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Cognitive Declines in Healthy Aging: Evidence From Multiple Aspects of Interference Resolution

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The present study tested the hypothesis that older adults show age-related deficits in interference resolution, also referred to as inhibitory control. Although oftentimes considered as a unitary aspect of executive function, various lines of work support the notion that interference resolution may be better understood as multiple constructs, including resistance to proactive interference (PI) and response-distractor inhibition (e.g., Friedman & Miyake, 2004). Using this dichotomy, the present study assessed whether older adults (relative to younger adults) show impaired performance across both, 1, or neither of these interference resolution constructs. To do so, we used multiple tasks to tap each construct and examined age effects at both the single task and latent variable levels. Older adults consistently demonstrated exaggerated interference effects across resistance to PI tasks. Although the results for the response-distractor inhibition tasks were less consistent at the individual task level analyses, age effects were evident on multiple tasks, as well as at the latent variable level. However, results of the latent variable modeling suggested declines in interference resolution are best explained by variance that is common to the 2 interference resolution constructs measured herein. Furthermore, the effect of age on interference resolution was found to be both distinct from declines in working memory, and independent of processing speed. These findings suggest multiple cognitive domains are independently sensitive to age, but that declines in the interference resolution constructs measured herein may originate from a common cause.

Keywords: aging, executive function, inhibition, interference resolution, proactive interference

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In the large literature on the factors that cause age-related cognitive decline, one influential account proposes that the underlying source is a deficit in interference resolution in older adults, the inhibitory deficit hypothesis of aging (Hasher, Stolzfus, Zacks, & Rypma, 1991; Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). However, researchers from a variety of perspectives maintain that there is more than one type of interference resolution (e.g., Friedman & Miyake, 2004; Hasher & Zacks, 1988; Hasher et al., 1999; Kok, 1999; Nigg, 2000), which raises the issue of whether age-related declines are found for all types of interference resolution, and if so, whether such age effects can be attributed to a common source. Given that prior findings are inconsistent with regard to age-related declines in interference resolution (e.g., Spieler, Balota, & Foust, 1996; Verhaeghen & De Meersman, 1998), the present study used various methodological approaches, including analyses at both the task and latent variable level, to examine whether a) age effects are found in one or multiple aspects of interference resolution, and b) the extent to which age independently influences the interference resolution constructs measured herein.

In their influential inhibitory deficit theory of aging, Hasher and colleagues (Hasher & Zacks, 1988; Hasher et al., 1999) proposed that there are three major interference resolution functions that act on the contents of working memory. The access function serves to restrict entry to working memory so that only relevant information is accessed. The deletion function serves to remove no longer relevant information from attentional focus, enabling one's focus to be updated with currently relevant information. And lastly, restraint over prepotent thoughts and actions serves to withhold strong, automatic responses (or thoughts) until they can be evaluated. Hasher, Zacks, and colleagues (Hasher et al., 1991; Hasher & Zacks, 1988; Hasher et al., 1999) posit that age-related cognitive declines are mediated by impairment to these interference resolution functions, with corresponding consequences for other aspects of cognition.

Friedman and Miyake (2004) explored the separability of three interference resolution constructs using structural equation modeling in an individual differences study of young adults. Although the constructs examined by Friedman and

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Miyake were not explicitly mapped one-to-one to those of Hasher and colleagues, conceptual similarities can be identified. The first construct, resistance to distractor interference, is similar to Hasher and colleagues' access function, as it measured the ability to resist interference from irrelevant information in the external environment. Second, resistance to proactive interference relates to Hasher and colleagues' deletion function, as it measured the ability to resist interference from no longer relevant information. Lastly, prepotent response inhibition, conceptually similar to Hasher and colleagues' restraining function, measured the ability to inhibit dominant or automatic responses. Though they initially hypothesized three distinct constructs, Friedman and Miyake found that the best-fitting confirmatory factor analysis model had two interference resolution factors, as resistance to distractor interference and prepotent response inhibition were very closely related. They called the single factor that combined these two constructs "response-distractor inhibition" (a term used in the present study). Friedman and Miyake proposed that these two factors "share the requirement to actively maintain task goals in the face of interference" (p. 126). Importantly, this response-distractor inhibition factor was unrelated to the resistance to proactive interference factor, which measured resistance to interference from information in memory, suggesting two distinct interference resolution constructs.

Turning to age related declines in these two aspects of interference resolution, older adults are more susceptible to PI than younger adults in a variety of tasks, including span tasks (e.g., May, Hasher, & Kane, 1999; McCabe, Robertson, & Smith, 2005), recent-probe tasks (e.g., Jonides et al., 2000; Thompson-Schill et al., 2002), build-up of PI over lists (e.g., Hasher, Chung, May, & Foong, 2002), and directed forgetting tasks (e.g., Titz & Verhaeghen, 2010). In contrast, the evidence for age-related impairments in response-distractor inhibition is much less consistent. For example, some studies have found exaggerated interference effects on individual response-distractor inhibition tasks such as the Stroop task (e.g., Spieler et al., 1996; West & Baylis, 1998), the Flanker task (e.g., Zhu, Zacks, & Slade, 2010), and reading tasks (e.g., Connelly, Hasher, & Zacks, 1991; Duchek, Balota, & Thessing, 1998), among others (e.g., Kramer, Humphrey, Larish, Logan, & Strayer, 1994). In fact, Hasher and colleagues have recently suggested that older adults unnecessarily encode concurrent distraction and also carry it forward in a way that effects performance on later tasks (e.g., Biss, Campbell, & Hasher, 2012; Campbell, Hasher, & Thomas, 2010; Thomas & Hasher, 2012). These findings suggest that older adults not only process distraction, but they have less control over it in the long run. However others have failed to find age differences in response-distractor inhibition tasks, failed to find distinct response-distractor inhibition factors in samples of older adults (e.g., Hedden & Yoon, 2006; Hull, Martin, Beier, Lane, & Hamilton, 2008), or have suggested these exaggerated interference effects are better attributed to general cognitive slowing (e.g., Fisk & Sharp, 2004; Madden, 1990; Wild-Wall, Falkenstein, & Hohnsbein, 2008; Verhaeghen & Cerella, 2002; Verhaeghen & De Meersman, 1998) or other aspects of cognition such as fluid intelligence (Shilling, Chetwynd, & Rabbitt, 2002). For example, in their study using Stroop-like interference tasks, Shilling et al. (2002) found no evidence for age-related impairments when processing speed was adequately taken into account. Such a finding is consistent with the view of Salthouse (1994; Salthouse & Babcock, 1991), who has suggested that age-related declines are mediated by declines in processing speed, rather than other cognitive abilities such as interference resolution. Processing speed accounts suggest that impaired performance results from slowed processing efficiency, such as information encoding or activation (Salthouse, 1994; Salthouse & Babcock, 1991). As a result, questions can be raised as to whether age-related declines in interference resolution are independent from declines in processing speed.

