Individual Differences in Executive Processing Predict Susceptibility to Interference in Verbal Working Memory

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Recent theories have suggested that resistance to interference is a unifying principle of executive function and that individual differences in interference may be explained by executive function (M. J. Kane & R. W. Engle, 2002). Measures of executive function, memory, and perceptual speed were obtained from 121 older adults (ages 63–82). We used structural equation modeling to investigate the relationships of these constructs with interference in a working memory task. Executive function was best described as two related subcomponent processes: shifting and updating goal-relevant representations and inhibition of proactive interference. These subcomponents were distinct from verbal and visual memory and speed. Individual differences in interference susceptibility and recollection were best predicted by shifting and updating and by resistance to proactive interference, and variability in familiarity was predicted by resistance to proactive interference and speed.

Keywords: aging, short-term memory, inhibition, recollection, source monitoring

Executive processes that modulate and coordinate the operation of disparate cognitive mechanisms have played a central role in theories regarding cognition, neuropsychology, and cognitive neuroscience. However, there remains little agreement on what constitutes executive function, how many such functions are necessary to explain human behavior, or where executive function may reside in the brain (Andrés, 2003; Miyake et al., 2000; Salthouse, Atkinson, & Berish, 2003). The concept of executive function arose from neuropsychological research on patients with frontal lobe lesions, who often display impairments in planning and organization of behavior (Mesulam, 2002; Milner & Petrides, 1984). Cognitive theories adapted the notion of executive function as a supervisory or centralized regulator or coordinator of multiple component processes (Baddeley, 1986; Meyer & Kieras, 1997; Norman & Shallice, 1986).

More recently, neuroimaging studies have investigated the neural correlates of executive functions (Collette & Van der Linden, 2002; Duncan & Owen, 2000). Despite a tendency to speak of executive function as though it were a single entity (Parkin, 1998), research both in individuals without lesions and in patients with frontal and nonfrontal lesions has suggested that executive processes need not be unitary and are likely to involve circuits among multiple brain regions, rather than residing only in the prefrontal cortex (Andrés, 2003; Baddeley, 1998; Stuss et al., 2002). Nonetheless, there remains an ongoing and lively debate on whether executive function is best conceptualized as a unitary process or as several separate but related subcomponent processes (Andrés, 2003; Miyake et al., 2000; Salthouse et al., 2003; Stuss et al., 2002). The present study was designed to further investigate the separation and overlap among hypothesized executive subcomponent processes and to explore their relationship to interference effects within the domain of working memory.

In an important investigation of the relationships among measures of cognitive processes and neuropsychological tests Miyake et al. (2000) used structural equation (SE) modeling to find that executive function was best characterized as consisting of three distinct processes, rather than as a unitary construct. These processes, defined a priori, were updating and monitoring of representations in working memory, inhibition of prepotent responses, and shifting among multiple tasks or mental sets. It is important to note that although the results showed that these three subcomponent constructs were clearly distinct from one another, they were nonetheless related, with correlations of .40–.60. These processes were further found by Miyake et al. to be separately related to performance on neuropsychological tasks of frontal function; for instance, shifting alone best predicted perseveration errors on the Wisconsin Card Sorting Test (WCST; Heaton, Chelune, Talley, Kay, & Curtis, 1993), inhibition best predicted performance on the Tower of Hanoi, and updating best predicted working memory capacity estimates using the operation span task.

In contrast to the above results, Salthouse, Atkinson, and Berish (2003) noted that behavioral tasks purported to measure subcomponents of executive function are only moderately correlated with one another and are often more strongly related to established cognitive constructs, such as perceptual speed, memory, vocabulary, and fluid intelligence. They questioned whether measures of executive functions share sufficient variance to constitute distinct and meaningful constructs, even when measured at the level of component processes.
The neuroimaging evidence also calls into question whether executive subcomponent processes should be considered as entirely distinct from one another. Collette and Van der Linden (2002) conducted a review of neuroimaging studies involving component processes similar to those identified by Miyake et al. (2000): updating working memory representations, inhibition of prepotent responses in tasks such as the Stroop (1935) paradigm and the go/no-go task, and shifting between perceptual dimensions or coordinating between multiple task goals. Despite the diversity of tasks surveyed and differences in methodology, there was remarkable consistency in the activation of lateral prefrontal cortex, anterior cingulate cortex, and parietal sites across all of the component processes (Collette & Van der Linden, 2002). However, there were also some consistent differences in activations across subcomponent processes, suggesting that executive function may rely primarily on domain-general regions, with specific networks being activated to carry out particular processing demands of subcomponent processes (see also Duncan & Owen, 2000).

EXECUTIVE FUNCTION SUBCOMPONENT PROCESSES

Shifting

One prominent class of proposed subcomponent processes governs goal management and shifting among multiple task demands, each of which may have its own set of goals (Monsell, 2003). Sometimes referred to as task switching, this process is thought to involve the engagement of a new set of rules, subgoals, or operations to direct attention and behavior in accordance with changing task demands. This may involve both the loading of a new goal set into working memory and the inhibition of prior, no-longer-relevant goal sets and their corresponding task dimensions (Miyake et al., 2000).

Updating

A second class of subcomponent processes involves the updating of representations held in working, or short-term, memory. As new information is encountered, the task-relevant portion of this information must be extracted and loaded into working memory for online use and maintenance. Simultaneously, information currently in working memory that is found to be no longer relevant to the task at hand should be removed from working memory. Updating may also involve the manipulation of representations stored in working memory, such as reordering or recombing in accordance with task demands (e.g., Doiseau & Isingrini, 2005; Morris & Jones, 1990).

Inhibition

Inhibitory processes are thought to be involved in the suppression of unwanted or irrelevant representations, goals, and responses. There has been some debate as to whether there are multiple types of inhibition or a unitary inhibitory process among executive function subcomponents that cuts across task domains. Friedman and Miyake (2004) examined the relationships among measures of inhibition of prepotent responses (e.g., the Stroop, stop-signal, and antisaccade tasks), resistance to distractor interference (e.g., the Eriksen flanker task and negative priming paradigms), and resistance to proactive interference (e.g., the Brown-Peterson task and list learning paradigms). The results of that study found that prepotent response inhibition and resistance to distractor interference constituted a single construct and that this construct was not correlated with a construct reflecting resistance to proactive interference, indicating that, at least in some cases, inhibition should be considered a multicomponent process. In this study, we focus on investigating two possible subcomponent processes of inhibition: prepotent response inhibition and resistance to proactive interference.

A commonly used measure of executive processing ability (sometimes called frontal function in the neuropsychological literature) is the fluency task (Glisky, Polster, & Routhiaux, 1995; Lezak, 1995). Fluency tasks typically measure an individual’s speed of accessing semantic or lexical representations. However, fluency tasks rely not only on speed of access, but also on the ability to overcome competitive inhibition, or proactive interference, from previously produced items (Gurd & Oliveira, 1996). One variant of fluency tasks, excluded letter fluency, may particularly rely on inhibitory processes in that it requires participants to produce words that do not contain a common letter (Bryan & Luszcz, 2000). Hence, excluded letter fluency may index both the process of keeping task-irrelevant representations from exceeding threshold for production and the processes involved in overcoming proactive interference from successfully produced responses. In the present study, we included several verbal fluency tasks to determine the extent to which resistance to proactive interference during lexical access is related to inhibition of prepotent responses, as in the antisaccade and Stroop color-naming tasks, as well as other executive processing constructs.

