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Aging and Attentional Control

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Abstract

The research examines the structural bottleneck account and the resource account of the substantial dual-task deficits among older adults. Procedures from two common dual-task methodologies--the psychological refractory period and the relative-priority manipulation--were used to encourage maximization of the joint performance. Performance and time-sharing strategies from subjects between the ages of 20 and 70 were examined. Age-related declines in time-sharing efficiency and in the precision of the executive control process were observed. The age-related effect was larger when two manual responses were required than when one manual and one vocal response were required but no evidence for obligatory sequential processing was found. Except for the most demanding conditions, comparable practice effects were observed between the younger and older subjects, suggesting considerable cognitive plasticity in the older subjects. Implications for the two attentional accounts were discussed.

The present research examines two attentional accounts of the often substantial dual-task deficits among older adults (e.g., McDowd & Shaw, 2000). These two attentional accounts constrain time-sharing performance¹ differently. One hypothesizes a bottleneck mechanism whereby only one task can be processed at a time at the bottleneck stage. A larger bottleneck has been proposed to be associated with increased age (e.g., Allen, Smith, Vires-Collins, & Sperry, 1998). The other hypothesizes that time-sharing performance is limited by resource scarcity. Associated with this view, reduced processing efficiency and reduced executive control effectiveness have been proposed to be associated with increased age (e.g., Tsang & Shaner, 1998). The present research investigates the potential contribution of two specific

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⁸The RT decrement averaged over the manual and speech responses when the Sternberg task was completed first in the equal-priority condition late in practice were 407 ms, 572 ms, and 608 ms for the young, middle-aged, and older group respectively

The data from young adults under the age of 30 have been published in Tsang (2006). Aspects of these data have been presented at the Annual Meeting of Psychonomics, November, 2003. The earlier paper focused on the theoretical implications of some of the methodological issues in examining the nature of time-sharing performance. The current paper included subjects from 20 to 70 years of age and focuses on understanding the attentional mechanisms that underlie the age-related difficulty in dual-task performance. The current paper is based on completely new analyses that included all subjects (three age groups) whereas the earlier paper included only the young subjects (one age group).

¹Time-sharing has been used both in the switching (e.g., Hirst & Kalmar, 1987) and in the simultaneous sharing (e.g., Gopher, 1993) sense in the literature. The present paper examines two theoretical frameworks that have opposing views on whether attention is switched or shared when more than one task is being processed. The paper therefore does not a priori specify an exclusive use of the term.

accounts to the understanding of age-related difficulties in time-sharing; the response-selection bottleneck model and the structure-specific resource model.

Bottleneck Account of Age-Related Difficulty in Dual-Task Performance

Bottleneck theories hypothesize that attention acts as a bottleneck along the information processing system. Processing at the bottleneck is *all or none*, necessitating multiple tasks to be processed sequentially. According to the response-selection bottleneck model, multiple tasks must be processed in sequence at the response selection stage even though parallel processing is possible at other stages such as during the perception stage (e.g., Band, Jolicoeur, Akyürek, & Memelink, J., 2006; Hazeltine, Teague, & Ivry, 2002; Kramer & Madden, 2008; McCann & Johnston, 1992; Miller, Ulrich, & Rolke, 2009; Pashler, 1994a; Ruthruff, Pashler, & Hazeltine, 2003; Van Selst & Jolicoeur, 1997; Watter & Logan, 2006).

The dominant methodology used with testing the bottleneck account is the *psychological refractory period* (PRP) paradigm (Pashler & Johnston, 1998). With this paradigm, two discrete tasks are presented in close temporal proximity. The main manipulation is the stimulus onset asynchrony (SOA)--the interval between the onset of Task 1 stimulus and Task 2 stimulus. Typically, Task 1 is presented first and subjects are to respond to it as quickly as possible. Task 1 reaction time (RT) is found to be independent of the SOA and is affected minimally by Task 2. Pashler (1994b) wrote, "At 0 SOA, why should the task that is performed first be performed more slowly, given that this task is presumed to receive priority treatment at the bottleneck? One would expect it to be just as fast." (pp. 339–340; see also Tombu & Jolicoeur, 2002; Watter & Logan, 2006; Welford, 1952). In contrast, Task 2 RT is found to be significantly slower than its single-task RT and the difference increases with shorter SOAs. This is referred to as the *PRP effect* and is taken as evidence for a single-channel bottleneck whereby Task 2 must wait for the completion of Task 1 processing. The PRP effect is attributed to a central limitation at response selection and not to a peripheral motor interference. Similar PRP effects have been observed whether both tasks require a manual response or whether one task requires a manual response and the other a speech response (Pashler & Johnston, 1988).

In regard to the age-related effects on dual-task performance, Hartley and Little (1999) found their older subjects to exhibit a larger PRP effect than their young subjects but the response-selection bottleneck model accounted well for the PRP effects for both age groups. They therefore attributed the age effect to generalized slowing rather than to an age-specific dual-task impairment. In a later study, Hartley (2001) found that dual tasks that required two manual responses produced larger interference than those that required one manual and one vocal response, especially for the older group. To account for this, Hartley proposed an additional age-related decline in the ability to generate and execute two similar motor programs. But Allen et al. (1998) did not find the use of separate response modalities to eliminate the age effect. They attributed the larger age-related PRP effect to a "larger processing bottleneck" (p. 221) at the response-selection stage.

Resource Account of Age-Related Difficulty in Dual-Task Performance

Resource theories hypothesize that attentional resources needed to fuel task processing are limited but can be allocated among tasks in *graded fashion* (Kahneman, 1973; Moray, 1967; Navon & Gopher, 1979; Sanders, 1997). If task demands are not met by a sufficient supply of resources, performance degrades. But the degradation is smooth and not catastrophic (Norman & Bobrow, 1975), suggesting that resources are continuously modulated via a closed feedback loop between demand evaluation and performance monitoring. Simultaneous processing of multiple tasks is hypothesized to be possible but perfect time-sharing is not guaranteed. Performance quality is a function of the supply and demand of attention for single task or multiple tasks.

In addition to the aforementioned properties, multiple-resource theories posit distinct resources for different cognitive processes (e.g., Kinsbourne & Hicks, 1978; Navon & Gopher, 1979). In particular, Wickens' (1980, 1984) structure-specific resource model delineates three dichotomous dimensions by which resources are defined: (1) stages of processing (perceptual/central vs. response processing), (2) codes of processing (spatial vs. verbal processing), and (3) input (visual vs. auditory) and output (manual vs. speech) modalities. Each distinct resource is scarce but sharable; but different resources are not exchangeable. According to this model, performance is affected by both the *intensity* of the task demand and the *similarity* of the resource demand of the time-shared tasks or their *structural similarity*. A higher degree of structural similarity should increase resource competition and performance decrement.

The typical methodology used for testing the resource predictions is the *relative-priority manipulation* whereby components of a task pair are assigned equal or differential priorities but the time-shared tasks are to be performed simultaneously. Presumably, because of resource scarcity, as more resources are allocated to the task of increased priority, less resources would be available for the other task, producing a *performance tradeoff* between the time-shared tasks (e.g., Kinchla, 1992; Low, Leaver, Kramer, Fabiani, & Gratton, 2009; Navon & Gopher, 1979; Newman, Keller, & Just, 2007; Sperling & Melchner, 1978).

Older adults are commonly observed to have larger dual-task performance decrement and poorer allocation control than young adults. Age-related dual-task decrement proportionate to single-task decrement has been attributed to a generalized overall reduction in processing resources or processing efficiency (e.g., Crossley & Hiscock, 1992; McDowd & Craik, 1988; Somberg & Salthouse, 1982). Disproportionate dual-task decrement attributed to a specific difficulty in the executive control required for coordinating multiple tasks also has been observed (e.g., Fraser et al., 2010; Kramer & Madden, 2008; McDowd, 1986; Nestor, Parasuraman, & Haxby, 1989; Salthouse, Fristoe, Lineweaver, & Coon, 1995; Prakash, et al., 2009; Salthouse & Miles, 2002; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). Importantly, several researchers have found that this age-specific dual-task decrement could be reduced by training, suggesting that dual-task processing is a skill that can be improved with practice (e.g., Bherer, et al., 2005, 2008; Kramer, Larish, & Strayer, 1995; Kramer, Larish, Weber, & Bardell, 1999).

Both generalized and specific age effects were observed by Tsang (1997) and Tsang and Shaner (1998). Consistent with the thesis of the structure-specific resource model, larger age-related dual-task decrement with increased degree of structural similarity was found. Older subjects, who presumably had reduced processing efficiency, were found to exhibit larger age-related performance decrement and allocation nonoptimality with the task pair that required responses of the same modality (heightened resource competition) than the task pair that required responses of mixed response modalities (manual and speech).