Furthermore, various theories have proposed a critical relationship between interference resolution and working memory (WM). For example, Hasher and Zacks (1988; May et al., 1999) have proposed that age-related WM declines result at least in part from deficits to interference resolution, whereas others have proposed the reverse, that excessive interference results from reduced or inefficient WM resources (e.g., Unsworth & Engle, 2007). Because there are various alternative perspectives on cognitive decline in aging (processing speed, WM), the present study considers individual difference in each when examining age-related changes in interference resolution.

Given previous psychometric support for the distinction between resistance to PI and response-distractor inhibition, the present study investigated whether each of these measures of interference resolution show similar patterns of decline with age, as might be hypothesized by the inhibitory deficit hypothesis of aging (Hasher & Zacks, 1988). This investigation made what we feel are methodological improvements over previous studies. First, we assessed both types of interference resolution in the same group of participants, as it is possible that differences across studies resulted from differences in the older individuals that were included. Second, we used multiple measures of each type of interference resolution to provide stronger evidence that any age-related decline was due to a deficit in the underlying construct rather than to task-specific demands. Thus, the present study tested both younger and older adults on multiple resistance to PI and response-distractor inhibition tasks to determine whether *consistent* patterns of age-related impairments could be found. Third, results were analyzed at both the individual task level (as commonly done) as well as the latent variable level, with each including controls for processing speed. The advantages of latent variable analyses are twofold. First, this allowed us to confirm whether resistance to PI and response-distractor inhibition are, in fact, best fit by two distinct constructs, as found by Friedman and Miyake (2004), and determine whether there is a significant effect of age on each of these latent variables. That is, while previous research has examined age effects at the individual task level, little work has asked whether age-related declines in multiple types of interference resolution might be explained by variance common to these constructs, versus independent effects of age on each. Second, the use of latent variable models allows for inclusion of other cognitive domains hypothesized to decline with age (here, WM) to determine whether age affects interference resolution and WM mechanisms separately.

Method

Participants

The young adult sample consisted of 105 individuals (18–32 years). Sixty-seven were recruited from the Rice University undergraduate subject pool and received experiment credit toward course requirements. The remaining 65 were recruited from the Houston community in order to sample a wider range of ability. Two young adults failed to return for the second session, and a third was excluded due to lack of English fluency. The remaining 102 young adults had a mean age of 21 years ($SD = 3.1$). The older adult sample consisted of 62 individuals (64–87 years) recruited from the Houston community through newspaper or Internet advertisements. One older adult's testing was discontinued and data excluded because of possible dementia, as indicated by a score of less than 26 on the Mini-Mental State Examination (MMSE; Folstein, Folstein, McHugh, & Fanjiang, 2001); the remaining older adults had scores greater than 26 (see Table 1). Data of another older adult were excluded because of an unwillingness to return for the second session. The remaining 60 older adults had a mean age of 71 years ($SD = 5.0$). Young and old community participants participated in exchange for monetary compensation ($10/hour).

Sample demographics and scores on background measures are shown in Table 1; relative to the young adults, older adults were comparable in cognitive status with those included in other aging studies in the literature. The older adults had more education than the young adults as they had, on average, completed an undergraduate degree. However, the two age groups had very similar scores on expressive vocabulary, indicating a close match on crystallized intelligence as measured by the vocabulary subtest of the WAIS-III (Weschler, 1997). Otherwise, the older adults showed standard patterns of age-related decline, including slower processing speed and reduced WM capacity.

Procedure

Participants completed a demographics questionnaire that asked about confounding disorders, history of neurological trauma (e.g., TBI), or other impairment that might affect cognitive functioning; for older adults, this also included the MMSE to screen for dementia. Study completion involved two separate 2-hr sessions with breaks provided between blocks during tasks and between tasks, as needed. With a few exceptions, all tasks were administered in a fixed order, the only exception being that some participants received the automated Ospan at a different time as a result of computer availability. Unless otherwise indicated, computerized tasks were administered on a Macintosh computer running PsyScope (Cohen, MacWhinney, Flatt & Provost, 1993). Data on two shifting tasks were collected as part of another study and are not reported here; additionally, saccade and antisaccade tasks were administered to only a subset of participants and are also not reported.

Materials and Task Descriptions

All tasks included a sufficient number of examples and practice trials for task familiarization and learning of stimulus-response mappings. Task stimuli were pseudorandomized and the stimulus order was fixed across subjects. In the interest of space, brief task descriptions are provided below; more detailed task descriptions can be found in online supplementary materials. The interference resolution tasks and their dependent variables are summarized in Table 2.

Resistance to Proactive Interference Tasks

Recent negatives task. In the recent negatives probe task (e.g., Monsell, 1978), participants heard a list of three words followed by a probe word and indicated whether the probe word was in the previous list by pressing *yes* or *no* buttons. This task contained three trial types. On positive trials, the probe word was presented in the most recently presented list (list n), requiring a *yes* response. On recent negative trials (interference trials), the probe word was not presented in the most recent list (list n), but it was presented in the previous trial (list n − 1), requiring a *no* response. On nonrecent negative trials (no interference trials), the probe word was not presented in any of the

Table 1
Demographic Information and Age Comparisons on Background Tasks for Young and Old Adults

Measure	Young ($n = 102$)	Old ($n = 60$)	
Demographics			
Age	21 (3.1)	71 (5.0)	$t(86.49) = 70.15$, $p < .001^*$
Years of education	14 (1.7)	16 (2.8)	$t(84.67) = 4.87$, $p < .001^*$
Background tasks			
MMSE (/30)	—	28.8 (1.1)	
Vocabulary (/66)	52 (7)	52 (8)	$t(120.65) = 0.24$, $p = .41$
Processing speed (/35)	24.8 (5.8)	16.3 (3.2)	$t(154.21) = 14.14$, $p < .001^*$
Working memory tasks			
Operation span	43.0 (16.5)	20.0 (17.0)	$t(115.81) = 8.32$, $p < .001^*$
Backwards digit span	8.4 (2.7)	7.6 (2.7)	$t(122.48) = 1.89$, $p = .03^*$
Sternberg recognition	89% (5)	85% (10)	$t(72.80) = 2.38$, $p = .01^*$

Note. Standard deviations are shown in parentheses and asterisks indicate significant effects of age ($p < .05$, one-tailed).