EXECUTIVE FUNCTION AND AGING

The debate regarding the unity or diversity of executive function and its neural correlates has drawn from research involving varied populations. One such population is that of healthy older adults, typically ranging in age from 60 to 90 years. Across the adult life span, the lateral prefrontal cortex exhibits volumetric declines that are larger than those in many connected regions, including parietal cortex and memory-related structures in the medial temporal lobes (see Hedden & Gabrieli, 2004, for review). Although the lateral prefrontal cortex is unlikely to be the sole site of executive processes, it is undoubtedly an important part of the neural circuits underlying several executive functions (Fuster, 2002). Supporting this interpretation, older adults display deficits related to inhibitory function (Hasher & Zacks, 1988), monitoring the source or context of information (Johnson, Hashtroudi, & Lindsay, 1993; Mitchell, Johnson, & Mather, 2003; Spencer & Raz, 1994), and performance on a variety of neuropsychological tests of executive function (Bryan & Luszcz, 2000).

The similarity between the behavioral deficits exhibited by frontal patients with dysexecutive syndrome and those exhibited by healthy older adults led to the development of the frontal theory of aging (Moscovitch & Winocur, 1995; West, 1996). Under this view, age-related declines in prefrontal structures impair the ability of older adults to monitor and control processes subserved by other brain regions that may be less affected by typical aging (Hedden & Gabrieli, 2004). In support of this hypothesis, several neuroimaging-
EXECUTIVE FUNCTION AND INTERFERENCE

Recently, Kane and Engle (2002) presented a unifying view of executive function as involving the maintenance of representations in the face of interference. According to this view, a primary function of dorsolateral prefrontal cortex is to maintain representations of task-relevant goal states across intervals during which interference is present. Failures to maintain such goal states result in diminished estimates of working memory capacity and general fluid intelligence (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999) and in increases in interference during dual-task performance, memory retrieval, and selective attention tasks (Conway, Cowan, & Bunting, 2001; Kane, Bleckley, Conway, & Engle, 2001; Rosen & Engle, 1997, 1998). This view draws parallels between interference resulting from prepotent responses (as in Stroop, negative priming, and antisaccade tasks), recently encountered information (proactive interference), and set switching (as in dual-task requirements) based largely on the shared variance among complex working memory tasks and these domains (Engle, 2002; Engle, Kane, & Tuholski, 1999; Kane & Engle, 2002). However, it remains possible that there are distinct subcomponents of executive function that underlie resistance to the different types of interference.

Older adults are a particularly informative population with respect to the relation of interference and executive control and, accordingly, the focus of the present study. Behavioral studies of older adults have shown that they are more susceptible than are younger adults to interference in a variety of domains, including dual-task interference (Verhaeghen, Steitz, Sliwinski, & Cerella, 2003), global task switching (Verhaeghen & Cerella, 2002), and proactive interference in both working memory (Bowles & Salthouse, 2003; Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999) and long-term memory (Jacoby, DeRen, & Hay, 2001). However, not all types of interference attributable to failures of executive function display age-related declines. Meta-analyses have found that age effects on interference in the Stroop task are largely attributable to differences in perceptual speed (Verhaeghen & De Meersman, 1998a), whereas age differences in negative priming are small or nonexistent (Gamboz, Russo, & Fox, 2002; Verhaeghen & Cerella, 2002; Verhaeghen & De Meersman, 1998b). This pattern of results suggests that interference in different types of executive function tasks are not affected by aging in the same manner and are therefore likely to have different underlying cognitive mechanisms.

Hedden and Park (2001, 2003) described a verbal working memory task involving the presentation of multiple lists, finding that older adults were more susceptible to retroactive interference than were younger adults. The interference in their task appears to stem from both an inhibitory and a source monitoring component, although the age-related effects were primarily attributable to failures of source monitoring (Hedden & Park, 2003). Furthermore, there were large individual differences within the group of older adults, with some individuals showing resistance to interference equivalent to that shown by younger adults and some being far more susceptible to interference.

Several studies have investigated individual differences in source monitoring among older adults from a neuropsychological approach (Glisky, Polster, & Routhieaux, 1995; Glisky, Rubin, & Davidson, 2001; Henkel, Johnson, & De Leonardis, 1998). In each of these studies, participants were classified on two factors on the basis of performance on neuropsychological tasks: one frontal factor derived from executive function tasks such as the WCST and one medial temporal factor derived from memory tasks such as the paired associates subtests from the Wechsler Memory Scale—Revised. All of these studies found that older adults with high executive function scores outperformed those with low executive function scores on memory tests that required recollection of the relation between an item and contextual features, whereas scores on the memory factor were unrelated to memory for contextual information. These findings demonstrated that individual differences in executive function among older adults are related to the ability to monitor source or contextual information. The capacity for source monitoring may be a primary means for avoiding interference from task-irrelevant representations when those representations remain active in memory (Hedden & Park, 2003).

Using the process dissociation procedure, Jacoby and colleagues (Hay & Jacoby, 1999; Jacoby, 1991) have mathematically separated the influences of two processes in memory, recollection and familiarity (see Jacoby, 1991, 1998, 1999, for discussion of the process dissociation procedure). The recollection process involves controlled retrieval from memory and therefore relies on the executive functions that govern source monitoring, which is an active and controlled effort to track contextual information in memory (Mulligan & Hirshman, 1997; Steffens, Buchner, Martensen, & Erdfelder, 2000). The familiarity (or habit) process, in contrast, relies upon automatic activation processes. In research by Jacoby and colleagues (Hay & Jacoby, 1999; Jacoby, 1999) involving long-term memory, the recollection process, but not the familiarity process, was impaired with aging. Nonetheless, these activation processes may be affected by the executive function of inhibition, which does appear to be impaired in older adults (Haser & Zacks, 1988; Lustig et al., 2001; Zacks, Radvansky, & Hasher, 1996). Under this view, inhibition may act as a controlled process to suppress the automatically activated representations in memory that contribute to estimates of familiarity. Insofar as inhibition is successful, estimates of familiarity will be reduced; failures of inhibition will be observed if familiarity increases. Consistent with these arguments, Hedden and Park (2003) found that older adults displayed reduced estimates of recollection and increased estimates of familiarity compared with younger adults in a working memory task.

The current study further investigates the issues regarding the unity or diversity of executive function in a sample of older adults by examining the relation of executive function tasks hypothesized to measure subcomponent processes of shifting, updating, prepotent response inhibition, and resistance to proactive interference with one another and with measures of memory, perceptual speed, and interference in working memory. Using SE modeling, we examined the shared variance among measures of executive func-
tion to determine whether a unitary executive function construct best accounted for the shared variance, or whether several constructs representing executive function subcomponents were required to account for the shared variance. Simultaneously, we investigated the relations between measures of executive function and between constructs of paired associate memory and perceptual speed to determine whether executive function constituted a cognitive construct distinct from these commonly used constructs of age-associated cognition. Finally, we investigated the relationships between executive function subcomponents and measures derived from a task involving interference in working memory to determine which subcomponents best accounted for individual differences in susceptibility to interference, recollection, and familiarity.

**METHOD**

**Participants**

Participants were 129 community-dwelling individuals in the Ann Arbor, Michigan area, ages 63–82 years. Eight participants were excluded from all analyses because of possible dementia, as indicated by a score of 24 or below on the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975; Lezak, 1995), leaving an effective sample size of 121 (69 women, 52 men). All participants were native English speakers, had vision sufficient to be able to read comfortably from a computer screen, had at least a 10th-grade education level, and were able to provide their own transportation to the study site. Participants were compensated $15 per hour for their participation.

**Procedure**

Participants were tested in single-day sessions of 3 hr in groups of 3 or fewer. Tasks were presented either with paper and pencil or with the E-Prime 1.1 software package (Psychology Software Tools, Pittsburgh, PA) on Dell Pentium III 933 MHz (Dell Computers, Round Rock, TX) computers with 15-in. color monitors. Each participant completed a series of cognitive tasks. Task order was invariant across participants. The task order is shown in Table 1. Breaks of 5–10 min in duration were provided after Tasks 6, 7, and 13. SE analyses were conducted with the LISREL 8.30 software (Jöreskog & Sörbom, 2001).

