, and that this might have been responsible for the failure of three older adults to meet criterion. On the one hand, Pashler (1989) and Pashler and Johnston (1989) found that a task with no time pressure to respond did not produce dual-task interference and Hartley and Little (1999) replicated this result with older adults. On the other hand, if the additional task did impose an additional load, the results strengthen rather than weaken our conclusion. Even with this extra burden, the majority of older adults demonstrated highly efficient dual-task processing.

Our findings of highly efficient dual-task processing do not permit a definitive conclusion that the central bottleneck is strategic and flexible rather than structural and immutable. Our operational criteria for highly efficient dual-task processing were simply that dual-task reaction time was not significantly greater than single-task reaction time for both tasks. Proponents of the bottleneck model argue that highly efficient processing could be observed even in the presence of a bottleneck. Noting that highly efficient dual-task processing is found with simple tasks that are highly practiced, they offer two alternative interpretations. One is that at least one of the tasks becomes automatized, that is that stimuli once identified are linked directly to responses, with no central processing required rendering the existence of the bottleneck moot (see, e.g., Ruthruff et al., 2006). A second interpretation is that because at least one of the tasks is so well-learned, processing of the central stages of the two tasks may never conflict (called the *latent bottleneck model* by, e.g., Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003). Either of these explanations could be applied to the present results.[5] Whether the bottleneck was mutable or it was immutable but not detectable, the important result is that the majority of older adults showed the same cognitive flexibility as younger adults. Further research will be required to determine whether highly efficient dual-task pro-

[5] There is a third possibility. Assume that central processing comprises stimulus classification (requiring time SC) and response selection (requiring RS). If it were the case that RS for one task finishes before SC on the other task were complete (i.e., $SC_2 + RS_2 \leq SC_1$ with 1 representing one of the tasks and 2, the other), then it would be possible to see highly efficient dual-task processing (including unitizing) even if a response-selection bottleneck remained in place.

cessing can be demonstrated in older adults with more complex tasks.

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Received February 27, 2009
Revision received June 21, 2010
Accepted July 14, 2010 ■