Table 2
Summary of Interference and No Interference Conditions for Each Resistance to Proactive Interference and Response-Distractor Inhibition Task

Task	Conditions	DVs
Resistance to PI tasks		
Recent negatives	No interference: Non-recent negative trials	a. *RT*
	Interference: Recent negative trials	b. Proportion correct
Cued recall, directed forgetting	No interference: One-block trials (/14)	a. *Proportion correct*
	Interference: Two-block control trials (/13)	b. List 1 intrusions in 2-block interference trials
	[Two-block interference trials (/13)]	
Release from PI	No interference: List 1 words recalled	a. Proportion correct
	Interference: List 2 words recalled	b. *Proportion of list 1 intrusions at list 2 recall*
Response-distractor inhibition		
Flanker task	No interference: neutral; OOOKOOO	a. *RT*
	Interference: incongruent; CCCKCCC	b. Proportion correct
Picture-word interference	No interference: *un*related superimposed picture	a. *RT*
	Interference: related superimposed picture	b. Proportion correct
Nonverbal Stroop	No interference: neutral; left arrow, center aligned	a. *RT*
	Interference: incongruent; left arrow, right aligned	b. Proportion correct
Stroop	No interference: neutral; *****	a. *RT*
	Interference: incongruent; Blue	b. Proportion correct

Note. The 'Conditions' column describes task conditions, with additional measures shown in brackets. The 'DVs' column shows the variables used for calculating regression residuals, as described in text. Italicized values indicate the measure used in the structural equation modeling, which were regression residuals unless otherwise indicated.

most recent lists, requiring a *no* response. The dependent variables were response times (RT) and accuracy for recent versus nonrecent negative trials.

Cued recall task. In the cued recall task (Tolan & Tehan, 1999; similar to Friedman & Miyake, 2004), a trial consisted of one or two lists of four sequentially presented words. After a filler task, participants saw a category cue and recalled the category exemplar from the most recently presented list. At the start of a trial, participants did not know whether there would be one or two lists. One list trials consisted of a list of words, the filler task, then a category cue. Of the trials with two lists, half were "control" trials in which only the second list contained an item from the cued category. The other half of the two list trials were "lure" trials in which both lists contained an item that matched the cued category (though participants only had to recall the item from the second list). The dependent variable was accuracy for one list versus two list control trials (similar to Friedman & Miyake, 2004). We also calculated the proportion of list one lures recalled during two list lure trials.

Release from proactive interference task. In the release from PI task (a variant of the task used by Peterson & Peterson, 1959; similar to Friedman & Miyake, 2004), participants completed blocks of trials, with each block containing four lists of eight items. Within each block, the first three lists contained items from the same semantic category and were used to build up interference; the fourth list consisted of items from a different semantic category (release from PI). After the final (eighth) item of each list, participants completed a filler task then freely recalled as many words as possible from that list. The dependent variable was the buildup of PI, measured as recall accuracy for the first versus second list of the same category. We also calculated the number of list 1 intrusions made during list 2 recall.

Response-Distractor Inhibition Tasks

Flanker task. In the Flanker task (e.g., Eriksen & Eriksen, 1974) participants indicated the identity of the central letter in a string of letters (e.g., KKKHKKK) by pressing one of two buttons. In the congruent condition, flanking letters were mapped to the same button as the target letter. In the neutral condition, flanking letters were not mapped to a response button. In the incongruent condition, flanking letters were mapped to opposite button as the target letter. The dependent variables were RT and accuracy for incongruent versus neutral trials. One young adult's flanker data were missing due to experimenter error.

Picture-word interference task (PWI). In the PWI task (Lupker, 1979; Schriefers, Meyer, & Levelt, 1990), participants saw a picture with a superimposed distractor word and they responded by naming the picture (while ignoring the word). Across the task, each picture was seen in a semantically related condition (i.e., picture and word come from the same semantic category; interference condition) and in a semantically unrelated condition (i.e., picture and word come from different categories; no interference condition). The dependent variables were RT and accuracy for semantically related versus unrelated trials. One young adult's PWI data were missing because of experimenter error.

Nonverbal (NV) Stroop task. In the NV Stroop task (Hamilton & Martin, 2005), participants pressed a button to indicate the direction an arrow was pointing (right, left), with arrows appearing on either the left side of the screen, the center of the screen, or the right side of the screen. The task contained incongruent trials (left-pointing arrow on the right side of the screen), neutral trials (left-pointing arrow on the center of the screen), and congruent trials (left-pointing arrow on the left side of the screen). The dependent variables were RT and accuracy for incongruent versus neutral trials.

Stroop task. In the Stroop task (Stroop, 1935), participants named the color of the target, which was either a word (in incongruent and congruent conditions) or string of asterisks (in the neutral condition). On incongruent trials, color words appeared in a color that was different from the written word (e.g., the word blue written in red ink). On congruent trials, color words appeared in the same color as the written word. The dependent variables were RT and accuracy for incongruent versus neutral trials. One older adult's Stroop data were missing due to color blindness.

Processing Speed

Symbol-digit coding. The symbol-digit coding task is a paper and pencil task from the MMSE-2 (Folstein et al., 1975, 2001). The top of the page contained a key with symbols that corresponded to the numbers 1–9; participants used this key to code as many numbers as possible within 30 seconds. The dependent variable was the number of items correctly completed.

Working Memory

Automated operation span (Ospan). In the automated Ospan (Turner & Engle, 1989; Unsworth, Heitz, Schrock, & Engle, 2005), participants first saw a math operation to verify (*true*/*false*), followed by a letter to remember. Following several math operation-letter pairs, participants recalled the previously presented letters in serial order. The dependent variable was the operation span defined as the sum of all perfectly recalled sets (Unsworth et al., 2005). Ospan data were missing from two older adults as a result of experimenter or computer error.