**Description of Tasks**

Brief task descriptions are provided below, with more complete descriptions and citations to source materials provided in the supplementary materials, which are available on the Web at http://dx.doi.org/10.1037/0894-4105.20.5.511.supp.

**Sample Characteristics**

**Demographics Questionnaire**

This self-report questionnaire collected information about the participants’ age, education level, gender, race, primary language, marital status, and occupational status.

**Health Questionnaire**

This self-report questionnaire collected information about the participants’ health status.

**Table 1**

Order and Description of Participant Tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Measure</th>
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<tbody>
<tr>
<td>1</td>
<td>Demographics questionnaire</td>
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<tr>
<td>2</td>
<td>Health questionnaire</td>
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<tr>
<td>3</td>
<td>Wisconsin Card Sorting Test</td>
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<tr>
<td>4</td>
<td>Trail Making Test (Forms A and B)</td>
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<tr>
<td>5</td>
<td>Mini-Mental State Examination</td>
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<tr>
<td>6</td>
<td>Backward digit span</td>
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<td>7</td>
<td>List memory task</td>
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<tr>
<td>8</td>
<td>Immediate visual paired associates</td>
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<td>9</td>
<td>Excluded letter fluency 1 (Version E)</td>
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<tr>
<td>10</td>
<td>Letter memory</td>
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<tr>
<td>11</td>
<td>Antisaccade</td>
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<tr>
<td>12</td>
<td>Delayed visual paired associates</td>
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<tr>
<td>13</td>
<td>Semantic fluency</td>
</tr>
<tr>
<td>14</td>
<td>Immediate verbal paired associates</td>
</tr>
<tr>
<td>15</td>
<td>Self-ordered pointing</td>
</tr>
<tr>
<td>16</td>
<td>Stroop color naming</td>
</tr>
<tr>
<td>17</td>
<td>Plus-minus task</td>
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<tr>
<td>18</td>
<td>Letter comparison 3, 6, and 9</td>
</tr>
<tr>
<td>19</td>
<td>Delayed verbal paired associates</td>
</tr>
<tr>
<td>20</td>
<td>Excluded letter fluency 2 (Version A)</td>
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</tbody>
</table>

**MMSE**

This dementia screening instrument was used to exclude participants with scores of 24 or below, which would indicate possible dementia (Folstein et al., 1975; Lezak, 1995).

**Executive Function: Shifting**

There were three tasks designed to measure the shifting component of executive function.

**Plus–Minus Task**

The task consisted of three lists of 30 two-digit numbers. On the first list, participants added 3 to each number. On the second list, participants subtracted 3 from each number. On the third list, participants alternated between adding 3 to and subtracting 3 from each successive number. The dependent measure was the cost of shifting between operations, calculated as the difference between the mean reaction time on the alternating list and the average of the mean reaction times on the addition- and subtraction-only lists.

**WCST**

The main dependent measure was the number of classical perseverative errors, which was the number of times participants failed to change sorting criteria and continued to sort using the previous criterion.

**Trail Making Test**

This task consisted of two forms. An experimenter recorded the time to complete each form in seconds using a stopwatch. The dependent measure was the cost of shifting between operations, calculated as the difference in time to complete Form B and Form A.

**Executive Function: Updating**

There were three tasks designed to measure the updating component of executive function.
**Letter Memory**

This task involved the serial presentation of letters in lists of varying length. The task was to recall the last four letters in each list. The dependent measure was the number of trials in which all of the last four letters were correctly recalled in the correct order.

**Backward Digit Span**

The experimenter read aloud a series of digits to the participant, who responded by repeating the same series of digits in the reverse order (i.e., 9-1-7 for 7-1-9). The dependent measure was the number of trials in which all of the numbers were correctly recalled in the reverse order.

**Self-Ordered Pointing**

Participants were presented with a series of $4 \times 4$ arrays containing random rearrangements of 16 abstract visual textures. For each array, participants could freely indicate one pattern, but they could not mark any pattern that had been previously marked. The dependent measure was the average number of patterns correctly marked.

**Executive Function: Inhibition**

There were four tasks designed to measure the inhibition component of executive function, two tasks each for prepotent response inhibition and resistance to proactive interference.

**Prepotent Response Inhibition**

*Antisaccade.* Each trial consisted of a fixation of varying duration, followed by a cue and a masked target. Participants were to suppress the impulse to look at the cue and instead look at the side opposite the cue and indicate the direction of the target by responding with a button press. The dependent measure was the proportion of correct trials.

*Stroop color naming.* Participants were instructed to indicate (with a button press) the color of a stimulus as quickly as possible on each trial. The dependent measure was the reaction time difference between conflict and neutral trials.

**Resistance to Proactive Interference**

*Excluded letter fluency 1 and 2.* Participants were given 60 s to write down as many words as possible that do not contain a given letter. Participants completed two versions of the task. The dependent measure for each version was the number of correctly produced words minus the number of incorrectly produced words.

*Semantic fluency.* Participants were given a category name (e.g., animals) and were instructed to write down as many members of the category as possible in 60 s. The dependent measure was the number of correct responses minus the number of incorrect responses.

**Verbal Memory**

There were two tasks intended to measure verbal paired-associate memory, each of which was adapted from the WMS–III (Wechsler, 1997).

**Immediate Verbal Paired Associates**

Participants were presented with a list of eight word pairs (e.g., OBEY–INCH) and instructed to remember the word pairs. After initial presentation, participants were presented with the first word in each pair (e.g., OBEY–?) and instructed to write down the associated word. The dependent measure was the average number of correct responses.

**Delayed Verbal Paired Associates**

After a filled interval of approximately 20 min, participants were presented with the first word in each pair from the immediate verbal paired associates task and instructed to write down the associated word. The dependent measure was the number of correct responses.

**Visual Memory**

There were two tasks intended to measure visual paired-associate memory, each of which was adapted from the WMS–III.

**Immediate Visual Paired Associates**

Participants were presented with a list of six pairings of an abstract figure with a color patch and instructed to remember the pairs. After initial presentation, participants were presented with the abstract figures from each pair and instructed to indicate with a button press the associated color. The dependent measure was the average number of correct responses.

**Delayed Visual Paired Associates**

After a filled interval of approximately 20 min, participants were presented with the abstract figure from each pair from the immediate visual paired associates task and instructed to indicate the associated color with a button press. The dependent measure was the number of correct responses.

**Perceptual Speed: Letter Comparison, Sections 3, 6, and 9**

Participants were presented with pairs of letter strings consisting of three, six, or nine letters each. Participants determined whether the two strings were the same or different. For each section, the dependent measure was the number correct minus the number incorrect.

**Outcome Measures: List Memory**

This task was adapted from the task described by Hedden and Park (2001, 2003). Participants were provided a pair of headphones with a microphone and told that their voice would be recorded during the experiment. Participants were given two blocks of 20 trials. In one block, exclusion instructions were provided, in which participants were to distinguish between studied and read word pairs. In the other block, inclusion instructions were provided, in which participants were to give the same response to studied and read pairs. Order of the instruction blocks was counterbalanced across participants. During the task, word pairs were presented on a computer screen in short lists of 3 word pairs each for 40 total trials. Each trial consisted of a study list of 3 word pairs, a read list of 3 word pairs or a rest period, and a recognition list consisting of 12 word pairs. Word pairs could be of four types: A–B pairs were always those pairs presented on the study list, A–C pairs consisted of the same cue word as an A–B pair joined with a new associated target word, D–E pairs were presented on read lists and consisted of paired associates that were unrelated to the A–B and A–C pairs, and novel pairs were never presented on study or read lists and were unrelated to all other pairs in the study. The trials were randomly distributed across two types of interference conditions: Outcome measures of hit and false alarm rates and estimates of recollection and familiarity were derived from this task.