In brief, there is considerable debate concerning the effects of aging on time-sharing. Bottleneck theorists attribute the age-related difficulty to a bottleneck stage and/or to generalized slowing. Resource theorists attribute the age-related difficulty to a generalized reduction in processing efficiency and an executive control nonoptimality pertinent to time-sharing. The present study examines the contribution of the response-selection bottleneck model and the structure-specific resource model in accounting for age-related difficulties in time-sharing.

Present Experimental Approach

Procedures from both the PRP and the relative-priority paradigms were adopted to maximize the potential for joint performance. This approach was to heed a number of concerns raised in the discussion of the methodological nuances of dual-task research in recent literature (Meyer & Kieras, 1997; Navon & Miller, 2002; Tombu & Jolicoeur, 2003; Tsang, 2006). As is typical of the PRP paradigm, two discrete tasks were used. To discourage unnecessary sequential processing, a zero SOA was used to afford simultaneous information availability and thereby feasibility of simultaneous processing. Task instructions emphasized the simultaneity of task processing rather than the speed of the first response.

To exercise attentional control, the time-shared tasks were assigned either equal or differential priority. The two hypothesized attentional mechanisms predicted different outcomes for these priority conditions. In the equal-priority condition, the response-selection bottleneck model predicted a significant performance decrement only for the task responded to second due to its wait for the bottleneck. An age-related larger bottleneck would result in larger Task 2 decrement with increased age. Task 1 should be affected minimally relative to its single-task performance. In contrast, according to the resource model, competition between the time-shared tasks should degrade the performance of both tasks. An age-related reduced processing efficiency would result in larger decrements in both tasks for the older subjects.

To better distinguish the two attentional mechanisms, graded priority levels were assigned to the two tasks in the differential-priority condition. The bottleneck model predicted that the low-priority task would be responded to second. Different priority levels could lead to a different percentage of times that a certain task would be responded to first, producing varying averaged response times. But this would not be considered true graded performance. The resource model predicted that less attention would be allocated to the low-priority task. Varying priority levels should lead to varying amounts of attention allocated to a task producing varying levels of performance. That is, both models predicted a *global priority*

effect with the high-priority performance superior to the low-priority performance. But graded performance tradeoffs with graded priority changes was predicted only by the resource account.

Further, according to the resource model, attentional control, being a skill, should improve with practice (e.g., Kahneman, 1973; Kramer et al., 1999; Gopher, 1993). In contrast, according to the bottleneck model, attentional control is accomplished by granting bottleneck access to one task or another due to a structural necessity that cannot be altered easily by practice (e.g., Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003). The varying priority levels used in the present approach would require a level of control that is rarely examined in the literature and afforded an opportunity to further examine the extent of cognitive plasticity in older adults.

Last, the two attention accounts differed in their prediction of the effects of the similarity of response modality of the two tasks. Response similarity was manipulated by having two task pairs, one requiring bimanual response and one requiring a manual and a speech response. According to the structure-specific resource model, the bimanual condition would incur greater resource competition for the manual processing resources and should produce a larger dual-task decrement than the mixed-modality condition. The heightened intensity of resource competition should exacerbate the effects of an age-related decrease in processing efficiency. But response modality was not expected to affect the response-selection demand, which is determined by the number of response choices (Pashler & Johnson, 1998).

Method

Subjects

Forty-eight subjects were equally divided among three age groups: 18–30 (25% female), 50 to 59 (81.3% female), and 60 to 70 (50% female) years of age. Because the younger subjects were all college students, older subjects who were recruited from the university and local community were also required to have at least 13 years of education. All subjects had normal hearing, normal or corrected to normal vision, and normal colour vision. They received \$6.50/hr and a performance-based prize.

Three psychometric tests were administered to gauge the background homogeneity of the different age groups. The Digit-Span raw score (subscales from the Wechsler Adult Intelligence Scale-Revised [WAIS-R]; Wechsler, 1981) provided a measure of the short-term memory capacity. The WAIS-R Digit-Symbol raw score provided a measure of perceptual speed and motor coordination. The Raven Advanced Progressive Matrices (APM; Raven, Raven, & Court, 1991) was a culturally unbiased test of spatial reasoning and a measure of intellectual efficiency (Dworetzky, 1982). Table 1 presents the subjects' characteristics. As commonly reported in the literature, significant age effects were found in the Digit Span score, $F(2, 42) = 4.93, p < .05$, the Digit Symbol score, $F(2, 42) = 17.90, p < .001$, and the APM score, $F(2, 42) = 17.06, p < .001$.

Tasks

Two pairs of dual tasks were constituted from three single tasks: a spatial orientation task called the Planikin task (Tsang & Shaner, 1998) and two variations of the Sternberg short-term memory task (Sternberg, 1969). The tasks were generated by a microcomputer and displayed on a 14" monitor.

Planikin task (PL)—A twin-engine airplane symbol was presented in 1 of 16 possible orientations (Figure 1). For each presentation, the colour of each engine was randomly selected from easily distinguishable colours (blue, yellow, or magenta). A colour cross directly below the airplane indicated the colour of the target engine. Subjects indicated whether the target engine was on the left or right wing of the airplane. The Planikin task was presented visually and responded to manually by a button press with the left hand. Depending on the orientation, the airplane symbols subtended a horizontal visual angle that ranged from 35' to 1° 47', a vertical angle that ranged from 32' to 1° 3' without the cross, and 1° 23' to 2° 10' with the cross.

Sternberg memory task (SB)—A memory set of 5 airplane symbols randomly selected from the 16 Planikin orientations was displayed. Subjects had as much time as needed to learn the memory set before initiating the trial. For each airplane presented during the trial, subjects determined whether it belonged (with a .5 probability) to the memory set regardless of the engine colours. The task was presented visually and responded to either manually via button presses with the right hand (mSB) or by speech (sSB) by saying "yes" or "no." A Votan VPC 2100 speech recognizer checked the response accuracy spoken into a Beyerdynamic model DT109 headset. A Med Associates model ANL-923 voice key detected speech reaction time.

Dual task—The Planikin task was paired with either the manual (PL-mSB) or speech (PL-sSB) Sternberg task producing two dual tasks with several important features. 1. The time-shared tasks shared the same stimulus producing a zero SOA and minimizing visual scanning between tasks. The same perceptual processes should serve both tasks. 2. Because the two tasks shared a visual-spatial stimulus, they were expected to compete for visual, spatial, and perceptual/central processing resources. Although the specific cognitive operations (memory and determining spatial orientations) involved in each task were different, neither the response-selection nor the structure-specific model distinguished these demands within the central processing stage or resources. 3. The two tasks had similar two-choice response selection demand (left/right response for the Planikin task; yes/no response for the Sternberg task) and were expected to compete for the response-selection bottleneck or response processing resources. 4. Response modality similarity between the component tasks was the only difference in structural similarity between the two task pairs.

All trials consisted of 35 stimuli that appeared one at a time over a duration of 180 s. A fixed interstimuli interval of 5 s was used and no stimulus presented during the first and last 5 s of the trial. Each stimulus remained on the screen until responded to or until 5 s had elapsed and an omission recorded. Percentage correct (%C), percentage omitted (%O), and the median reaction time (RT) of the correct responses for the trial were analysed. Response

time to the individual stimulus and the interresponse interval between the Sternberg and Planikin tasks in the dual-task conditions were also examined.

Priority Manipulation

Task priority was manipulated to induce attentional control at a global level and at a more precise level. At the global level, the dual tasks were either of equal priority or of differential priority. For the equal-priority condition, subjects were asked to devote equal attention to the two tasks. For the differential-priority condition, the *optimum-maximum method* was used to guard against suggesting to the subjects that the time-shared tasks were expected to tradeoff (Navon, 1984, 1985, 1990). With this method, the high-priority task was designated the *optimised task*, the low-priority task the *maximized task*. Subjects were to perform as closely as possible to an *individually determined* performance standard provided for the optimised task and to perform their best on the other task. No standard was provided for the maximized task.

At the more precise level, three *performance standard levels* for the optimised task were used to induce *graded control*. A higher performance standard should necessitate increased effort or resources to meet. For the highest performance standard level, the subject's own best single-task performance served as the optimised task performance standard. For the second level, an average of the subject's best single-task and equal-priority dual-task performance served as the standard. For the third level, the subject's best equal-priority dual-task performance served as the standard. Stringent performance standards requiring full attention were used to preclude subjects from meeting the standards by increasing their overall effort rather than by apportioning all their attention to the component time-shared tasks. The optimised standards were derived from stabilized performance to assure that the optimised performance was not accomplished through continued improvement with practice.

To summarize, for the differential-priority condition, two global priorities (i.e., each task being designated as either optimised or maximized) and three performance standard levels for the optimised task (single-task, average, and dual-task performance standards) generated six priority conditions. The Planikin and Sternberg task of a task pair took turn to serve as the optimised task in different trials.