Backwards digit span. In the backward digit span (Weschler Adult Intelligence Scale—Revised; Weschler, 1981), participants heard a series of numbers which they recalled in backward order, starting with the most recently presented item. The dependent variable was the total number of trials correctly recalled.

Sternberg recognition task. In the Sternberg recognition task (McElree & Dosher, 1989; Nee & Jonides, 2008), participants saw a list of five serially presented words, each presented for 500 ms. A 300-ms mask was presented over the last word, followed by a probe word which remained on the screen for 700 ms. Participants indicated whether the probe word was in the most recently presented list by pressing *yes* or *no* buttons. The dependent variable was accuracy across all trials. Data were missing for two older adults as a result of unwillingness to complete this task because of frustration with the speed of item presentation.

Results

Data Processing and Dependent Variables

Response times from errors and voice key errors were removed. Following this, outlying RTs were removed in two stages. First, extreme outliers (RTs <250 ms and >10,000 ms) were removed. Second, RTs falling 2.5 standard deviations beyond an individual's mean by condition were also removed.

Both the individual task and latent variable level analyses used regression residuals as the primary dependent variables for the interference resolution tasks (with one exception in the latent variable level analyses, noted below). In these analyses, we regressed the interference condition on the no interference condition (conditions listed in Table 2) across all subjects and saved the residuals. Such regression methods have been suggested as a more appropriate way to investigate group differences, rather than simple difference scores (e.g., Cerella, 1990; Cronbach & Furby, 1970; Zhang, Han, Verhaeghen, & Nilsson, 2007), as they indicate whether an individual's performance on the interference condition is larger or smaller than would be predicted from their baseline (i.e., no interference) score. These residuals control for individual differences in baseline task variance attributable to factors other than interference resolution, including individual differences in processing efficiency, such as information encoding or activation (Salthouse, 1994; Salthouse & Babcock, 1991).

Analyses of Individual Tasks

A MANOVA was first carried out separately for the PI tasks and for the response-distractor inhibition tasks, including age (young, old) as a between-subjects variable. MANOVAs were followed up by between-subjects univariate ANOVAs for each task, examining the main effect of age (young, old) on the interference residuals. The main effect of age reveals whether interference effects were larger for older than younger subjects, controlling for individual variability in no interference conditions. The only exceptions to these ANOVAs on residuals were univariate between-subjects ANOVAs of intrusions in the cued recall and release from PI tasks, as there was only one dependent measure per subject—that is, intrusions of no longer relevant list 1 items during list 2 recall. Table 3 summarizes performance on each task, by condition and age, and also includes the ANOVA results.

Resistance to PI tasks. Scatterplots for each resistance to PI task are shown in Figure 1; these scatterplots show conditions from which residual scores were calculated. In the MANOVA, the dependent measures were residual interference effects for the three resistance to PI tasks, including both RT and accuracy for the recent negatives task.[1] There was a significant main effect of age, $F(4, 157) = 21.81$, $p < .001$, $\eta^2 = .36$.

ANOVA results from analyses at the individual task level are shown in Table 3. In line with the MANOVA results, there were significant effects of age for all four resistance to PI dependent variables, with older adults consistently demonstrating larger interference effects than young adults. In addition, the main effect of age was significant in both the cued recall and release from PI intrusion analyses, $F(1, 160) = 18.76$, $MSE = 0.04$, $p < .001$, $\eta^2 = .11$ and $F(1, 160) = 119.77$, $MSE = 0.06$, $p < .001$, $\eta^2 = .16$, respectively. In both, older adults were more likely to intrude no longer relevant items.

Response-distractor inhibition tasks. We ran separate MANOVAs on RT and accuracy residuals, each including all four response-distractor inhibition tasks. Scatterplots for these DVs are shown in Figure 1. There was a significant effect of age for RTs,

[1] Recall and accuracy residuals were reverse scored so larger residuals would reflect larger interference effects, as is the case for RT residuals.

Table 3
Descriptive Statistics (Means, Standard Deviations) by Age Group and Condition

Task	No interference	Interference	AVOVA results – Effect of age
Resistance to PI tasks			
Recent negatives, RTs			
Young	1034 (236)	1125 (273)	$F(1, 160) = 7.39$, $MSE = 0.96$, $p = .007$, $\eta^2 = .04$
Old	1358 (562)	1562 (644)	
Recent negatives, accuracy			
Young	0.98 (0.07)	0.93 (0.09)	$F(1, 160) = 13.45$, $MSE = 0.92$, $p < .001$, $\eta^2 = .08$
Old	0.97 (0.05)	0.88 (0.10)	
Cued recall, accuracy			
Young	0.81 (0.15)	0.74 (0.21)	$F(1, 160) = 27.65$, $MSE = 0.85$, $p < .001$, $\eta^2 = .15$
Old	0.67 (0.19)	0.46 (0.23)	
Release from PI, words recalled			
Young	4.93 (1.01)	4.11 (0.96)	$F(1, 160) = 34.15$, $MSE = 0.82$, $p < .001$, $\eta^2 = .18$
Old	4.00 (1.12)	2.84 (0.88)	
Response-distractor inhibition tasks			
Flanker, RTs			
Young	640 (115)	720 (144)	$F(1, 159) = 1.32$, $MSE = 0.99$, $p = .25$, $\eta^2 = .008$
Old	794 (171)	864 (160)	
Flanker, accuracy			
Young	0.974 (0.03)	0.955 (0.04)	$F(1, 159) = 13.34$, $MSE = 0.92$, $p < .001$, $\eta^2 = .08$
Old	0.986 (0.02)	0.983 (0.02)	
PWI, RTs			
Young	897 (105)	936 (110)	$F(1, 159) = 2.92$, $MSE = 0.98$, $p = .09$, $\eta^2 = .02$
Old	1045 (138)	1101 (153)	
PWI, accuracy			
Young	0.98 (0.04)	0.98 (0.04)	$F(1, 159) = 0.07$, $MSE = 1.00$, $p = .79$, $\eta^2 = .00$
Old	0.97 (0.02)	0.97 (0.03)	
NV Stroop, RTs			
Young	438 (60)	485 (58)	$F(1, 160) = 9.69$, $MSE = 0.94$, $p = .002$, $\eta^2 = .06$
Old	636 (118)	702 (116)	
NV Stroop, accuracy			
Young	0.98 (0.04)	0.95 (0.06)	$F(1, 160) = 7.48$, $MSE = 0.96$, $p = .007$, $\eta^2 = .05$
Old	0.99 (0.02)	0.97 (0.03)	
Stroop, RTs			
Young	698 (78)	841 (116)	$F(1, 159) = 7.19$, $MSE = 0.96$, $p = .008$, $\eta^2 = .04$
Old	907 (144)	1194 (231)	
Stroop, accuracy			
Young	0.99 (0.02)	0.97 (0.04)	$F(1, 159) = 14.83$, $MSE = 0.92$, $p < .002$, $\eta^2 = .09$
Old	0.96 (0.05)	0.91 (0.08)	