**RESULTS**

Detailed demographic, health, and neuropsychological characteristics of the sample are provided in the supplementary materials (see Table S1). Performance on each task is reported in Table S2.
Reliabilities were all in the acceptable to high range, with the majority of tasks exceeding a reliability of .75. Missing values (2% of the data) were replaced with the mean for each task. Before development of the models reported below, all scores (with the exception of the outcome measure of false alarms) were transformed so that higher scores indicated better performance. Correlations among transformed scores are reported in the supplementary materials (see Table S3).

List Memory Performance

Performance from the list memory task is reported in detail in the results section of the supplementary materials. Measures derived from this task are reported in Table S2 and were used as the outcome measures in subsequent modeling of the influences of executive processing, memory, and speed on susceptibility to interference, recollection, and familiarity.

Individual Differences in Executive Function

The analyses were designed so that we could first determine whether executive function in this older adult sample was best described as a unitary process or as several distinct component processes. In addition, the relationship of executive processing to verbal and visual memory and to perceptual speed was investigated. To accomplish this first step, we constructed competing measurement, or correlated factors (CF), models to assess the relationships between individual tasks and their associated latent constructs in the sample. A model containing a unitary executive function construct was directly compared with models containing various combinations of multiple subcomponents of executive function. Within these models, we included constructs of verbal and visual memory and perceptual speed to assess whether the executive function constructs were distinct from other cognitive constructs. Second, the contributions of executive function, verbal and visual memory, and speed to interference susceptibility in a working memory task were examined. Third, the contributions of executive function, verbal and visual memory, and speed to recollection and familiarity processes in working memory were investigated. To accomplish these latter two steps, we estimated confirmatory SE models using the latent constructs developed in the CF models. The SE models provided an estimate of the contributions of executive function, verbal and visual memory, and speed to the indicators of interference susceptibility, and to recollection and familiarity.

Correlated Factors Models

The first step involved the development of competing CF models to determine whether executive function was best described as a unitary or multicomponent construct in this sample, and whether executive function constructs were distinct from constructs of memory and perceptual speed. A CF model measures whether the indicators hypothesized to form conceptual latent constructs (e.g., plus–minus, WCST preservation errors, and the Trail Making Test were hypothesized to be indicators of the latent construct of shifting) shared sufficient variance to form latent constructs. Alternative CF models can be directly compared to determine which model provides a better fit to the observed data. The CF models used in this study included 11 dependent measures as indicators of the executive function constructs, 2 dependent measures as indicators of each of the paired-associate memory constructs (verbal and visual), and 3 indicators of the perceptual speed construct. The initial CF model specifying the full set of estimated relationships among indicators and latent constructs is depicted in Figure 1. Note that the model yields information about the correlations among the latent constructs, but it does not specify the directionality or hierarchy of relationships among the constructs (as do the SE models described later). The overall goodness of fit of the initial model was quite high, suggesting that the hypothesized relationships between indicators and constructs were statistically confirmed. Also of note were the relatively high correlations among several of the constructs, indicating that some constructs may not be distinct from one another. Although no single criterion for assessing goodness of fit has been established, a model considered to have good fit would have several characteristics. First, perhaps the most likely statistic to become a standard measure of model fit is the root-mean-square error of approximation (RMSEA), an estimate of the amount of error in the model. RMSEA should be less than .08 for acceptable fit and less than .05 to be considered an excellent fit (see Browne & Cudeck, 1993, p. 144; Loehlin, 1998, pp. 76–78). Second, the incremental (IFI) and comparative fit indexes (CFI) should be greater than .90 for acceptable fit and greater than .95 for close fit (Bentler & Bonett, 1980). Third, some researchers have suggested that an indication of good fit occurs when the chi-square value is no greater than twice the degrees of freedom (Bollen, 1989, p. 278). Although ideally a model will have a nonsignificant chi-square value, sometimes even a model with excellent fit will possess a significant chi-square value (Tanaka, 1993).

Goodness of fit statistics are reported in Table 2, and most of the models tested exhibited acceptable to good fit. Given two models with reasonable fit, the models can be directly compared with one another if they are nested models. Nesting of models occurs when one model is a subset of the other. For example, the one-factor model (Model 2) is nested within the initial, seven-factor model (Model 1) through restricting all correlations among the seven factors to be equal to 1. Nested models are compared by examining the change in chi-square (Δχ²) values across the models. If the more complex model has a Δχ² value that is significant for the loss of degrees of freedom, it is accepted as the model of better fit. The one-factor model (Model 2) exhibited very poor fit, and the Δχ² value was significant when compared with Model 1, indicating that at least some of the constructs were distinct. To assess the unitary or distinct nature of executive function, we first tested models in which subsets of the executive function constructs were constrained to be equal to one another (Models 3–13). We did this by fixing the correlations between the tested constructs equal to 1 and by constraining their correlations with the other constructs to be equal to one another. Although all of these models exhibited good fit, only the model in which shifting and updating were equivalent (Model 3) fit as well as did Model 1 (i.e., Model 1 did not fit significantly better than Model 3 according to Δχ²). Model 3 was therefore accepted as the model of best fit from this group. To assess whether the cognitive constructs of verbal and visual memory and processing speed were equivalent to or distinct from one another, we next tested models in which these constructs were constrained to be equivalent (Models 14–17). As a class, these
models exhibited relatively poor fit, and all fit significantly worse than did Model 1 by the $\Delta\chi^2$ metric, indicating that the three cognitive constructs were distinct from one another.

On the basis of the above tests, we combined the shifting and updating constructs into a single construct (Model 3) and tested whether the executive function constructs were distinct from the cognitive constructs of memory and speed (Models 18–26). Several of these models fit relatively poorly, and all but one fit significantly worse than did Model 3 by the $\Delta\chi^2$ metric. The exception was the model in which prepotent response inhibition and speed were equivalent to one another (Model 23), which was therefore accepted as the final model of best fit and is displayed in Figure 2. The final model includes two constructs of executive function, shifting/updating and resistance to proactive interference, which are distinct from the three constructs of cognition. The correlations between the constructs are in the low to moderate range (.22–.62).

**SE Models**

**Models of Interference Susceptibility**

The second step in the analyses used the constructs developed in the CF models above as the basis for SE models that allowed the specification of relationships among the constructs to measures of interference susceptibility in a working memory task. These SE models were intended to determine whether certain executive function subcomponents, memory, or speed most contributed to interference susceptibility in working memory for older adults.

In these SE models, the outcome measures of interference susceptibility were the hit and false alarm rates calculated for the interference condition under exclusion instructions from the list memory task (see supplementary materials). The hit and false alarm rates potentially measure two different aspects of interference susceptibility within working memory. The hit rate measures
correct responding, or the ability to maintain target representations in the presence of interference. The false alarm rate, in contrast, measures the intrusion rate, or the inability to effectively resist intrusions from interfering representations that were presented in a different task context. Several potential models were compared. In all models, the constructs of shifting/updating, resistance to proactive interference, verbal and visual memory, and speed were allowed to correlate as exogenous variables. Shifting/updating was expected to be the most likely candidate for explaining variance in interference susceptibility as measured by hit and false alarm rates, as the ability to rapidly shift attention among relevant task dimensions and to update the contents of working memory are crucial for those context monitoring processes related to the identification and avoidance of interference. In addition, resistance to proactive interference was hypothesized to be related to hits and false alarms because resistance to proactive interference, such as encountered in fluency tasks, is likely to recruit processes that overlap with effective resistance to retroactive interference in verbal working memory. These constructs were expected to have a positive relationship to correct responding (hits) and a negative relationship to error rates (false alarms). To test these hypotheses, we created a series of models and compared them with one another (see Table 3 for fit statistics).