Procedure

Overview—Table 2 provides an overview of the experimental procedure. The young group had 6 experimental sessions comprised of 5 single-task blocks (Blocks S1–S5), 5 equal-priority dual-task blocks (Blocks E1–E5), and 4 differential-priority dual-task blocks (Blocks D1–D4). Single-task and equal-priority dual-task blocks were intermixed because single-task performance often improves after dual-task practice. Because preliminary testing showed that the older subjects would require additional practice to stabilize performance, the two older groups had seven experimental sessions with one additional single-task block and one additional equal-priority dual-task block following the second single-task and equal-priority dual-task blocks. Data from the additional block were not analysed such that an equal amount of data from all age groups entered the analysis. Including several short

breaks, each session was of 3 hr duration approximately. As much as possible, all sessions were scheduled within a two-week period.

Each single-task and equal-priority dual-task block consisted of two or three consecutive trials of each task condition (the Planikin task required more practice for performance to stabilize). Task order was randomised for each block and all the subjects followed the same order. For the differential-priority condition, each task component (Planikin or Sternberg) in a task pair was optimised at each of the three performance standards once in Block D1 and twice consecutively in Blocks D2 to D4. One fourth of the subjects started with optimising the Planikin task with the highest performance standard level (i.e., single-task performance standard first, dual-task performance standard last) and then optimising the Sternberg task with the highest performance standard level. Another fourth started with optimising the Planikin task with the lowest performance standard level. The other half of the subjects started with optimising the Sternberg task with the highest or lowest performance standard level.

Instructions—Throughout the experiment, subjects were asked to devote their full attention to the tasks. Subjects were to respond as quickly as possible and to try to attain 100% accuracy. The accuracy emphasis provided a uniform performance expectation for all the subjects and should discourage speed-accuracy tradeoff. For all dual-task trials, subjects were asked to process the two tasks simultaneously. To discourage response grouping², subjects were asked to respond as soon as they have the answer for each task. For the equal-priority trials, subjects were asked to pay equal attention to the two tasks. For the differential-priority trials, subjects were asked to pay close attention to which task was optimised, treat it as the high-priority task, and adhere to the performance standard provided at the beginning of the trial. They were to perform their best with the maximized task. Performance feedback was provided verbally at the end of each trial. Starting with the second session, subjects were encouraged to exceed their previous best performance.

Establishing performance standards for the optimised task—Stringent algorithms³ were used to discourage speed-accuracy tradeoffs and subjects from favouring one task exclusively. Subject's best response times from only the high accuracy trials were used for establishing the performance standards. Best performance through Block S3/E3 served as the standards for the first differential-priority block (Block D1). Best performance through Block S5/E5 served as the standards for Blocks D2–D4.

For added motivation, a point system was used in conjunction with the differential-priority instructions. The point system was designed to convey to the subjects that their top priority

²Response grouping whereby Task 1 response was deliberately delayed to coincide with Task 2 response was discouraged because it is a response tactic that is not mandated by either of the two hypothesized attentional mechanisms. Intentional response grouping however can obscure the true process that underlies the dual-task performance (e.g., Ulrich & Miller, 2007). Results obtained with the explicit instructions to group the responses (e.g., Hartley & Maquestiaux, 2007) are therefore difficult to interpret.

³To determine the best reaction time of a single-task condition, the trials with the highest accuracy for that task were first identified. The fastest trial reaction time among these high accuracy trials would be recorded as the best reaction time for that task condition. For dual tasks, to determine the best performance of Task A in the A–B pair, the trials with the best Task B performance were first identified (using the same procedure for the single-task condition), then the best Task A performance among these trials would be recorded.

was to adhere to the optimised performance standard provided for the trial and to encourage them to perform the maximized task to the extent possible. The closer the subject's performance was to the optimised standard, the more points were awarded for the trial⁴. If optimised points were earned, additional points could be earned if the maximized performance exceeded the subject's best equal-priority dual-task performance but subjects were not informed of the criterion used for awarding maximized points. Subjects received a prize commensurate with the total points earned for the experiment. The prizes ranged from a pen to a coffee mug to a beach umbrella.

Results

Results are presented in four sections. The first section examines the single-task performance to provide a baseline for interpreting the dual-task performance. The second examines the dual-task performance decrement in the equal-priority condition. The third examines the attentional control in response to differential task priorities in terms of performance tradeoffs and the extent to which subjects could adhere to the graded performance standards. The fourth examines the time-sharing strategies at the individual response level. Greenhouse-Geisser (G-G) corrections for repeated measures are reported only when the corrected significance level exceeded .05. All post-hoc comparisons were conducted with the Tukey Studentized Range method with a significance level of .05.

Single-Task Performance

Block (S1–S5) x Age (young, middle-aged, older) x Task (PL, mSB, sSB) ANOVAs were conducted. The more stabilized performance from the last block is presented in Table 3. The Age main effect and Tukey comparisons showed that the young group was reliably faster ($F(2, 45) = 22.70, p < .0001, MSE = 966576.66$) and more accurate ($F(2, 45) = 11.75, p < .0001, MSE = 225.92$) than the two older groups. The Planikin task was slower ($F(2, 90) = 215.97, p < .0001, MSE = 181270.17$) and less accurate ($F(2, 90) = 5.71, p < .01, MSE = 92.37$) than the Sternberg tasks. Omissions were rare. An Age x Task interaction showed that the young group had comparable manual and speech Sternberg reaction time (RT) whereas the two older groups had slower manual RT ($F(4, 90) = 3.95, p < .01, MSE = 181270.17$).

Practice led to substantial performance improvement (RT: $F(4, 180) = 283.10, p < .0001, MSE = 73201.10$; %C: $F(4, 180) = 33.48, p < .0001, MSE = 38.98$). The two older groups improved their RT more than the young group over blocks of practice ($F(8, 180) = 4.87, p < .0001, MSE = 73201.10$) but performance was stabilized by the end of practice with no reliable difference detected between the last two blocks for all age groups.

⁴Subjects could earn the most points by being within 3% of their optimised accuracy standard and fewer points by being within 6%. If points were earned for accuracy, additional points could be earned for RT being within 100 ms and 75 ms of the optimised Planikin and Sternberg standards respectively. Fewer points would be earned if the RT was within 200 ms and 150 ms of the optimised Planikin and Sternberg standards respectively. The accuracy and RT ranges used were based on preliminary testing.

Equal-Priority Dual-Task Performance

Table 3 presents the equal-priority dual-task performance late in practice but *dual-task performance decrements* were analysed to take into account the individual differences at the single-task level. Performance decrement was obtained by taking the difference between the single- and dual-task performance from the same block (e.g., single-task RT from Block S1 was subtracted from dual-task RT from Block E1). Block (E1–E5) x Age x Task (Planikin vs. Sternberg) x Modality (manual vs. speech Sternberg response) ANOVAs were conducted. Recall that the bottleneck model predicted a significant performance decrement only for the task responded to second (Task 2) and the resource model predicted performance degradation for both tasks. Further, the bottleneck model predicted an especially large Task 2 effect for the older subjects due to their larger bottleneck but response similarity would not affect the response-selection bottleneck. In contrast the structure-specific resource model predicted a heightened resource competition for the bimanual responses whose performance degradation would be further amplified by a reduction of age-related processing efficiency.

The young group had significantly smaller RT ($F(2, 45) = 10.28, p < .0001, MSE = 226688.54$) and accuracy ($F(2, 45) = 11.00, p < .0001, MSE = 130.72$) decrement than the two older groups. The Planikin task had larger RT ($F(1, 45) = 12.15, p < .001, MSE = 841796.77$) and accuracy ($F(1, 45) = 7.71, p < .01, MSE = 96.69$) decrement than the Sternberg task. Manual responses had larger RT ($F(1, 45) = 72.19, p < .0001, MSE = 106235.46$) and accuracy ($F(1, 45) = 7.84, p < .01, MSE = 35.16$) decrement than speech responses. Figure 2 displays an Age x Task x Modality interaction. The two older groups had substantially larger Planikin RT decrement when both tasks required manual responses ($F(2, 45) = 11.88, p < .0001, MSE = 73240.23$). Practice reduced the RT ($F(4, 180) = 2.92, p < .05, G-G p < .1, MSE = 226688.54$) and accuracy ($F(4, 180) = 3.55, p < .01, G-G p < .1, MSE = 54.96$) decrement. No differential practice effects were observed, showing that all age groups benefited from practice to a similar extent. Performance was stabilized by the end of practice as no difference was detected between the last two dual-task blocks.

Summary of single-task performance and equal-priority dual-task decrement

—Reliable age differences were observed in the single-task performance and dual-task performance decrements. The young group performed better than the two older groups but the two older groups did not differ from each other. The Planikin task had poorer single-task performance and larger dual-task decrement than the Sternberg task, suggesting that the Planikin task was more difficult. Substantial performance decrement was observed in both tasks and the manual task pair had larger decrement than the speech task pair. The difficulty of the Planikin task together with the demands of bimanual responses exacerbated the age effects (Figure 2). Although these results were consistent with the resource account, a later analysis will check whether the performance decrement from both tasks could have been an artifact produced by subjects responding to each task first some of the time, thereby producing an averaged slower dual-task RT for both tasks. Substantial dual-task decrements and practice effects showed that the tasks were demanding, but performance was stabilized by the end of practice. With practice, the two older groups improved their single-task RT

more than the young group but all age groups reduced their dual-task performance decrement by a similar extent.

