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Dual-task processing in younger and older adults: Similarities and differences revealed by fMRI

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ABSTRACT

fMRI was used to explore age differences in the neural substrate of dual-task processing. Brain activations when there was a 100 ms SOA between tasks, and task overlap was high, were contrasted with activations when there was a 1000 ms SOA, and first task processing was largely complete before the second task began. Younger adults (M = 21 yrs) showed activation in dorsolateral prefrontal cortex and in parietal areas as well as in ventral medial frontal cortex and sub-lobar areas. Activations in older adults (M = 71 yrs) did not differ significantly from younger adults except for higher activations in occipital and polar prefrontal cortex. The results were well fit by a model with two networks managing dual-task interference, a medial prefrontal network that detects changes in the stimulus situation and maps them to associated changes in the valence of response mappings and a lateral frontal–parietal network that initiates and carries out the shift from one task to the other. The additional activations in older adults as a group and the correlations of individual differences in activation with performance were consistent with recruitment within each of these networks. Alternative explanations such as hemispheric asymmetry reduction and reactive rather than proactive processing in older adults were not supported.

1. Introduction

Carrying out more than one task at the same time is commonplace in everyday life, for example driving an automobile while conversing, either on a mobile telephone or with a passenger. Despite anecdotal claims that this can be done successfully, empirical evidence shows that under most circumstances, there is noticeable interference with both tasks. In the instance of telephoning while driving, both driving performance and conversation flow are significantly impaired (Charlton, 2009; Strayer & Drews, 2007). A very substantial body of evidence from controlled laboratory experiments confirms the validity of the findings from real world tasks (for reviews, see Pashler, 1994, 1998). Further, the difficulty in managing overlapping tasks appears to increase with advancing age (for reviews, see McDowd & Shaw, 2000; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). The existence and nature of age-related differences in dual-task management are of both theoretical interest and practical concern.

The method for studying dual-task performance that provides the most leverage in understanding interference gives two simple tasks and systematically manipulates the onset time for the stimuli for each task. For example, in a study of simulated driving, Levy, Pashler, and Boer (2006) had participants carry out two tasks: The first task was to determine whether a brief auditory or visual stimulus had been presented once or twice; the second task was to press the brake pedal whenever the brake lights of a lead car illuminated. The SOAs between the auditory or visual stimulus and the brake light change ranged from 0 ms to 1200 ms. With single-task reaction times under 1000 ms for the auditory–visual task, this meant that there was substantial overlap between the tasks at the shortest SOAs whereas with the longest SOA the response to the first task would likely have been given before the stimulus for the second task appeared. Nevertheless, all of the processes involved in managing both tasks were present on each trial, unlike other approaches in which dual-task performance is simply compared to single-task performance. A large number of experiments using the varied-SOA procedure have been reported with very consistent results (for reviews, see Pashler, 1994, 1998). As SOA decreases (and, therefore, task overlap increases), RTs to Task 2 are slowed dramatically. RTs to Task 1 show little or no effect of SOA. This period over which the RT to Task 2 is slowed has been called the *psychological refractory period* (PRP, Vince, 1948; Welford, 1952) in analogy to the period after an initial firing when a neuron is unresponsive; the general paradigm is often called the

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PRP procedure. The overwhelming weight of the empirical evidence is consistent with *response-selection bottleneck models*.[1] These models assume that there are broadly three stages of processing, an early stage involving perceptual processing, a central stage involving response selection, and a final stage involving execution of the response. The critical assumption is that there is a bottleneck at the central processing stage, such that processes such as response selection can only be carried out for one task at a time (e.g., Lien, Ruthruff, & Johnston, 2006). Central processing of the other task must be postponed until central processing of the first task is complete. Unlike central processing, perceptual processing of the two tasks can occur largely in parallel as can execution of the responses for the two tasks (but see de Jong, 1993).

Age-related differences in cognitive function have been attributed to a reduction of executive control of cognitive processes in old age (e.g., Hull, Martin, Beier, Lane, & Hamilton, 2008). From one point of view, the PRP procedure provides an ideal vehicle to examine this hypothesis because of the need for additional executive control when the second task follows closely on the first (e.g., Erickson et al., 2005): (a) Two task sets must be maintained in working memory; (b) the order in which the two tasks are to be carried out must be prepared and then managed; (c) once processing of one task has begun, processing of the other task must be interrupted and delayed, while maintaining the results of processing already completed; (d) when processing can be returned to the second task, there must be a fast switch of attention back to that task and reinstatement of the processing; and (e) responses must be programmed and executed for two incompatible tasks. Any of these executive operations would be a plausible locus for age-related differences. In contrast to claims that the PRP procedure requires active, executive control, there is also a second and very different view point. In this point of view the behavioral slowing is simply due to passive queuing as the second task waits for necessary resources to become available (Jiang, Saxe, & Kanwisher, 2004; Marois, Larson, Chun, & Shima, 2006). In this view, the slowing is due not to increased executive demands but simply to postponement. If this point of view is correct, we might not expect any greater effect of task overlap in older adults than in younger adults, other than what would be expected from normal age-related slowing of all processes (e.g., Hartley, 2006; Salthouse & Miles, 2002).