In the initial model (Model 1), paths from all five constructs to both hit and false alarm rates were freely estimated. This model exhibited good fit characteristics. In comparison, when all paths to hits and false alarms were constrained to 0 (Model 2), the model exhibited relatively poor fit, showing that at least some of the constructs of interest explain significant variance in hit and false alarm rates. To determine which constructs account for the majority of the variance in hit and false alarm rates, we constrained each path to hits and false alarms to 0 in sequence. If this constraint did not significantly alter fit when compared to Model 1 by the $\Delta \chi^2$ statistic, that path was eliminated from subsequent models and the next path was constrained to 0 and compared with Model 1. If the constraint did significantly alter fit, the constraint was relaxed in subsequent models, and the next path was constrained and tested.

For hit rates, the only path whose elimination individually resulted in a significant decrease in fit was that from visual memory to prepotent response inhibition (Model 4). However, when the paths to hits from both shifting/updating and resistance to proactive interference were constrained to 0 (Model 8), there was a significant decrease in fit. Because allowing a path from either of these constructs to hits resulted in a nonsignificant change in model fit (Models 6 and 7), these two paths were constrained to be equal to one another. That is, both paths were included, but only one was freely estimated, and the
other was assigned the same value (Model 9). This model exhibited equivalent fit to the initial model.

For false alarm rates, the only path whose elimination individually resulted in a significant fit decrease was that from the construct of speed (Model 10). Again, although neither individually resulted in a significant decrease in fit (Models 13 and 14), when both shifting/updating and resistance to interference were constrained to 0 (Model 15), there was a significant decrease in fit. When these two paths were both included, but constrained to be equal to one another (Model 16), the model exhibited equivalent fit to the initial model and explained 36% of the variance in hit rates and 29% of the variance in false alarm rates. When all other paths to hits were allowed, 43% of the variance in hit rates was explained; allowing all other paths to false alarms explained a total of 31% of the variance in false alarms. Thus, estimating only four parameters achieved equivalent fit to a model with 10 estimated parameters and accounted for the vast majority of variance in the outcome measures. The accepted model of best fit (displayed in Figure 3) therefore included a path from visual memory to hits, from speed to false alarms, and paths from both shifting/updating and resistance to proactive interference to hits and to false alarms.

However, the paths from these latter constructs to hits were constrained to be equivalent, as were their paths to false alarms. This model shows that executive function subcomponents are major contributors to explaining individual differences in interference susceptibility within working memory. However, both executive function subcomponents contribute equally to interference susceptibility, both for accurate working memory traces (hit rates) and for contextual errors (false alarms).

**Models of Recollection and Familiarity**

The third step in the analyses involved the construction of SE models through use of the executive processing subcomponents, verbal and visual memory, and perceptual speed. All values are from the completely standardized solution. The proportion of variance in each indicator explained by the model is calculated by subtracting the error variance for an indicator from 1. WCST = Wisconsin Card Sorting Task; BDS = backward digit span; SOP = self-ordered pointing; ELF = excluded letter fluency; Fl. = fluency; Immed. = immediate; Comp. = comparison; Stroop = Stroop color naming; P.I. = proactive interference.
processes of recollection and familiarity. These models had as outcome measures the estimates of recollection and familiarity obtained from recollection and familiarity estimates. To determine which constructs account for the majority of the variance in recollection and familiarity estimates, we constrained each path to recollection and familiarity to 0 in sequence. If this constraint did not significantly alter fit when compared with Model 1 by the $\Delta \chi^2$ statistic, that path was eliminated from subsequent models, and the next path was constrained to 0 and compared with Model 1. If the constraint did significantly alter fit, the constraint was relaxed in subsequent models, and the next path was constrained and tested.

For estimates of recollection, the elimination of any individual path failed to result in a significant decrease in fit (Models 3–7). However, when the paths to recollection from both shifting/updating and resistance to proactive interference were constrained to 0 (Model 8), there was a significant decrease in fit. Because allowing a path from either of these constructs to recollection resulted in a nonsignificant change in model fit (Models 6 and 7), these two paths were constrained to be equal to one another. That is, both paths were included, but only one was freely estimated, and the other was assigned the same value (Model 9). This model exhibited statistically equivalent fit to the initial model, despite the elimination of paths to recollection from visual memory, verbal memory, and speed.

For estimates of recollection, the elimination of a path from speed resulted in a significant decrease in fit (Model 10). Although this model did not display a significant change in fit relative to Model 1, a significant decrease in fit was observed for the gain of one degree of freedom associated with only the elimination of the path from speed (i.e., relative to Model 9). Similarly, the elimination of the path from resistance to proactive interference to familiarity resulted in a significant decrease in fit (Model 13), but this was true only when the change in fit associated with the degree of freedom gained from eliminating this one path was examined (i.e., relative to Model 12). For completeness, a model with the paths to familiarity from shifting/updating and resistance to proactive in-

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$</th>
<th>df</th>
<th>RMSEA</th>
<th>GFI</th>
<th>CFI</th>
<th>IFI</th>
<th>$\Delta \chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. All constructs to hits and FAs</td>
<td>159.78</td>
<td>152</td>
<td>.02</td>
<td>.88</td>
<td>.97</td>
<td>.98</td>
<td></td>
</tr>
<tr>
<td>2. No paths to hits or FAs</td>
<td>221.59*</td>
<td>162</td>
<td>.06</td>
<td>.84</td>
<td>.86</td>
<td>.87</td>
<td>61.81*</td>
</tr>
<tr>
<td>3. All but Sp to hits; all to FAs</td>
<td>159.33</td>
<td>153</td>
<td>.02</td>
<td>.88</td>
<td>.96</td>
<td>.97</td>
<td>.04</td>
</tr>
<tr>
<td>4. Sh/U, RPI, VerM to hits; all to FAs</td>
<td>167.71</td>
<td>154</td>
<td>.03</td>
<td>.88</td>
<td>.96</td>
<td>.96</td>
<td>7.93</td>
</tr>
<tr>
<td>5. Sh/U, RPI, VisM to hits; all to FAs</td>
<td>159.36</td>
<td>154</td>
<td>.02</td>
<td>.88</td>
<td>.97</td>
<td>.97</td>
<td>.02</td>
</tr>
<tr>
<td>6. Sh/U, VisM to hits; all to FAs</td>
<td>162.33</td>
<td>155</td>
<td>.02</td>
<td>.88</td>
<td>.96</td>
<td>.97</td>
<td>2.55</td>
</tr>
<tr>
<td>7. RPI, VisM to hits; all to FAs</td>
<td>160.82</td>
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<td>.88</td>
<td>.97</td>
<td>.97</td>
<td>1.04</td>
</tr>
<tr>
<td>8. VisM to hits; all to FAs</td>
<td>171.39</td>
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<td>.03</td>
<td>.88</td>
<td>.94</td>
<td>.94</td>
<td>11.61*</td>
</tr>
<tr>
<td>9. Sh/U = RPI, VisM to hits; all to FAs</td>
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<td>155</td>
<td>.02</td>
<td>.88</td>
<td>.97</td>
<td>.97</td>
<td>.03</td>
</tr>
<tr>
<td>10. Sh/U = RPI, VisM to hits; all but Sp to FAs</td>
<td>176.46</td>
<td>156</td>
<td>.02</td>
<td>.88</td>
<td>.96</td>
<td>.96</td>
<td>16.68*</td>
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<td>.97</td>
<td>.97</td>
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<td>12. Sh/U = RPI, VisM to hits; Sh/U; RPI, Sp to FAs</td>
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<td>.96</td>
<td>.96</td>
<td>5.10</td>
</tr>
<tr>
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<td>.01</td>
<td>.88</td>
<td>.97</td>
<td>.97</td>
<td>1.56</td>
</tr>
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<td>15. Sh/U = RPI, VisM to hits; Sp to FAs</td>
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<td>.03</td>
<td>.87</td>
<td>.93</td>
<td>.93</td>
<td>20.62*</td>
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<tr>
<td>16. Sh/U = RPI, VisM to Hits; Sh/U = RPI, Sp to FAs</td>
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<td>158</td>
<td>.01</td>
<td>.88</td>
<td>.97</td>
<td>.97</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Note. Model of best fit is indicated in bold. $\Delta \chi^2$ is relative to Model 1. RMSEA = root mean square error of approximation; GFI = goodness of fit index; CFI = comparative fit index; IFI = incremental fit index; FAs = false alarms; Sp = perceptual speed; Sh = shifting; U = updating; RPI = resistance to proactive interference; VerM = verbal memory; VisM = visual memory.