Note. ANOVA results show the effect of age on interference residuals from the task level analyses for resistance to PI and response-distractor inhibition tasks, as described in text.

$F(4, 154) = 5.03$, $p = .001$, $\eta^2 = .12$, and accuracy, $F(4, 154) = 7.50$, $p < .001$, $\eta^2 = .16$.

ANOVA results from analyses at the individual task level are shown in Table 3. In the NV Stroop and Stroop tasks, older adults' interference effects were significantly larger than those for young adults, and this effect was marginal for the PWI task ($p = .09$). In contrast, the effect of age was nonsignificant for the flanker task. In accuracy, there were significant effects of age on the Stroop, NV Stroop, and flanker tasks. The Stroop effect was driven by larger interference effects for older relative to younger adults, whereas the reverse was true for the NV Stroop and Flanker tasks. For the PWI task, the age groups did not differ. On average, however, accuracy was quite high in these tasks (Stroop = 96.9%, NV Stroop = 97.6%, Flanker = 97.7%, PWI = 97.8%).

Despite high accuracy on the NV Stroop task, the opposite pattern of age effects for RT and accuracy analyses raises the possibility of a speed–accuracy trade-off. We examined this possibility in two ways. First, we correlated the RT and accuracy effects, as measured by difference scores between interference and no interference conditions; a speed–accuracy trade-off would be indicated by a significant positive correlation. Across all subjects, RT and accuracy effects were not significantly correlated ($r = -0.11$, $p = .17$). Second, we ran a follow-up analysis on a subset of subjects performing at high accuracy (mean accuracy >97.5% across interference and no interference conditions). Previous studies have found that older adults tend to be more cautious than younger adults, resulting in longer RTs but lower error rates (e.g., Salthouse, 1979). By examining those subjects who performed at such a high level, we assumed that the young and old subjects would be behaving with a similar degree of caution. In this subset ($n = 47$ young, $n = 45$ old), there was a significant effect of age for RT residuals, $F(1, 90) = 4.26$, $MSE = 0.96$, $p = .04$, $\eta^2 = .05$, with older adults demonstrating larger interference effects; in contrast, the age effect for accuracy residuals was not significant, $F(1, 90) = 0.54$, $MSE = 0.99$, $p = .46$, $\eta^2 = .006$. Thus, the NV Stroop RT age effects appear to reflect true age differences.

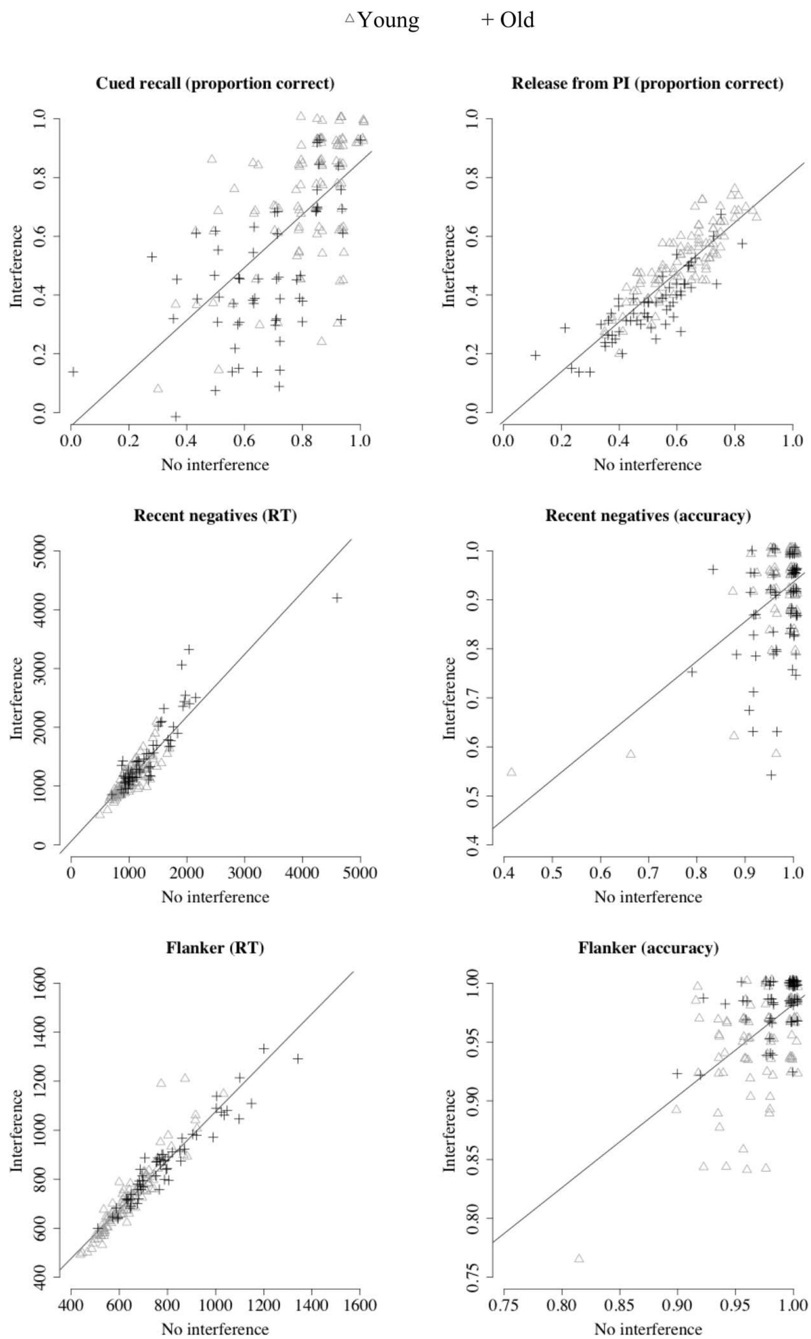

Figure 1. Scatterplots for each interference resolution task dependent variable, showing the conditions used to calculate regression residuals and the best fitting regression line. Noise was added to data points in the accuracy scatterplots to better display overlapping values, given the high accuracy of both age groups.