Earlier studies of age differences in dual-task performance used procedures with little control over the relative onset of processing in the two tasks (e.g., McDowd & Craik, 1988). More recent age group comparisons have adopted variants of the PRP procedure with controlled onset of two simple tasks. The results for older adults, as for younger adults, have been well fit by response-selection bottleneck models. Allen, Smith, Vires-Collins, and Sperry (1998) concluded that interference in central stage response selection between the two tasks was greater in older than in younger adults. Glass et al. (2000) and Hartley and Little (1999), however, concluded that after general slowing was taken into account, the age differences were small, and could be localized to greater difficulty at input and to a slowed central process of the "unlocking" of processing in the second task. Consistent with Glass et al., Hein and Schubert (2004) concluded that older adults were more sensitive to interference in input modalities. Maquestiaux, Hartley, and Bertsch (2004) also implicated greater difficulty in the switching of central processing when they found that highly trained older adults—but not younger adults—were aided by shifting to tasks that were comparable but with simpler response selection rules. Hartley and Maquestiaux (2007) concluded that central operations were equivalent in younger and older adults, but that older adults showed greater output interference. Hartley (2001) showed that much of the age difference in switching between two different tasks could be eliminated by removing output interference. Thus there are indications of age-related differences at all three phases: input processes, central processes, and output processes.

Neuroimaging is very promising as a way to put constraints on theories of dual-task interference (Jiang et al., 2004). Marois and Ivanoff (225) reviewed a number of approaches that have been used, among them comparing dual-task performance to that of the two tasks done singly and comparison of dual-task performance with high task overlap to that with low task overlap. As they note, each approach has strengths and limitations.

Despite the variety of approaches that have been taken to neuroimaging of dual-task performance and although there are differences from study to study, the areas of activation have been relatively consistent (see Marois & Ivanoff, 2005, for a meta-analysis). Activations have been reliably found in lateral prefrontal cortex (Broadmann's Areas—BAs—9, 44, 45, 46), supplementary motor areas (BAs 6, 8), and parietal areas (BAs 7, 40). Activations have frequently been observed in the anterior cingulate cortex (BAs 24, 32), posterior areas such as cuneus (BAs 18, 19), orbital frontal cortex and anterior insula (BA 47), polar prefrontal cortex (BA 10), temporal areas (BA 37), and subcortical structures such as cerebellum, the basal ganglia, and the thalamus. Activations in these regions have been obtained in the left hemisphere, in the right hemisphere, and bilaterally.

Although different researchers describe it somewhat differently, a consensus model has emerged of how these areas might be involved in executive control of dual-task processing. In this view, the lateral prefrontal cortex is optimized for rapid, adaptive, amodal control (Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008; Dosenbach et al., 2006, 2007; Marois et al., 2006) and is involved in the fast adaptation of response sets and the coordination of selection-for-action in situations with interfering information (Collette et al., 2005; Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999; Schubert & Szameitat, 2003; Szameitat, Schubert, Müller, & Von Cramon, 2002). Medial areas, including anterior cingulate, are optimized for stable set maintenance, maintaining and monitoring associations between actions and their outcomes and the implementation of task sets particularly in situations of conflict (Dosenbach et al., 2006, 2008; Fleck, Daselaar, Dobbins, & Cabeza, 2006; MacDonald, Cohen, Stenger, & Carter, 2000; Rowe, Hughes, Eckstein, & Owen, 2008). The lateral and medial prefrontal areas interact to exercise top-down control, biasing signals to parietal areas that load, transmit, or implement the required task-set parameters (Dosenbach et al., 2006, 2008; MacDonald et al., 2000; Sigman & DeHaene, 2006). The parietal areas can also operate to feed information forward for stimulus-driven bottom-up shifts of attention.

Other studies have found little or no evidence for recruitment of executive areas in the dual-task situation beyond those activated in the single-task situation (Adcock, Constable, Gore, & Goldman-Rakic, 2000; Bunge, Klingberg, Jacobsen, & Gabrieli, 2000; Erickson et al., 2005; Jiang et al., 2004; also see Sigman & DeHaene, 2008). These studies are consistent with the passive-queuing model in which the processes carried out at short SOAs are no different from those carried out at long SOAs. Rather than active monitoring and management of processes in the two tasks, a delay is simply

[1] It has been argued that the central response-selection bottleneck is strategic and not obligatory (Meyer & Kieras, 1997a, 1997b), however the evidence for this comes from highly practiced individuals, using a very constrained set of stimuli and with 0 ms SOA (Hazeltine, Teague, & Ivry, 2002; Schumacher et al., 2001; see Meyer and Kieras (1999) and Meyer, Kieras, Schumacher, Fencsik, and Glass (2001), for lists of possibly necessary conditions). Miller, Ulrich, and Rolke (2009) have demonstrated that, even if parallel processing of two tasks were possible, serial processing would still produce the optimal outcome under a wide range of circumstances and, indeed, whether strategic or not, the bottleneck—evidenced by dual-task interference—is almost always present with non-zero SOAs. We will not attempt to resolve here the issue of whether the bottleneck is structural and immutable or strategic and malleable.