*p < .05.
interference removed (Model 15) and a model that constrained these two paths to be equal (Model 16) were tested. Neither of these models fit as well as that with a path from resistance to proactive interference to familiarity and without a path from shifting/updating to familiarity (Model 14). This model (Model 14, displayed in Figure 4) was accepted as the model of best fit and exhibited statistically equivalent fit to the initial model, accounting for 34% of the variance in recollection estimates and 16% of the variance in familiarity estimates. When all other paths to recollection were allowed, 44% of the variance in recollection was explained; allowing all other paths to familiarity explained a total of 18% of the variance in familiarity. When all other paths to recollection were allowed, 44% of the variance in recollection was explained; allowing all other paths to familiarity explained a total of 18% of the variance in familiarity. The accepted model included paths from both shifting/updating and resistance to proactive interference to recollection that were constrained to be equivalent, and paths from resistance to proactive interference and from speed to familiarity.

Although the amount of variance explained in familiarity was relatively low, eliminating either the path from speed or from resistance to proactive interference to familiarity does significantly decrease the fit of the model, indicating that these paths contribute substantially to model fit. In addition, the directionality of the paths to recollection and familiarity is informative. The paths to recollection were both positive and equal in magnitude, indicating that both shifting/updating and resistance to proactive interference contribute equally to recollection such that as executive function capacity increases, recollection also increases. In contrast, the paths to familiarity were of opposite signs, with speed having a positive relationship to familiarity and resistance to proactive interference having a negative relationship. As speed increases, one’s access to automatically activated representations also increases regardless of the appropriateness of those representations, resulting in an increase in familiarity. In contrast, and as hypothesized, as executive ability to overcome interference increases, familiarity scores decrease, presumably because automatically activated but inappropriate representations are more easily identified and suppressed. The fact that the relationship of resistance to proactive interference with recollection is positive, whereas that with familiarity is negative, suggests that although the same executive process affects both recollection and familiarity processes, it does so through different mechanisms, thereby lending support to the assumption that recollection and familiarity are independent processes. In addition, the presence of a path from shifting/updat-
ing to recollection, but not to familiarity, further supports the independence of recollection and familiarity estimates.

**DISCUSSION**

The results of the present study have several implications regarding the organization of executive function and its relationship to interference in the working memory domain. First, the results suggest that executive function is best described as consisting of at least two distinct, yet related, subcomponent processes rather than as a purely unitary process. Second, the subcomponent processes of shifting/updating and resistance to proactive interference constitute cognitive constructs that are distinct from other common measures of cognition. Third, the component processes of shifting/updating, resistance to proactive interference, visual memory, and speed have differential influences on measures derived from a task of interference susceptibility. Individual differences in susceptibility to interference and recollection were predicted by both shifting/updating and resistance to proactive interference, with an additional influence of visual memory on susceptibility to interference as measured by hit rates, whereas individual differences in familiarity were predicted by resistance to proactive interference and speed. The implications of each of these results are discussed in detail.

### Unitary or Multiple Processes of Executive Function?

In this sample of older adults, executive function was best described by the subcomponent process of shifting and updating goals and representations in working memory, and a separate subcomponent process of resisting proactive interference. Although distinct from these other executive function subcomponents, the subcomponent process of inhibition of prepotent responses was not distinct from the construct of perceptual speed. When compared with a model with a unitary executive function construct, this subcomponent model provided a better fit to the data. It is possible that other subcomponent processes of executive function exist but were not included in this study. The current results found that shifting and updating were best treated as a single process, whereas the findings reported by Miyake et al. (2000) indicated a distinction between these two subcomponents, which had a correlation of .56 in their data. The larger correlation between these constructs in the current study may have been due to the restriction of the sample to older adults, who sometimes exhibit “dedifferentiation,” or increased interrelationships among cognitive variables (Anstey, Hofer, & Luszcz, 2003; Balinsky, 1941; Ghisletta & Lindenberger, 2003). However, the general pattern of correlations among the executive function constructs in this study does not appear to be inflated. Despite samples with different age ranges, largely different measures of the subcomponent processes, and somewhat different final models of the subcomponent constructs, the construct loadings from the executive function subcomponents in the current study (.40–.69, Mdn = .53) were of similar magnitude as those reported by Miyake et al. (.30–.63, Mdn = .46) and by Friedman and Miyake (2004; .28–.66, Mdn = .44). Likewise, the final executive function subcomponent model in the current study accounted for a median of 28% of the variance (ranging from 16% to 47%) in the executive function variables, which is similar to that reported by Miyake et al. (12%–39%, Mdn = 21%) and by Friedman and Miyake (7% to 44%, Mdn = 19%).

Salthouse et al. (2003) have suggested that the modest amounts of variance explained in tasks of executive function may indicate that executive function does not form a coherent cognitive construct. In their study (Salthouse et al., 2003; see Model A for executive function and subcomponents), a median of 28% of the variance in executive function variables was explained by subcomponent constructs similar to those used in this study and by Miyake et al. (2000), despite a larger range of variance explained in

### Table 4

**Structural Models for Recollection (R) and Familiarity (F)**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$</th>
<th>df</th>
<th>RMSEA</th>
<th>GFI</th>
<th>CFI</th>
<th>IFI</th>
<th>$\Delta\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. All constructs to R and F</td>
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<td>152</td>
<td>.00</td>
<td>.87</td>
<td>.99</td>
<td>.99</td>
<td>32.82*</td>
</tr>
<tr>
<td>2. No paths to R or F</td>
<td>179.72</td>
<td>162</td>
<td>.03</td>
<td>.85</td>
<td>.90</td>
<td>.91</td>
<td>5.46, $p = .05$</td>
</tr>
<tr>
<td>3. All but Sp to R; all to F</td>
<td>148.50</td>
<td>153</td>
<td>.00</td>
<td>.87</td>
<td>.98</td>
<td>.98</td>
<td>1.60</td>
</tr>
<tr>
<td>4. Sh/U, RPI, VerM to R; all to F</td>
<td>148.28</td>
<td>154</td>
<td>.00</td>
<td>.87</td>
<td>.98</td>
<td>.98</td>
<td>1.38</td>
</tr>
<tr>
<td>5. Sh/U, RPI to R; all to F</td>
<td>150.46</td>
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<td>.87</td>
<td>.98</td>
<td>.98</td>
<td>3.56</td>
</tr>
<tr>
<td>6. Sh/U to R; all to F</td>
<td>153.17</td>
<td>156</td>
<td>.00</td>
<td>.87</td>
<td>.97</td>
<td>.97</td>
<td>6.27</td>
</tr>
<tr>
<td>7. RPI to R; all to F</td>
<td>152.78</td>
<td>156</td>
<td>.00</td>
<td>.87</td>
<td>.98</td>
<td>.98</td>
<td>5.88</td>
</tr>
<tr>
<td>8. No paths to R or F</td>
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<td>157</td>
<td>.03</td>
<td>.86</td>
<td>.91</td>
<td>.92</td>
<td>21.51*</td>
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<td>.00</td>
<td>.87</td>
<td>.98</td>
<td>.98</td>
<td>2.81</td>
</tr>
<tr>
<td>10. Sh/U = RPI to R; all but Sp to F</td>
<td>155.17</td>
<td>157</td>
<td>.00</td>
<td>.87</td>
<td>.98</td>
<td>.98</td>
<td>8.27*</td>
</tr>
<tr>
<td>11. Sh/U = RPI to R; all but VisM to F</td>
<td>149.85</td>
<td>157</td>
<td>.00</td>
<td>.87</td>
<td>.98</td>
<td>.98</td>
<td>2.95</td>
</tr>
<tr>
<td>12. Sh/U = RPI to R; Sh/U, RPI, Sp to F</td>
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<td>.98</td>
<td>.98</td>
<td>2.18</td>
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<tr>
<td>13. Sh/U = RPI to R; Sh/U, Sp to F</td>
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<td>.00</td>
<td>.87</td>
<td>.97</td>
<td>.98</td>
<td>6.72*</td>
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<tr>
<td>14. Sh/U = RPI to R; RPI, Sp to F</td>
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<td>.98</td>
<td>.98</td>
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<tr>
<td>15. Sh/U = RPI to R; Sp to F</td>
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<td>160</td>
<td>.00</td>
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<td>.97</td>
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<td>16. Sh/U = RPI to R; Sh/U = RPL, Sp to F</td>
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<td>.00</td>
<td>.87</td>
<td>.98</td>
<td>.98</td>
<td>3.27</td>
</tr>
</tbody>
</table>