Differential-Priority Dual-Task Performance

Both attention models predicted a global priority effect with the high-priority task (optimised) having superior performance to the low-priority task. But since the bottleneck access is granted in an all-or-none fashion, only the resource account predicted graded performance changes in response to the graded performance standard levels. Attentional control was examined in two ways. One set of analyses examined the performance tradeoffs between the time-shared tasks as the optimised performance standard varied. A second set examined the optimality of allocation control by examining the degree to which performance conformed to the optimised performance standards.

Task priority and performance tradeoffs—Block (D1–D4) x Age x Modality x Priority (optimised vs. maximized) x Performance Standard Level (single-task, average, dual-task standards) ANOVAs were conducted. One set of ANOVAs examined the optimised Sternberg-maximized Planikin combination; another set examined the optimised Planikin-maximized Sternberg combination. A reliable Priority x Performance Standard Level interaction with the optimised performance improving with increased optimised performance standards and a corresponding worsening of the maximized performance would be a strong indication of graded performance tradeoff.

For ease of comparison, RT was standardized⁵ separately for each age group and each task to take into account the age-related variance and the variance inherent in the amount of time required to process the Planikin and Sternberg tasks (Table 3). The means and standard deviations used for standardization were derived from the differential-priority blocks, across priorities and performance standard levels.

Global priority effects were as expected. Optimised Sternberg performance was superior to maximized Planikin performance (RT: $F(1, 45) = 13.80, p < .001, MSE = 4.19$; %C: $F(1, 45) = 9.79, p < .01, MSE = 436.92$; %O: $F(1, 45) = 19.39, p < .0001, MSE = 49.86$; Figure 3A). Optimised Planikin performance was generally superior to maximized Sternberg performance (RT: $F(1, 45) = 8.10, p < .01, MSE = 7.13$; Figure 3B). That subjects were following the priority instructions was evident. Subjects from all age groups protected their optimised task's accuracy across the performance standard levels (Figures 3A and B, middle graphs, filled symbols). Note also that the older group had higher optimised Planikin accuracy and lower optimised Planikin omission than their equal-priority Planikin performance (Figure 3B middle and bottom graphs and Table 3). They also had poorer maximized Sternberg accuracy and higher maximized Sternberg omission than their equal-priority Sternberg performance.

⁵Standardizing the RT was especially helpful in the differential-priority condition because RT reflected not only the demand of the individual task but also its priority. For example, if the raw optimised Sternberg RT was faster than the maximized Planikin RT, it could reflect a true priority effect or simply that the Sternberg task naturally required less processing time. Similarly, if the raw optimised Planikin RT was slower than the maximized Sternberg RT, it could reflect a violation of task priority or simply that the Planikin task required more processing time. Analysis of the raw performance was reported in Tsang et al. (2003) and produced essentially the same statistical results.

When the Sternberg task was optimised (Figure 3A), no tradeoff was observed in RT (top graph). Reaction time of both tasks improved with higher optimised standards. An Age x Priority x Performance Standard Level interaction however was observed in accuracy ($F(4, 90) = 2.99, p < .05$, G-G $p < .1$, $MSE = 17.62$, middle graph). The high level of optimised accuracy (filled circles) across the optimised standards for the young group and the older group showed that their optimised RT was not a result of a speed-accuracy tradeoff. However, the young group's maximized accuracy (open triangles) degraded with increased optimised standards, suggesting a potential speed-accuracy tradeoff in their maximized RT. The middle-aged group exhibited a classic performance tradeoff in accuracy.

When the Planikin task was optimised (Figure 3B), the Priority x Performance Standard Level interaction was reliable for RT ($F(2, 90) = 25.20, p < .0001$, $MSE = .45$) and accuracy ($F(2, 90) = 5.32, p < .01$, $MSE = 45.77$) and marginally so for omission ($F(2, 90) = 3.0, p < .06$, G-G $p < .1$, $MSE = 4.99$). All subjects protected their optimised accuracy across the performance standard levels (flat lines across the filled triangles in the middle graph). Maximized accuracy degraded (open circles, middle graph) and maximized omission increased (open circles, bottom) with increased standards. No speed-accuracy tradeoff was evident in any measures. However, an Age x Priority x Performance Standard Level interaction showed that only the young exhibited a reliable RT tradeoff ($F(4, 90) = 8.99, p < .0001$, $MSE = .45$, top).

Task priority was found to moderate the effect of the Sternberg task's response modality. The manual task pair had poorer performance than the speech task pair, as in the equal-priority condition. But it was the low-priority maximized task that showed a greater modality effect regardless of whether the Planikin or Sternberg task was maximized (Figure 4). This trend was observed in the RT, accuracy, and omission measures even though the Priority x Modality interaction was significant only in the RT ($F(1, 45) = 25.54, p < .0001$, $MSE = .22$; top graph) and omission ($F(1, 45) = 11.99, p < .001$, $MSE = 6.19$) measures when the Planikin task was maximized. Also, the tendency towards a larger modality effect in the maximized task increased with age. A reliable Age x Priority x Modality interaction was observed in the RT measure when the Planikin task was maximized, ($F(2, 45) = 5.16, p < .01$, $MSE = .22$, Figure 5, top) and the same trend was observed when the Sternberg task was maximized (bottom).

While there was significant practice effect, no differential practice effects across age groups were observed. There were also indications that the older subjects were making an effort to improve their performance in a direction consistent with the priority instructions. When the Sternberg task was optimised, the two older groups increased their maximized omission especially in the manual dual task ($F(6, 135) = 3.29, p < .01$, $MSE = 3.67$) over practice more than the young group. When the Planikin task was optimised, practice improved the older group's optimised accuracy ($F(6, 135) = 3.340, p < .01$, $MSE = 53.95$) and reduced their optimised omissions for the manual condition more than the young group ($F(6, 135) = 3.23, p < .01$, $MSE = 10.98$).

Conformance to the optimised performance standards—An age-related specific difficulty in the executive control should be particularly evident in the differential-priority

condition because of the precision of control required. Further, according to the resource account, allocation control is a skill that should improve with practice. In the present context, attentional control referred to the extent to which the subject could perform at an externally imposed performance level. To examine this, *optimised scores* were obtained by taking the difference between the optimised performance and the individualized performance standard for each subject. A zero optimised score across the performance standards would indicate perfect attentional control. *Maximized scores* were obtained by taking the difference between the maximized performance and the subject's best equal-priority dual-task performance for that task condition. Optimised and maximized scores were analysed in separate Block x Age x Modality x Performance Standard Level ANOVAs.

First, significant age effects on the optimality of attentional control were observed. The fan-shaped graphs in Figures 6A and B (left) show that departure from the optimised standards in both speed and accuracy increased with age. The older groups did not simply perform poorer than their optimised single-task standard (large, positive optimised scores), they also performed better than necessary for their dual-task standard (negative scores).

When the Sternberg task was optimised (Figure 6A), even though the two older groups' optimised RT and accuracy did not reach the higher standards (left), their maximized RT was faster than needed to be (large negative RT maximized scores, top right). When the Planikin task was optimised (Figure 6B), the young group maintained their optimised performance relatively close to their standards (left) but at a considerable cost to the maximized task RT (top right). The two older groups were less successful at meeting their optimised standards and exhibited little compensation in their maximized performance. The Age x Performance Standard Level interaction was reliable for all the optimised scores (Sternberg RT: $F(4, 90) = 6.95, p < .0001, MSE = 240056.60$; Sternberg %C: $F(4, 90) = 3.86, p < .01, MSE = 34.80$; Planikin RT: $F(4, 90) = 8.64, p < .0001, MSE = 387317.16$; Planikin %C: $F(4, 90) = 5.52, p < .001, MSE = 33.37$).

Second, all age groups became better able to adhere to their optimised standards with practice (Figure 7). Departure from the optimised performance standards diminished with practice and converged toward the zero optimised score (SB RT: $F(6, 270) = 14.26, p < .0001, MSE = 38955.43$; SB %C: $F(6, 270) = 2.07, p < .06, G-G p < .1, MSE = 26.17$; PL RT: $F(6, 270) = 2.97, p < .01, G-G p < .1, MSE = 60202.02$; PL %C: $F(6, 270) = 2.67, p < .05, G-G p < .1, MSE = 18.46$). No differential practice effects among the age groups were observed.