Structural Equation Modeling

We also examined age effects on resistance to PI and response-distractor inhibition tasks at the level of latent variables, using structural equation modeling (SEM), which poses several advantages over the previous analyses. SEM allowed us to simultaneously estimate the effect of age on resistance to PI, response-distractor inhibition, and WM constructs, given that each of these constructs has been hypothesized to account for age-related declines in cognition. Furthermore, we also examined whether these three constructs were best fit by separate latent variables, or whether some age effects are shared among variance that is common to these factors. To do so, we compared the fit of the three-factor model to its various nested models. In nested models, variables from a subset of the constructs were allowed to load on

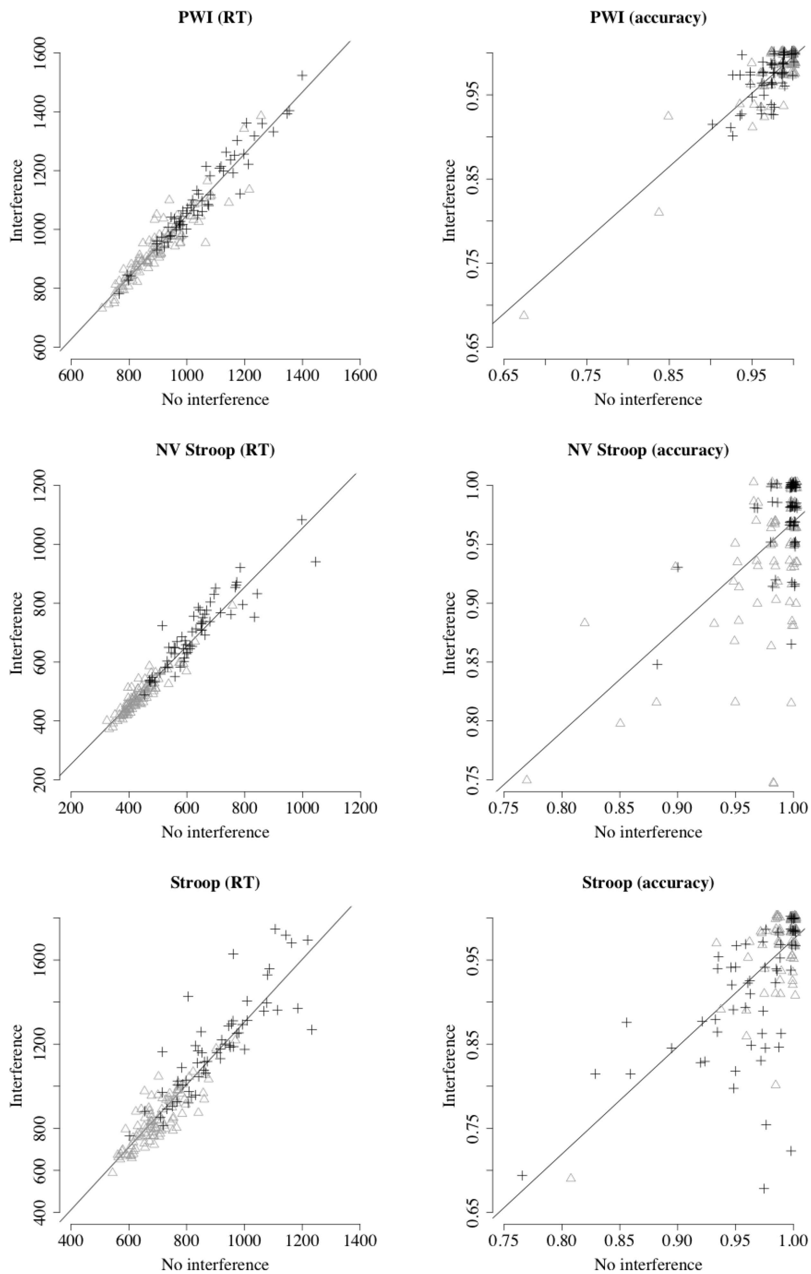

Figure 1 (continued).

a single factor (e.g., a single factor for the resistance to PI and WM tasks), and the effect of age was estimated on the remaining latent variables. This is equivalent to setting the correlation between different latent variables to 1.0, and constraining their relationship with other constructs to be equal to each other.

In addition, we also tested a common factor model[2] (Schmiedek & Li, 2004) to determine whether age independently influences each of these variables, or alternatively, whether the effects of age results from shared variance (i.e., a common cause) between interference resolution and WM tasks. To accomplish this, we examined specific and general age effects (Brunner, Nagy, & Wilhelm, 2012; Schmiedek & Li, 2004; see also Salthouse & Ferrer-Caja, 2003) by simultaneously estimating latent variables reflecting specific constructs (here, interference resolution, WM) and a "common" factor that represents variance common to all tasks. Unlike hierarchically structured models, all factors were extracted at the level of the observed variables (see Schmiedek & Li, 2004 for discussions on model selection). This allowed us to determine whether age-related declines across these cognitive do-

[2] We use "common factor model" over Schmiedek and Li's (2004) "nested factor model" to distinguish this model from the nested first order latent variable models.

mains are best accounted for by a) independent age effects on specific cognitive constructs or b) a common cause, such as the shared variance between tasks.

For all models, age effects were estimated by including age as a dichotomous predictor on each latent variable. Furthermore, we controlled for individual differences in processing speed in the interference resolution tasks by using regression residuals, as discussed above.

Missing data. As mentioned in the Method, seven data points were missing, though no individual subject was missing data for more than one task. Given the small number of missing points, and to avoid excluding these subjects altogether, missing values were replaced with the mean for that age group.