**Note.** Model of best fit is indicated in bold. $\Delta\chi^2$ is relative to Model 1. RMSEA = root mean square error of approximation; GFI = goodness of fit index; CFI = comparative fit index; IFI = incremental fit index; Sp = perceptual speed; Sh = shifting; U = updating; RPI = resistance to proactive interference; VerM = verbal memory; VisM = visual memory. $a \Delta\chi^2 = 5.46, p = .02$ relative to Model 9. $a \Delta\chi^2 = 4.54, p = .03$ relative to Model 12. $a \Delta\chi^2 = 9.30, p = .01$ relative to Model 12. $* p < .05$. 

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individual variables (8%–92%). The consistency of such results across studies suggests that although only modest amounts of variance may be shared among measures of executive function subcomponents, the variance that is shared appears to be substantially reliable and sufficient to form valid constructs. Further, despite strong correlations among executive function subcomponents in each of these studies (.42–.63 in Miyake et al., 2000; .71–.94 in Salthouse et al., 2003; and .46–.92 in the current study), models that treat executive function as a single construct tend to fit the data more poorly than do models that postulate distinct subcomponents of executive function.

Relations of Executive Function with Cognitive Constructs

The current results also indicate that the subcomponent processes of shifting, updating, and resistance to proactive interference are distinct from verbal memory, visual memory, and perceptual speed, three other cognitive constructs that are highly affected by aging (Park et al., 2002; Salthouse, 1996). The construct of inhibition of prepotent responses, however, was not distinct from perceptual speed. The correlations of the executive function subcomponent constructs in the accepted measurement model with verbal memory, visual memory, and perceptual speed (.28–.58, Mdn = .44) were weaker than the correlation between executive function subcomponents (.62), and were of similar magnitude as the correlations among the cognitive constructs (.22–.62, Mdn = .48).

The current results appear to be in contrast to the interpretation offered by Salthouse et al. (2003), who based their conclusion that executive function tasks do not form distinct constructs from other cognitive variables largely on the presence of significant correlations between executive function subcomponent constructs with the cognitive constructs of memory, speed, vocabulary, and fluid intelligence in a sample that included individuals ranging from 18 to 84 years of age. However, a reexamination of the results from Salthouse et al. (2003) suggests that measures of executive function are more highly related to one another than they are to other measures of cognition, although they do have significant relationships to other cognitive measures (see supplementary materials for detailed discussion). Even though their results could be regarded as suggesting that tasks of executive function merely provide additional indicators of a fluid intelligence construct, they are also

![Figure 4. Structural model for recollection (R) and familiarity (F). All values are from the completely standardized solution. Paths included in the final model are indicated by bold lines. Nonsignificant paths (p > .05) are indicated by dashed lines. P.I. = proactive interference.](image-url)
consistent with the view that fluid intelligence represents high-
level coordination of multiple component processes of executive
function (Conway, Kane, & Engle, 2003).

Executive Function and Interference

SE models indicated that subcomponents of executive function
were important for explaining individual differences in measures
of interference in a working memory task. Interference suscepti-
bility, measured by hit and false alarm rates in a short-term list
memory task (Hedden & Park, 2001, 2003), was predicted by both
shifting/updating and resistance to interference. Hits were addi-
tionally predicted by visual memory, and false alarms were also
predicted by perceptual speed. With only these direct paths in the
model, 36% of the variance in hit rates and 29% of the variance in
false alarm rates was explained, accounting for the vast majority of
variance attributable to any of the constructs measured. These
results indicate that an individual’s abilities to shift among and to
update, or refresh, representations of task contexts, along with the
ability to suppress competing representations that arise through
proactive interference, are primary indicators of how susceptible
that individual will be to retroactive interference in working
memory.

Estimates of recollection, a proxy for controlled monitoring of
source information in the task, and familiarity, a proxy for auto-
matic activation of representations and the inhibition of those
representations, were also calculated through application of the
process dissociation procedure (Jacoby, 1991, 1999) to perfor-
mance in the working memory task. Results from the SE models
showed that recollection was best predicted by both shifting/
updating and resistance to proactive interference, with 34% of the
variance in recollection being explained. This result suggests that
the abilities to shift between mental sets or task goals, update
representations, and manage interference from no-longer-relevant
representations are related to the extent to which an individual
exhibits controlled or explicit recollection of contextual informa-
tion in a task. Examples of contextual information that must be
tracked in working memory include temporal ordering, list iden-
tity, and relationships between presented items.

Familiarity was best explained by resistance to proactive inter-
ference and also by speed. As predicted, resistance to proactive
interference had a negative path to familiarity, suggesting that such
resistance acts to decrease the influence of task-irrelevant repre-
sentations held in working memory. Speed, in contrast, had a
positive path to familiarity, suggesting that individuals with faster
perceptual speed also have more efficient access to representations
maintained in working memory. However, only 16% of the var-
iance in familiarity was explained by the model, suggesting that
these cognitive constructs are only modestly related to the auto-
matic activation of representations in working memory. That is,
inhibitory mechanisms related to interference resistance may be
used to modulate the activation of representations, but the ability
to do so is limited. These results therefore support the view that
familiarity represents a primarily automatic process that is largely
outside the purview of executive function, as suggested by dual-
process theory (Jacoby, 1991, 1999). Further, the differential ef-
fects of shifting/updating and resistance to proactive interference
on recollection and familiarity suggest that recollection and fami-
liarity are largely independent processes.

Hedden and Park (2003) found large individual differences
among older adults in performance on this verbal working memory
task. Some older adults were highly susceptible to interference,
whereas others were no more susceptible to interference under
certain conditions than were younger adults. Hedden and Park
(2003) found that increasing source monitoring demands caused
greater difficulty for older adults compared with younger adults
but were unable to isolate what distinguished older adults who
were resistant to interference from those who were highly suscep-
tible to it. The current results demonstrate that individual differ-
ences in interference susceptibility among older adults are due
largely to variability in executive function subcomponents. That is,
those older adults who are best able to shift between changing task
goals, to update representations in working memory, and to inhibit
representations activated by proactive interference are also best
able to resist interference and to recollect the source of information
in verbal working memory. To a lesser extent, older adults with
superior visual paired associate memory are also better able to
resist interference, and those with better inhibitory ability over
proactive interference display less activation of irrelevant repre-
sentations in working memory.