Summary—The global priority effect was as expected with the high-priority, optimised performance being superior to the low-priority, maximized performance (Figure 3). Significant age effects were found but performance tradeoff was not consistently observed. Except for a hint of performance tradeoff in the accuracy measure in the two younger groups, no tradeoff was observed when the Sternberg task was optimised. Performance tradeoffs were more generally observed when the Planikin task was optimised but RT tradeoff was observed only for the young group (Figure 3B). Significant age effect was also observed with attentional control. Departure from the optimised performance standards increased with age (Figure 6) but diminished with practice for all age groups (Figure 7).

Further, task priority moderated the modality effect with the low-priority task bearing the burden of dual manual responses (Figure 4), especially for the older groups (Figure 5). Of note, although significant age effects were observed, all subjects improved substantially with practice in a direction consistent with the priority instructions.

Strategic Time-Sharing

Three sets of analyses examined whether subjects varied the percentage of responding to one task first in order to produce an averaged reaction time that would match their performance standards. This could produce an apparent decrement in both tasks that might be interpreted as supporting the resource account. Further, if subjects varied the percentage of time responding to one task first depending on the optimised performance standard level, this could produce an apparent graded averaged RT across the performance standard levels. To check this, response to the individual stimulus was examined. The first set of analysis examined the propensity with which one task was completed prior to the other. *Completing a task first* here did not presuppose that the task was sequentially responded to first or that the task simply required less processing time. Since the Sternberg task naturally had faster RT than the Planikin task (Table 3), a high propensity of completing the Sternberg task first would be expected at least in the equal-priority condition. The second set of analysis examined the time-sharing performance of known response order. These results could not possibly be due to the averaging of response times of tasks being responded to sequentially in different orders. The third set identified five time-sharing strategies based on the interresponse intervals (IRIs) that afforded a micro examination of the propensity of sequential and shared processing strategies used. Because the bottleneck model mandates sequential access to the bottleneck, shared processing could be accommodated only by the resource model. The data in this section were based on a maximum of 70 datapoints (2 trials x 35 stimuli) for each condition for each subject. Cases in which the response to either task component was incorrect were excluded.

Propensity of completing the Sternberg task first—The equal-priority condition was examined by a Block (E2, E5) x Age x Modality ANOVA. The percentage of time that the Sternberg task was completed first (%SB) was over 91% late in practice. No age or modality effect was detected.

The differential-priority condition was examined by a Block (D2, D4) x Age x Modality x Priority x Performance Standard Level ANOVA. The Sternberg task was mostly completed first but %SB was moderated by age, task priority, response modality of the Sternberg task, and practice. Figure 8 displays a Block x Age x Priority x Performance Standard Level interaction, $F(4, 90) = 2.84, p < .05$, G-G $p < .1$, $MSE = 195.42$. The Sternberg task was completed first more often when optimised than when maximized. The optimised Sternberg task was completed first more often with higher Sternberg performance standard. The maximized Sternberg task was completed first less often with increased Planikin performance standard, especially late in practice (contrast top and bottom graphs). This was most evident in the young group.

Interestingly, the Sternberg task was completed first less often in the manual than in the speech task pair only when it was of low priority (Figure 9; $F(1, 45) = 9.77, p < .01, MSE = 458.08$). These results showed that the Priority x Modality interaction in the optimised SB RT (Figure 4, top) could not be attributed solely to a variation in the percentage of time responding to the Sternberg task first, and thereby the percentage of time responding to the Planikin task second, because the %SB remained the same across modalities (Figure 9, Opt SB).

Time-sharing performance of known response order—This section examines only those instances in which the Sternberg task was completed first. Due to the very high %SB, there were insufficient data (empty cells) for analysing the Planikin first responses. The equal-priority results are not presented here because they closely resembled those with no regard to the order of task completion (presented above) due to the very high %SB. The optimised Sternberg and optimised Planikin conditions were analysed separately by Block (D2, D4) x Age x Modality x Performance Standard Level ANOVAs. In addition to RTs, interresponse intervals (IRIs) were examined. The IRIs were obtained by subtracting the Sternberg RT from the Planikin RT for each stimulus. A positive IRI resulted when the Sternberg RT was faster than the Planikin RT.

When the Sternberg task was optimised, two subjects were excluded from the analyses due to insufficient data. One young subject used primarily a response grouping strategy; one older subject completed the Planikin task first in all conditions (the only subject in the study). As with the full analysis (Figure 3A, top), the higher the Sternberg performance standard, the faster both the optimised Sternberg (Figure 10A) and maximized Planikin (Figure 10B) RT. With practice, RT became more differentiated across the performance standard levels (optimised Sternberg: $F(2, 86) = 9.61, p < .0001, MSE = 16644.30$; maximized Planikin: $F(2, 86) = 6.56, p < .01, MSE = 21505.99$).

Importantly, although Sternberg and Planikin RT changed in the same direction across the performance standards, they did not change by the same extent. An Age x Block x Performance Standard Level interaction showed that late in practice for the young and older groups but not the middle-aged group, IRI increased with higher Sternberg standards (Figure 10C, $F(4, 86) = 3.06, p < .05, G-G p < .1, MSE = 5664.72$). Because IRIs were obtained by subtracting the Sternberg RT from the Planikin RT, algebraically, IRIs could be increased by a faster Sternberg RT, a slower Planikin RT, or both, as would be expected with increased Sternberg priority.

When the Planikin task was optimised, 13 subjects (10 young and 3 older) were excluded due to insufficient data. As shown in Figure 8, young subjects were less likely to complete the Sternberg task first when the Planikin task was optimised (Max SB). For the remaining subjects, the higher the performance standard, the faster the optimised Planikin RT (Figure 10E, $F(2, 64) = 4.86, p < .05, MSE = 46995.49$) and the shorter the IRI especially late in practice (Figure 10F). Although not statistically significant, the IRI became more differentiated across the standards over practice. Algebraically, a shorter IRI here would have been produced by a faster Planikin RT, a slower Sternberg RT, or both, as would be expected with increased Planikin priority. Figure 10E further shows that although the older

group became generally faster with practice, they did not adjust their response times according to the standards as much as the two younger groups, $F(4, 64) = 5.20, p < .001, MSE = 46995.49$.

In summary, the Sternberg task was mostly completed first in the equal-priority condition. In the differential-priority condition, there was a clear distinction between the global optimised and maximized conditions. Differentiation across the performance standards indicative of a more precise allocation control increased with practice (Figure 8). Importantly, the Priority x Modality interactions showed a poor correspondence between the propensity of completing the Sternberg task first and the resultant reaction times (Figures 4 and 9). Further, with most of the young subjects excluded when the Planikin task was optimised and when only the Sternberg first responses were examined, performance tradeoff in RT was not observed as in the full analysis above. Nevertheless, late in practice, graded changes in the IRI across the performance standards (Figures 10C and F) suggested subtle graded performance changes that were not apparent in the averaged reaction times for the trial. Notably, the two younger groups became better at adjusting their optimised Planikin performance in accordance to the externally imposed standards with practice but not the older group (Figure 10E). That this age effect was detected in the differential-priority but not in the equal-priority condition lent further support to an age-specific difficulty in time-sharing and not just with the complexity of performing multiple tasks.

Time-sharing strategies—Each subject was characterized by the strategy that he or she adopted under the various priority conditions for each task pair. The strategies were characterized by the distribution of the interresponse intervals that were placed into 200 ms bins⁶. The zero IRI bin spans from -100 ms to +100 ms. Recall that a positive IRI resulted when the Sternberg RT was faster than the Planikin RT. Figures 11 and 12 present sample histograms⁷ of the various time-sharing strategies. Five strategies were identified: (a) Sternberg First, (b) Planikin First, (c) Mixed, (d) Response Grouping, and (e) Priority Dependent.

The Sternberg First strategy was to always complete the Sternberg task first. This was characterized by having only positive IRIs (Figure 11A). The Planikin First strategy was to complete the Planikin task first, characterized by negative IRIs (Figure 11B). The Mixed strategy was one in which the Sternberg task and the Planikin task was each completed first some of the time. Both unimodally distributed IRIs spanning the zero IRI bin and bimodally distributed IRIs with a break at the zero IRI bin were included in this strategy. But only a bimodal distribution of IRIs (Figure 11C) would be indicative of sequential processing of the two tasks: responding to one task first some of the time and responding to the other task first the rest of the time (Pashler, 1994). The Response Grouping strategy entailed making two responses at practically the same time with IRIs concentrating around the zero IRI bin (Figure 11D).

⁶Although the 200 ms cutoff was somewhat arbitrary, no dual-task standard deviation for any age group was smaller than 200 ms late in practice for any task in any priority condition. The 200 ms cutoff was also one that had been used in the literature (e.g., Tombu & Jolicœur, 2005; Ulrich & Miller, 2007).

⁷Each sample histogram was based on two trials of responses from a single subject. Additional samples can be found in Tsang et al. (2003).