Dependent variables and additional data processing. Task DVs, descriptive statistics, estimates of distributional normality, and internal reliabilities are shown in Table 4. Reliabilities were variable, with some being unacceptably low (e.g., PWI, cued recall), others being excellent (e.g., Stroop, WM measures), and everything else falling somewhere in between. Our low to moderate reliabilities are consistent with other executive function work (e.g., Friedman & Miyake, 2004; Miyake et al., 2000).

Task performance was estimated by regression residuals, with three exceptions. First, for the cued recall task, the regression residuals were reverse scored so higher scores indicated larger interference effects, as is the case for the other interference resolution measures. Second, it was found that the release from PI difference score had extremely low reliability, likely due to the small number of trials; therefore, we instead used the *z*-scored proportion of list 2 intrusions as this task's DV. This measure resulted in a substantially improved reliability (.31 vs. .76, respectively). Third, we used *z*-scored accuracy measures as the dependent variables for the three WM tasks so these variables would be on the same scale as the regression residuals. Before calculating regression residuals or *z*-scores, accuracy measures (proportions correct) included in the latent variable models were arcsine transformed (as done by Miyake et al., 2000). For the interference resolution tasks, higher scores indicated larger interference effects, and therefore worse performance. For WM measures, higher scores indicated larger WM capacities (i.e., better performance).

Each DV was examined for distributional normality. For measures with unacceptable skew or kurtosis, outliers identified as being both beyond the overall interquartile range and 2.5 standard deviations beyond the overall mean were replaced with values that were 2.5 standard deviations beyond the mean for that individual's age group. This trimming affected less than 2% of the total number of observations and resulted in acceptable skew and kurtosis levels (see Table 4). Correlations among the modeled tasks are shown in the Appendix. Similar to previous executive function work, the correlations among interference resolution measures were generally low (e.g., Friedman & Miyake, 2004; Miyake et al., 2000).

Model estimation. Latent variable models were estimated in R using the lavaan (*la*tent *va*riable *an*alysis) package (Rosseel, 2012). Model fit was evaluated via multiple fit indices. The chi-square goodness-of-fit statistic tests model fit by assessing the "discrepancy between the sample and fitted covariance matrices" (Hu & Bentler, 1998, p. 426); for this index, a small, nonsignificant value indicates good fit. In addition, continuous fit indices were also evaluated (Hu & Bentler, 1999). Bentler's comparative fit index (CFI) is an incremental fit index with range of 0–1; this index compares the fitted model to a restricted baseline model, with values $>$ .90 indicating acceptable fit (Blunch, 2008) and values $\geq$ .95 indicating good (Hu & Bentler, 1999). The root mean square error of approximation (RMSEA) and standardized root-mean-square residual (SRMR) are both residual-based fit indices, measuring a model's ability to fit sample data; for each, lower values indicate good fit (RMSEA $<$ .06, SRMR $<$ .08; Hu & Bentler, 1999). Additionally, we directly compared fits of nested models by examining changes in chi-square values across models. If the fuller, more complex model has a change in chi-square that is significant given the loss of degrees of freedom, it is accepted as having better fit. If multiple models provided good fit, with no statistical difference in cross-model chi-square comparisons, the principle of parsimony dictates that the simplest model is to be preferred, until alternative evidence is presented.

The progression of model fits is described below, and shown in Figure 2 (though only one of the nested two-factor models is displayed); fit indices are reported in Table 5. Model 1 fit the three-factor model, in which resistance to PI, response-distractor

Table 4
Descriptive Statistics for the Dependent Variables Included in Models 1–6

Task	*M*	*SD*	Skew	Kurtosis	Reliability
Resistance to PI tasks					
Recent negatives (RT, interference effect)	−0.02	0.86	0.43	1.05	.65
Cued recall (prop. recalled, interference effect)	0.00	1.00	0.51	−0.28	.59
Release from PI (prop. list 2 intrusions)	0.00	1.00	1.23	1.25	.76
Response-distractor inhibition tasks					
Flanker (RT, interference effect)	−0.04	0.82	0.24	1.20	.53
PWI (RT, interference effect)	0.01	0.93	0.16	0.96	.45
NV Stroop (RT, interference effect)	0.007	0.90	0.35	0.94	.64
Stroop (RT, interference effect)	−0.02	0.87	0.45	1.13	.91
Working memory					
Ospan (prop. recalled)	0.00	1.00	0.52	0.46	.78[a]
Backwards digit span (prop. recalled)	0.00	1.00	0.91	1.13	—
Sternberg recognition (accuracy)	0.02	0.92	−0.46	−0.04	.95

Note. Reliabilities were calculated using a split-half correlation adjusted by the Spearman-Brown formula, unless otherwise indicated. Dash indicates that reliability was not calculated.
[a] Split-half reliability as reported by Unsworth et al. (2005).