The results from the SE models in this study hold several
important implications for a number of prominent cognitive theo-
ries. The finding that shifting/updating and resistance to proactive
interference predict individual differences in interference suscep-
tibility within working memory supports the notion that executive
function plays a large role in maintaining representations in the
face of interference (Kane & Engle, 2002). Kane and Engle (2002)
suggested that complex span tasks provide a good proxy for a core
executive function of resisting interference because they require
the maintenance of representations during intervals while a sec-
ondary, and interfering, task is performed. Many studies have used
such complex span tasks to predict individual differences in a
variety of domains, including reading (Daneman & Carpenter,
1980), memory (Hedden, Lautenschlager, & Park, 2005; Park et
al., 2002), and fluid intelligence (Engle, Tuholski, et al., 1999;
Kyllonen & Christal, 1990). These results suggest that a unified
executive function that maintains representations in the face of
interference may be a key predictor of individual differences on
many cognitive tasks.

The finding that recollection was predicted by shifting/updating
provides a link between common measures of task switching,
dual-process theory (Jacoby, 1991, 1998), and the processes hy-
pothesized by the source monitoring framework (Johnson et al.,
1993). This finding suggests that recollection processes that track
the source, or context, of information in working memory and bind
it to associated representations may overlap with processes that
enable one to effectively shift between mental sets or task goals.
Likewise, the updating or refreshing of representations in working
memory may assist in tracking both the current task goal and the
context information associated with to-be-remembered items. In-
deed, updating, refreshing, and shifting or task coordination pro-
cesses have all been found to activate overlapping regions in the
dorsolateral prefrontal cortex, as well as in parietal cortex (Collette
& Van der Linden, 2002; Raye, Johnson, Mitchell, Reeder, &
Green, 2002). These same regions have been found to be involved,
along with other cortical areas, in remembering source information
during episodic memory tasks (Dobbins, Foley, Schacter, & Wag-
ner, 2002; Dobbins, Rice, Wagner, & Schacter, 2003).
The observed relationships between resistance to proactive interference and recollection and familiarity hold implications both for dual-process theories of memory (Jacoby, 1991, 1999) and for theories involving inhibitory processes (Anderson & Green, 2001; Hasher & Zacks, 1988). The positive relationship with recollection indicates that some types of inhibitory processing are likely involved in cognitive control over working memory. The negative relationship with familiarity, however, has multiple implications. On the one hand, it suggests that familiarity processes are not entirely automatic and may be influenced to some extent by controlled processes of executive function. That is, inhibitory control over competing representations can be used to modulate the activation of representations held in working memory. Independent models of recollection and familiarity (Jacoby, Begg, & Toth, 1997) may therefore fail to account for the influences of the controlled process of resistance to proactive interference on familiarity, which is distinct from, but related to, other executive function subcomponents that influence recollection. On the other hand, the influence of interference resistance on familiarity is relatively small, so an independence model may account for the vast majority of effects.

The failure to find a distinct construct representing prepotent response inhibition and the small size of the effects of inhibition of proactive interference on familiarity suggests that inhibition may be less important in understanding susceptibility to interference than are other executive function subcomponents. Indeed, inhibition may represent not a single mechanism, but rather a diverse set of mechanisms that contribute differentially to aspects of cognition (Friedman & Miyake, 2004). Although older adults may be impaired in some types of inhibitory function (Lustig et al., 2001; Zacks & Hasher, 1998; Zacks et al., 1996), the consequences of this impairment may be smaller than the consequences of age-related impairments in source monitoring (Hedden & Park, 2003) or in shifting and updating functions. The failure to find a single inhibitory construct, or to find a distinct construct of prepotent response inhibition, may be a consequence of less coherence among individual measures of inhibitory function, as several studies have reported relatively weak relationships among measures of inhibition (Davidson & Glisky, 2002; Earles, Connor, Frieske, Park, & Smith, 1997; Park et al., 1996; Shilling, Chetwynd, & Rabbitt, 2002). A possible, but untested, alternative is that certain inhibitory functions are so central to executive function that they cannot be estimated separately from other subcomponent processes. For example, shifting between two task sets may require the inhibition of the prior task set as well as the activation of the new task set.

The current results are also relevant to debates concerning normal and pathological processes in aging (Hedden & Gabrieli, 2004; Rabbitt, Lowe, & Shilling, 2001; Small, 2001; Small, Tsai, DeLaPaz, Mayeux, & Stern, 2002). Normal aging appears to be related to ongoing changes in the volume, neurotransmitter availability, and functional activation of lateral prefrontal cortex (Bäckman et al., 2000; Raz et al., 2004; Rypma, Prabhakaran, Desmond, & Gabrieli, 2001; Volkow et al., 2000). Pathological processes related to the prodromal stage of Alzheimer’s disease, on the other hand, appear to impair the entorhinal cortex and its connections with the hippocampus and adjacent medial temporal structures, in some cases years before diagnosis (Killiany et al., 2002). The present results indicate that executive function subcomponents, which are likely subserved by circuits that rely heavily on the prefrontal cortex (Collette & Van der Linden, 2002; Stuss et al., 2002), are primarily responsible for individual differences in the ability to resist interference, to recollect the source of information in working memory, and, to a lesser extent, the ability to reduce activation of irrelevant representations. These findings are in line with those from a number of neuropsychological studies that have found that tasks of frontal function, but not medial temporal function, predict the ability to monitor source or context information (Butler, McDaniel, Dornburg, Price, & Roediger, 2004; Glisky et al., 1995, 2001; Henkel et al., 1998). However, the current study did find a significant contribution of visual memory to the ability to resist interference. This suggests that both executive function and memory function, and their associated neural correlates in the prefrontal cortex and medial temporal lobes, are responsible for individual differences in age-related performance on tasks of interference susceptibility and source monitoring. Because the previous neuropsychological studies selected a subset of older adults who exhibited frontal but not medial temporal deficits, and vice versa, they may have been comparing only those older adults affected primarily by either normal or pathological developmental processes. In most samples of older adults, however, the likelihood is that many individuals are experiencing both types of processes (Hofer & Sliwinski, 2001; Sliwinski, Lipton, Buschke, & Stewart, 1996) and that normal and pathological aging may interact with one another. The interaction of prefrontal cortex and parahippocampal function was recently observed in a functional neuroimaging study of memory encoding in younger and older adults, in which the direction of correlations between activation in the two regions was found to change with age (Gutchess et al., 2005).

The current results are limited by the restriction of the sample to older adults. Despite the older age range in the present study, the loadings of, variance explained by, and correlations among the executive function subcomponents were in the same range as those found in samples of college-aged adults (Friedman & Miyake, 2004; Miyake et al., 2000) and in a sample including adults between the ages of 18 and 84 (Saltouse et al., 2003). The congruence of the current results with those from other samples supports the general pattern regarding age differences in structural models of cognitive function. The pattern of loadings and constructs has generally been found to be age invariant, although quantitative group differences have been reported in the relationships between indicators and the constructs they measure and in relationships among constructs for young adults compared with older adults (Babcock, Laguna, & Roesch, 1997; Hedden et al., 2005; Hertzog, 1987; Nyberg et al., 2003). The results may also be limited by the small range of cognitive constructs examined, which involved only paired-associate memory for verbal and visual information and for perceptual speed. Other cognitive constructs, or the same constructs measured with different tasks, may have higher relationships with some executive function subcomponents.

In summary, the current results indicate that executive function is made up of at least two distinct subcomponent processes, including shifting between relevant task goals and updating representations in working memory, and resisting proactive interference. These components of executive function appear to vary independently, rather than jointly, across older individuals. Further, these subcomponents are distinct from, rather than con-
founded with, other cognitive constructs, such as verbal and visual memory and perceptual speed. In addition, these subcomponent processes are differentially related to aspects of performance in a task requiring source monitoring and resistance to interference in verbal working memory. Shifting and updating and resistance to proactive interference were related to individual differences in interference susceptibility and to recollection of source information in working memory, and to a lesser degree, resistance to proactive interference and perceptual speed were related to familiarity, or the activation of representations in working memory.

References


EXECUTIVE PROCESSING AND INTERFERENCE


Received August 8, 2005
Revision received March 23, 2006
Accepted April 24, 2006