The Priority Dependent (PD) strategy applied only in the differential-priority condition. Here, the response patterns depended on task priority or the performance standard level. Three variants were identified. One variant was the *PDs* strategy whereby the optimised Sternberg task was completed first. Sample histograms are presented in Figure 12 (left). Note that as the Sternberg performance standard increased, the IRI distribution as a whole shifted right from mostly in the 500–900 ms bins for the lowest standard (bottom) to mostly in the 700–1100 ms bins for the highest standard (top). In other words, IRIs increased with increased Sternberg standards. As noted above, IRIs could be increased by quickening the Sternberg RT and/or slowing the Planikin RT. These changes could not be produced by varying the percentage of responding to the Sternberg task first because the entire IRI distribution was to the right of the zero bin meaning that the Sternberg task was consistently completed first for this sample.

Another Priority Dependent variant strategy was the *PDp* strategy whereby the Planikin task was completed first consistently. Completing the Planikin task first would produce negative IRIs and the entire IRI distribution would be to the left of the zero IRI bin. With this strategy, the IRI distribution as a whole shifted to the left with higher Planikin performance standards. The higher the standard, the longer the IRI (larger negatives). Algebraically, a longer IRI could be produced by a faster Planikin RT, and/or a slower Sternberg RT, as would be expected for increased Planikin priority.

A third Priority Dependent variant strategy was the *PDI* strategy whereby the optimised task was completed first for the higher performance standard(s) but then subjects shifted to completing the other task first for the lower standard(s). The histograms on the right side of Figure 12 illustrate an optimised Planikin condition. The Planikin task was completed first for the highest Planikin standard (mostly negative IRIs on top) but the Sternberg task was completed first for the lowest Planikin standard (mostly positive IRIs at the bottom). Importantly, even though the middle histogram shows a mixture of completing the Sternberg task and Planikin task first some of the time for the averaged performance standard level, the unimodal IRI distribution that spanned across the zero bin was not consistent with a sequential processing of the two tasks.

Table 4 displays the prevalence of the various strategies adopted late in practice. Since whether both tasks required a manual response did not produce systematic differences in the choice of strategy, averages for the two task pairs are displayed. For the equal-priority condition, the Sternberg First strategy was by far the most common strategy adopted across age groups (> 84%). When the Sternberg task was optimised, the Sternberg First strategy was also prevalent across age groups (65% – 88%). The next most prevalent was the Priority Dependent, *PDs*, strategy (9%–19%). When the Planikin task was optimised, a greater variation across age groups as well as within an age group was observed. Most of the young subjects (87.5%), half of the middle-aged subjects (50%), and one fourth of the older subjects (25%) adopted the Priority Dependent strategy. Among the Priority Dependent strategies, the *PDI* strategy (Figure 12, right) was the most prevalent for the young and older groups; the *PDs* (Figure 12, left) was the most prevalent for the middle-aged group. Almost 50% of the older subjects continued to use the Sternberg First strategy when the Planikin task was optimised, none of the young subjects did.

In summary, the Sternberg First strategy was the overwhelmingly chosen strategy in the equal-priority condition with no apparent age effect. A wider variety of strategies and a greater age-related variance were observed in the differential-priority condition especially in the optimised Planikin condition. The variety of the time-sharing strategies observed showed that subjects did not universally respond to the high-priority task first. Beside the Sternberg First strategy, the Priority Dependent strategy was the next most prevalent. An important feature of the Priority Dependent strategy was the graded shift of the unimodal IRI distribution as a whole as the performance standard levels varied. Notably, response grouping and sequential processing were rarely used. Last, response modality of the Sternberg task did not appear to contribute systematic variation to the time-sharing strategies adopted.

Discussion

Two major attention views suggest that different mechanisms underlie the often substantial age-related decrement in dual-task performance: (a) an age-related larger bottleneck, or (b) a loss in resource processing efficiency and reduced attentional control. The compatibility of the present results with these mechanisms is examined for a better understanding of the age-related difficulties with time-sharing and the workings of the attention system.

Performance Decrement in the Equal-Priority Condition

Substantial dual-task decrement was observed in both tasks (Table 3, Figure 2). With the PRP paradigm, only Task 2 was expected to be significantly delayed compared to the single-task condition and Task 1 should suffer little interference from the other task. In the literature, when a Task 1 effect was observed, it was commonly attributed to several nonattentional factors such as response grouping, failure to follow instructions to respond to Task 1 first, or task uncertainty (e.g., Allen et al., 1998; Hartley & Little, 1999; Pashler & Johnston, 1998; Ulrich & Miller, 2007). But none of these factors could easily account for the present results.

First, response grouping was rare in the present data (Table 4). Tombu and Jolicoeur (2005) also found that response grouping could not explain the Task 1 effect that they observed with IRI bins as short as 50 ms. Second, a substantial Sternberg RT decrement was observed even when it was completed first and the magnitude of the decrement increased with age. Third, the task uncertainty hypothesis seemed improbable in the present context. Task uncertainty could be engendered when two simultaneously presented tasks afforded opportunities for responding to each task first some of the time. Such sequential processing would be characterized by a bimodal IRI distribution. But bimodal IRI distributions were extremely rare in the present data. Further, the very high propensity of completing the Sternberg task first suggested that subjects did not deliberate which task to respond to first in every instance.

In short, the substantial Task 1 decrement presently observed could not be accounted for easily by the bottleneck model, rendering a larger bottleneck account for the age-related dual-task decrement improbable. In contrast, that performance decrement was observed in both tasks was quite compatible with a resource competition explanation. The larger age-

related decrement observed could be accounted for easily by the confluence of resource competition in the dual-task condition and an age-related reduction in processing efficiency.

Executive Control in the Differential-Priority Condition

Time-sharing requires more than the sum of performing multiple single tasks and involves additional coordination and resource management however resource might be defined (e.g., Salthouse, Atkinson, & Berish, 2003). Although there is not yet a consensus, there are both behavioural (e.g., Bourke, Duncan, & Nimmo-Smith, 1996; Gopher, 1993) and neurophysiological (e.g., D'Esposito et al., 1995; Just, Carpenter, & Miyake, 2003; Newman et al., 2007) support for a unique time-sharing skill. There also appears to be mounting behavioural (e.g., Bherer et al., 2008; Hein & Schubert, 2004; Kramer & Madden, 2008; Salthouse et al., 2003; Salthouse & Miles, 2002; Sverko, Maslic-Sersic, Zeljko, & Gurdulic-Sverko, 1994; Verhaeghen et al. 2003) and neurophysiological (e.g., Erickson et al., 2007; Kramer & Madden, 2008; Voelcker-Rehage, & Alberts, 2007; West, 1996) support for an age-specific decline in executive control. Further support for age-related difficulties in the executive control can be gleaned from the present results.

Graded performance tradeoff—Reduced performance tradeoff for the older subjects was most evident in the RT when the Planikin task was optimised (Figure 3B, top). This age effect could not be attributed to a general performance superiority of the young group because performance standards were individually determined. Also, as shown in the figure, the young attained their high-priority (optimised) task's performance standard by sacrificing their low-priority (maximized) performance. Their performance tradeoff could not be attributed to a speed-accuracy tradeoff (Figure 3B) or to a deliberate tactic that varied the percentage of times of responding the Sternberg task first in order to produce an average reaction time that would match their performance standards. Zero percent of the young group used the Sternberg First strategy when optimising the Planikin task and no bimodal IRI distribution was observed (Table 4).

Optimality in allocation control—Age difference in the precision of allocation control was most evident in Figure 6. Departure from the individually determined optimised standards increased with age. In some cases, large departure from the standard was a result of the older subjects surpassing the standards. Note that the young group's more precise adherence to the performance standards did not come free. In the optimised Planikin condition, the higher the optimised standard, the larger the toll on the maximized RT (Figure 6B, top). That is, the young appeared to be more actively apportioning their attention to the time-shared tasks according to task priorities.

Strategic time-sharing—An increasing number of dual-task studies are demonstrating the strategic nature in time-sharing. For example, Miller et al. (2009) showed that although a serial mode of processing may be the more efficient mode in many contexts, subjects could shift to a parallel processing mode in certain situations such as when the time-shared tasks are presented in close temporal proximity. Age differences in response to changing task demands have also emerged. For example, Glass et al. (2000) found older adults to use a more cautious task coordination strategy than younger adults to avoid task conflicts. Prakash

et al. (2009) found older adults to lack the sensitivity and flexibility of the young adults' neuronal response to increased attentional control conflicts.

Similarly, the present results showed that the older subjects were less adaptive than the young subjects to the changing task priorities. In the equal-priority condition, no age effect was detected in that subjects of all ages exhibited a similarly high propensity of completing the Sternberg task first. In the differential-priority condition when the faster Sternberg task was optimised, subjects of all ages tended to complete the Sternberg task first and more young subjects than older subjects adopted the Priority Dependent strategy, characterized by a unimodal IRI distribution that shifted in a graded fashion with varying performance standards (Figure 12). When the slower Planikin task was optimised, subjects did not simply complete it first. Most of the young subjects and half of the middle-aged subjects used the Priority Dependent strategy. But almost 50% of the older subjects continued to complete the Sternberg task first. However, this was not necessarily due to a complete lack of control but a reflection of their Planikin RT being substantially slower than their Sternberg RT (Table 3). Given that the older subjects showed significant performance improvement in a direction consistent with task instructions (e.g., Figure 7) their allocation nonoptimality would not be due to a lack of motivation or effort.

Of note, the rarity of the Mixed strategy with a bimodal IRI distribution detected in any age group suggested that sequential processing of the two tasks was rarely used, providing little support for an obligatory serial bottleneck. Other researchers also have found that a serial response selection processing is not obligatory under a variety conditions, (e.g., Hazeltine et al., 2002; Hazeltine, Ruthruff, & Remington, 2006; Luria & Meiran, 2005; Watter & Logan, 2006).

Response Modality Effects

Consistent with a common finding in the dual-task literature (e.g., McLeod, 1977; Pashler, 1990; Tsang, 1997; Tsang & Wickens, 1988; Vidulich, 1988; Wickens, 1976), the present manual task pair incurred greater dual-task decrement than the speech task pair. Because response modality should not affect response selection, auxiliary assumptions to the response selection bottleneck model have been proposed to account for modality effects. For example, Pashler (1990) proposed an "additional response-programming-related factor" (p. 840) when the order of two manual responses was ambiguous as in the present zero SOA condition. But the preponderance of the Sternberg first responses in the present data suggested minimal deliberation about which task to respond to first and thereby minimal constant response reprogramming.

Of particular interest here is the Age x Task x Modality interaction in the dual-task performance decrement (Figure 2). The modality effect was particularly prominent in the Planikin task of the manual task pair for the older subjects. This result cannot be reconciled with a larger bottleneck at the response selection stage because a change in the response modality should not have altered the response selection demand. Also, the disproportionately large Planikin decrement for the older subjects was larger than could be accounted for by a propagation of the longer manual Sternberg response to the Planikin task (see Table 3).

To account for the larger age effect associated with bimanual responses, Hartley (2001) proposed an age-related difficulty in generating and executing two similar responses. But such a mechanism cannot explain why, in the differential-priority condition, it was the low-priority task that bore a greater burden of the bimanual responses, regardless of whether it was the Sternberg or Planikin task. This was especially so for the older subjects (Figure 5). The interaction with task priority—an instructional variable that could not have altered the tasks, strongly suggested an effect that was subject to voluntary control rather than to an obligatory bottleneck.

The present results in fact are quite compatible with a parsimonious account of the structure-specific resource model that proposes distinct processing resources for manual and speech responses. In the equal-priority condition, the Age x Task x Modality interaction (Figure 2) is consistent with a confluence of increased task demand (a more difficult Planikin task), heightened resource competition (increased structural similarity), and an age-related reduction in processing efficiency. In the differential-priority condition, the Age x Priority x Modality interaction (Figure 5) is easily explained by the subject's attempt to allow the low-priority task to bear the burden of the heightened manual resource competition. Having received less attention, the low-priority task would be especially hurt by an age-related reduced processing efficiency. Along the same vein, Lee, Wishart, and Murdoch (2002) suggested that bimanual coordination was especially attention demanding for older adults. Lindenberger, Marsiske, and Baltes (2000) proposed that motor behaviour might incur increasing need of cognitive control, but that the efficiency of cognitive control might decrease with advancing age.

Cognitive Plasticity in Older Adults

Although substantial age effects were observed in the present results, note that the present tasks were extraordinarily demanding (as evidenced by the magnitude of the response times, the magnitude of dual-task decrement, and the amount of practice required to stabilize performance). In addition, two aspects of the experimental tasks--spatial processing (e.g., Hertzog, Vernon, & Rypma, 1993; Horn & Masunaga, 2000) and bimanual responses--have been known to be particularly age sensitive. The time-sharing demand was also unusually high due to the precision of control required. There was not simply a dichotomous global priority condition but also three graded performance standards for the optimised task. In addition, extremely demanding performance standards were used for the optimised task and only performance very close to the standards received bonus points. These are not requirements that are likely to be encountered on a daily basis or in a normal job situation. Rather, the requirements were designed to highly stress a system in order to reveal the underlying operating mechanism.

Importantly, substantial practice effects were observed for subjects of all ages. In the equal-priority condition, the older groups reduced their dual-task decrement by an extent similar to that of the young group. In the differential-priority condition, older subjects did not have any difficulty managing the global task priority; their high-priority performance was generally superior to the low-priority performance, as was observed in the young subjects. The age-related difficulty was mostly related to the precision required to manage the graded

performance standards. The older subjects departed from their optimised performance standards more than the young (Figure 6) but they exhibited similar converging trends to conforming to the optimised standards as the young (Figure 7).

Notably, whereas there was little distinction between the middle-aged and older groups in the single-task and equal-priority task conditions, distinction between them became noticeable in the differential-priority condition especially when the Planikin task was optimised. By the end of practice, middle-age subjects exhibited differentiation of the performance standards for the optimised task similar to that of the young subjects, but not the older subjects (Figure 10E & F). The substantial practice effects observed strongly suggested that time-sharing is a trainable skill. It is possible that extended training or other training regimens could improve the attentional control of the older subjects further. Here, Bherer et al.'s (2008) and Kramer et al.'s (1999) success with the adaptive and variable-priority training is particularly encouraging.

Implications on the Attention Mechanisms

Two attentional mechanisms were examined for their ability to account for the age-related difficulties in dual-task performance. There were signature predictions from both attention mechanisms that were not met in the present results. At odds with the bottleneck's prediction, a significant Task 1 effect was observed. At odds with the resource's prediction, performance tradeoff was observed only in a subset of the experimental conditions. However, the ability of the two attention mechanisms to account for dual-task performance does not appear to be age-dependent. That is, the age-related difference does not appear to be one effected via different attentional mechanisms.

Voluntary sequential processing?—Contrary to the tenet of the structural immutable bottleneck model, the present data suggest that sequential processing in a dual-task condition may be voluntary rather than obligatory. The major indicators of sequential processing in a PRP paradigm include a significant Task 2 delay, minimal Task 1 delay, and a bimodal IRI distribution. But these results also could be produced by subjects meeting the demand characteristics of the PRP paradigm (Meyers & Kieras, 1997; Navon & Miller, 2002). To heed these concerns, the present study used a zero SOA to avoid asynchronous availability of the stimuli, copious instructions to process the tasks simultaneously, and a point system designed to reward superior performance in both tasks. The results were that significant decrement was observed in both tasks but a bimodal IRI distribution was rarely observed. Similarly, Tombu and Jolicoeur (2002; 2005) observed a Task 1 effect when simultaneous processing was encouraged with no restriction on the order of response. Other studies also have reported that parallel processing at response selection is possible (e.g., 2Hazeltine et al., 2002; Watter & Logan, 2006). In fact, Miller et al. (2009) showed that although sequential processing could be strategically advantageous in many task situations, it is not obligatory.

Dual-task increment?—Performance tradeoff as a function of task priority is a signature prediction of the resource account. The present study adopted the optimum-maximum method (Navon, 1990) to avoid procedures that could lead subjects to expect performance to

tradeoff (e.g., Navon, 1984). Graded performance tradeoffs were observed with this method previously with young (Tsang, Velazquez, & Vidulich, 1996) and older subjects (Tsang & Shaner, 1998). But in the present study, performance tradeoff was observed only in the young group when the Planikin task was optimised (Figure 3B). One possible explanation is the combination of the very high demand of the tasks and the poor allocation control of the older subjects. However, this could not account for the general absence of performance tradeoff even in the young group when the Sternberg task was optimised (Figure 3A). This issue was addressed at length in Tsang (2006) with additional analysis that focused on the young group's data. A summary of that discussion will be presented here because the logic can be extended to the present data that include older subjects.

At first glance, it appeared that a bottleneck mechanism might be better able to account for the optimised Sternberg RT data with both the optimised and maximized performance quickening with increased Sternberg performance standards. This performance pattern resembled the classic carryover effect from Task 1 to Task 2 in a PRP paradigm. The sooner the bottleneck was released by Task 1 (Sternberg), the sooner Task 2 (Planikin) could be responded to. But two aspects of the data were problematic. One, even though the Sternberg task was mostly completed first, it suffered significant dual-task decrement (Figure 2). Two, the bottleneck mechanism would predict a fairly constant interresponse interval across performance standards because the bottleneck access should be all or none. But Figure 10C displays a trend that suggested a gradual shift in the IRIs in a direction consistent with a concomitant quickening of the Sternberg RT and a slowing of the Planikin RT with higher Sternberg standards. Although only a portion of the subjects adopted the Priority Dependent strategy that entailed graded changes in the IRI (Table 4), no bimodal IRI distribution indicative of sequential processing was detected when the Sternberg task was optimised.

A plausible resource account can be attributed to the differential amount of processing time required for the two tasks. Because the Sternberg task could be processed much faster than the Planikin task, it would be most natural to make every effort to meet the optimised Sternberg performance standards. The higher the standard, the more resources would be allocated to the Sternberg task and the sooner it could be completed. Resources could then be dedicated to the Planikin task and the sooner it could be completed. The considerable "Task 1" decrement even in the optimised Sternberg condition suggested that subjects were following the instructions to process both tasks without abandoning the low-priority task. In addition, that the IRIs changed in the opposite direction across the performance standards depending on whether the Sternberg task (Figure 10C) or the Planikin task (Figure 10F) was optimised suggested an active control in response to the graded task priority.

Conclusion

The present results provided little support for the notion of a larger response selection bottleneck as a primary source of age-related dual-task difficulties. The especially large age-related dual-task decrement in Task 2 (second to complete or low-priority task) was as predicted by the age-related larger bottleneck mechanism. But the Task 1 effect was not. Further, the especially large bimanual decrement for the older subjects in the equal-priority condition and the Age x Modality x Priority interaction in the differential-priority condition

could not be explained easily by the response-selection bottleneck mechanism without auxiliary assumptions of additional mechanisms. This of course did not mean that sequential processing did not or could not occur, only that it was not obligatory and other explanations would be needed for when sequential processing was not the dominant mode of processing.

The present findings showed that the structure-specific resource view could ably account for: (a) a substantial age-related decrement in both time-shared tasks; (b) an exaggerated age-related response modality effect; (c) an exaggerated age-related modality and priority interaction; (d) age-related differences in the graded performance as evident in performance tradeoffs, optimality of allocation control, strategic response to varying task priorities, and (e) practice effects on allocation control. Overall, these results support an age-related reduction in resource processing efficiency and attentional control optimality.

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Figure 1.
One of sixteen possible orientations of the experimental stimulus.

Figure 2.

Older subjects had larger dual-task decrement in the Planikin task especially when it was time-shared with the manual Sternberg task in the equal-priority condition. SB = Sternberg task, PL = Planikin task, RT = reaction time.

Figure 3.

A. Optimised Sternberg. B. Optimised Planikin. Age x Priority and Performance Standard Level effects averaged over the two task pairs late in practice (Block D4). Performance tradeoff is indicated only when the Planikin task was optimised. SB = Sternberg task, PL = Planikin task, Opt = optimised, Max = maximized, RT = reaction time.

Figure 4.

Response modality of the Sternberg task affected the low-priority task more than the high-priority task regardless of whether the Sternberg or Planikin task was maximized. SB = Sternberg task, PL = Planikin task, Opt = optimised, Max = maximized, RT = reaction time.

Figure 5.

Response modality affected the maximized performance more than the optimised performance especially for the older groups. SB = Sternberg task, PL = Planikin task, Opt = optimised, Max = maximized, RT = reaction time.

Figure 6.

A. Optimised Sternberg. B. Optimised Planikin. Departure from the optimised standards increased with age late in practice. A zero optimised score indicates perfect attentional control (i.e., the optimised performance matched the standard). A zero maximized score indicates that the maximized performance was the same as the equal-priority dual-tasks performance. SB = Sternberg task, PL = Planikin task, S, A, D = single-task, average, dual-task performance standard respectively, RT = reaction time, %C = percentage correct.

Figure 7.

Optimised performances converged toward optimality with practice. A zero optimised score indicates perfect attentional control (i.e., the optimised performance matched the standard). S, A, D = single-task, average, dual-task performance standard respectively, RT = reaction time, %C = percentage correct.

Figure 8.

The optimised Sternberg task was mostly completed first. The young group reduced the frequency of completing Sternberg first when it was maximized, especially when the other task was optimised at a higher performance standard level (Max SB). Practice further reduced the frequency of completing the maximized Sternberg task first. SB = Sternberg task, Opt = optimised, Max = maximized.

Figure 9.

Response modality of the Sternberg task affected the percentage of time that the Sternberg task was completed first when the task was of low-priority. SB = Sternberg task, Opt = optimised, Max = maximized.

Figure 10.

A–C Optimised Sternberg. D–F Optimised Planikin. Age x Block x Performance Standard Level interactions when the Sternberg task was completed first in the differential-priority condition. The interresponse interval (IRI) changed in different directions across the performance standards depending on which task was optimised. Early = early in practice (Block D2), Late = late in practice (Block D4), RT = reaction time.

Figure 11.

Sample time-sharing strategies. A. Sternberg First. B. Planikin First. C. Mixed. D. Response Grouping. Vertical dashed line indicates zero IRI (interresponse interval).

Figure 12.

Variants of the Priority Dependent strategy. On the left, the Sternberg task was always completed first (PDs) and the IRI distribution systematically shifted to the right with increasing performance standard. SBs, SBa, SBd = optimising the Sternberg task with single-task, average, and dual-task standard respectively. On the right, the task completed first depended on the performance standard level (PDI). PLs, PLa, PLd = optimising Planikin with single-task, average, and dual-task standard respectively. Vertical dashed line indicates zero IRI (interresponse interval).

Table 1

Subjects' Characteristics

Background Variable	Young			Middle			Older		
	<i>M</i>	Range	<i>SD</i>	<i>M</i>	Range	<i>SD</i>	<i>M</i>	Range	<i>SD</i>
Age	23.50	19–27	2.25	54.69	50–59	3.03	64.38	60–70	3.38
Education	16.00	14–18	1.55	16.63	14–19	1.54	16.44	13–20	2.28
Digit Span	20.06	13–27	3.92	15.31	9–22	3.63	15.94	11–24	3.92
Digit Symbol	70.25	57–83	8.39	60.63	41–70	8.04	55.06	39–83	9.18
APM ^a	27.56	20–34	3.67	19.31	11–26	4.44	19.06	9–29	6.69

Note. APM^a = Advanced Raven Progressive Matrix.

Table 2

Experimental Procedure Overview

Session					
1	2	3	4	5	6
S1	S3	S4	D2	D3	D4
E1	E3	E4			
S2	D1	S5			
E2		E5			

Note. S = single-task block; E = equal-priority dual-task block; D = differential-priority dual-task block.

Table 3

Single-Task and Equal-Priority Dual-Task Performance Late in Practice

Performance Measures	Young	Middle	Older
Single-task performance			
Planikin (PL)			
RT (ms)	1,145	1,788	1,882
%C	98.19	94.71	90.35
%O	0.00	0.04	0.42
Sternberg (mSB)			
RT	856	1,400	1,523
%C	97.75	94.66	92.94
%O	0.00	0.06	0.13
Sternberg (sSB)			
RT	952	1,256	1,354
%C	98.25	96.06	94.06
%O	0.00	0.00	0.19
Dual-task performance			
PL-mSB			
PL RT	1,770	2,841	3,030
PL %C	97.84	91.19	84.47
PL %O	0.00	1.88	5.19
SB RT	1,310	1,946	2,174
SB %C	97.84	91.03	90.00
SB %O	0.00	0.41	1.06
PL-sSB			
PL RT	1,758	2,576	2,872
PL %C	97.38	91.00	85.47
PL %O	0.00	0.69	3.60
SB RT	1,263	1,698	2,148
SB %C	97.69	92.97	89.69
SB %O	0.00	0.13	1.22

Note. Data from the last block of practice. Single-task performance from Block S5 and dual-task performance from Block E5 are displayed. RT = reaction time, %C = percentage correct, %O = percentage omitted.

Table 4
Percentage of Subjects Adopting the Various Time-Sharing Strategies Averaged Over Task Pairs Late in Practice

Age	Strategy	Equal Priority		Differential Priority	
		Optimised Sternberg	Optimised Planikin	Optimised Sternberg	Optimised Planikin
Young	Sternberg First	84.63	65.63	0	0
	Planikin First	3.13	0	3.13	3.13
	Response Grouping	12.50	6.25	6.25	6.25
	Mixed	0	0	3.13	3.13
	Priority Dependent		28.13	87.50	87.50
	PDs			18.75	15.63
	PDp			0	12.50
Middle	PDI			9.38	59.38
	Sternberg First	90.63	87.50	31.25	31.25
	Planikin First	0	0	0	0
	Response Grouping	0	0	3.13	3.13
	Mixed	9.38	0	15.63	15.63
	Priority Dependent		12.50	50.00	50.00
	PDs			9.38	43.75
Older	PDp			0	0
	PDI			3.13	6.25
	Sternberg First	87.50	78.13	46.88	46.88
	Planikin First	6.25	6.25	18.75	18.75
	Response Grouping	0	0	0	0
	Mixed	6.25	0	9.38	9.38
	Priority Dependent		15.63	25.00	25.00
	PDs			12.5	6.25
	PDp			0	0
	PDI			3.13	18.75

Note. Equal-priority data were obtained from Block E5, differential-priority data from Block D4. The Priority Dependent strategy was further classified into PDs (completing the Sternberg task first), PDp (completing the Planikin task first), and PDI (completing the Sternberg or Planikin task first depending on the priority level).