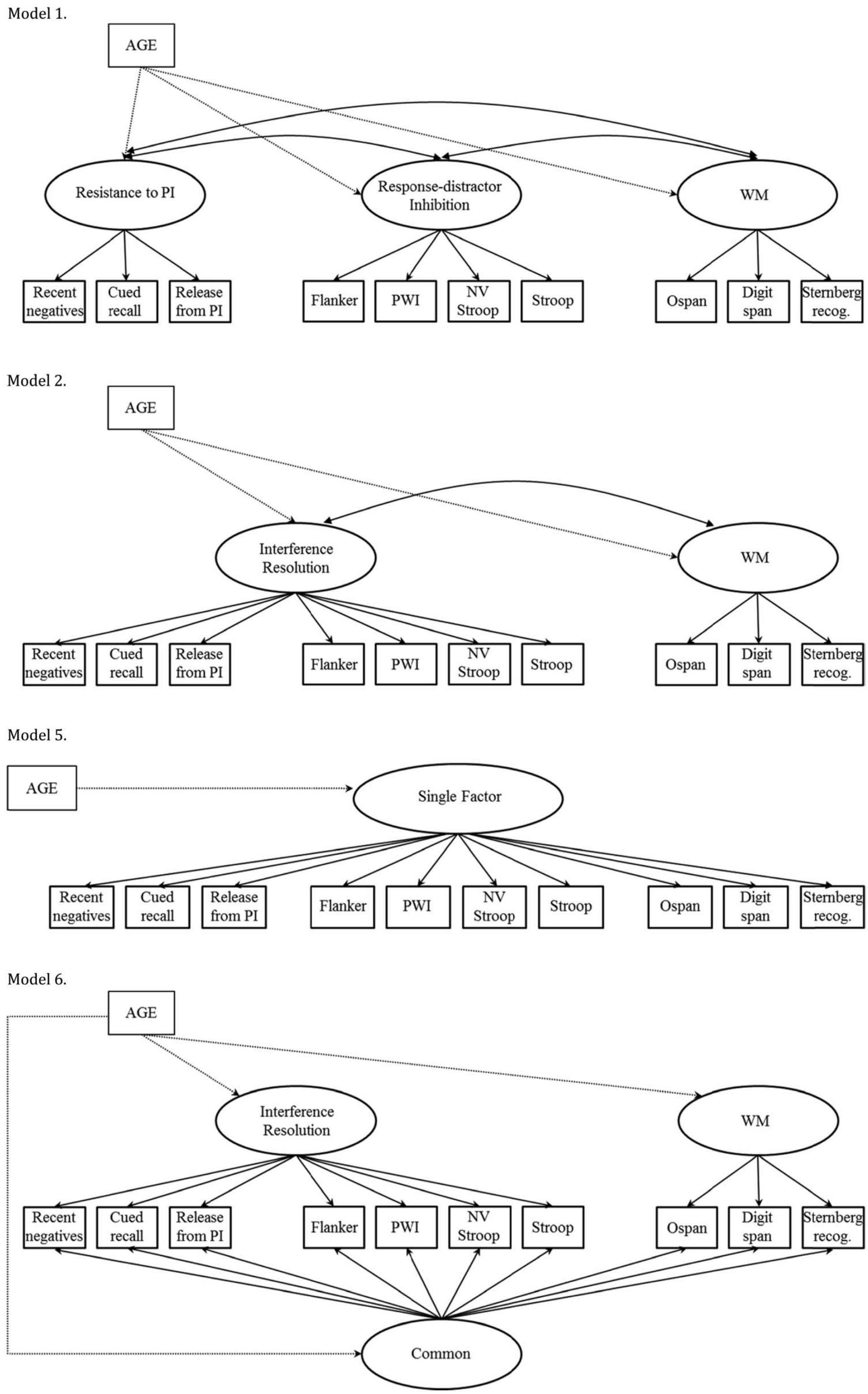

Figure 2. Model structures evaluated in the present study. Only one of the nested two-factor models is depicted (Model 2), though the two other alternative nested factor models (Models 3 and 4) were also tested, as described in text.

Table 5
Fit Indices of Models 1 Through 6

Model	χ^2	*df*	CFI	RMSEA (90% CI)	SRMR	$\Delta\chi^2$, *df*
1) 3-factor model	51.97	39	0.95	0.05 (.00–.08)	0.06	—
2) 2-factor model, inhibition = resistance to PI	**55.23**	**42**	**0.95**	**0.04 (.00–.07)**	**0.06**	**3.26, 3**
3) Two-factor model, inhibition = WM	69.66*	42	0.90	0.06 (.04–.09)	0.07	17.69, 3*
4) Two-factor model, resistance to PI = WM	104.01*	42	0.78	0.10* (.07–.12)	0.08	52.04, 3*
5) Single-factor model	107.10*	44	0.78	0.09* (.07–.12)	0.08	55.13, 5*
6) Two-factor interference resolution and WM model, with additional common factor	29.77	32	1.00	0.00 (.00–.05)	0.04	—

Note. Best fitting first order latent variable level model is indicated in bold. Change in χ^2 calculated relative to Model 1. CFI = comparative fit index; RMSEA = root mean square error of approximation; CI = confidence interval; SRMR = standardized root-mean-square residual.
* $p < .05$.

inhibition, and WM formed three distinct yet correlated latent variables. As shown in Table 5, this model provided a good fit to the data. With the exception of the flanker task, all tasks loaded significantly on their hypothesized factor, and there were significant age effects on each factor (for age effects, all *p*s ≤ .001). The correlation between the resistance to PI and response-distractor inhibition latent variables was moderate but nonsignificant (r = .43, p = .14). This was the largest correlation among the latent variables, with the absence of high correlations between these latent variables providing evidence that these three latent variables do, in fact, represent distinct constructs.

Model 2 fit the two-factor nested model in which the response-distractor inhibition and resistance to PI constructs were considered as reflecting the same underlying factor (see Figure 2). This model also provided a good fit to the data (see Table 5); as with Model 1, all tasks loaded significantly on their factors, with the exception of the flanker task. Again, there were significant age effects on the interference resolution and WM factors (both *p*s < .001). Furthermore, the change in chi-square values between Models 1 and 2 was nonsignificant (see Table 5), indicating that these two models provided statistically equivalent fits to the data; the corresponding factor loadings are shown in Figure 3.

Models 3 and 4 compared the remaining two-factor models. In Model 3, the response-distractor inhibition and WM constructs were considered equivalent, and in Model 4, the resistance to PI and WM constructs were considered equivalent (models not shown in Figure 2). In addition, Model 5 fit the single-factor model, in which all variables loaded on a single factor (see Figure 2). In each of these models, age was again a significant predictor of each latent variable (data not shown). However, the change in chi-square values for Models 3, 4, and 5 (relative to Model 1) were significant (see Table 5), indicating that Model 1 provided a better fit to the data. Using qualitative comparisons of fit indices, one can also see that these Models fit worse than Model 2. On the grounds of parsimony, then, Model 2, with one factor reflecting interference resolution for both PI and response distractor-interference, provides the best fit to the data.

One issue with the first-order latent variable models just discussed is that they underestimate the influence of age on the variance that is shared among all latent variables (Salthouse & Ferrer-Caja, 2003), an issue that was overcome in the common factor model (Model 6, Figure 2; Schmiedek & Li, 2004). This model includes a "common" factor estimated at the level of observed variables to determine whether age effects result from shared variance among all tasks. However, the results of this model should be interpreted with caution, given some have suggested that the ratio of the sample size to the number of parameters estimated should be greater than 5 (Bentler & Chou, 1987); for this

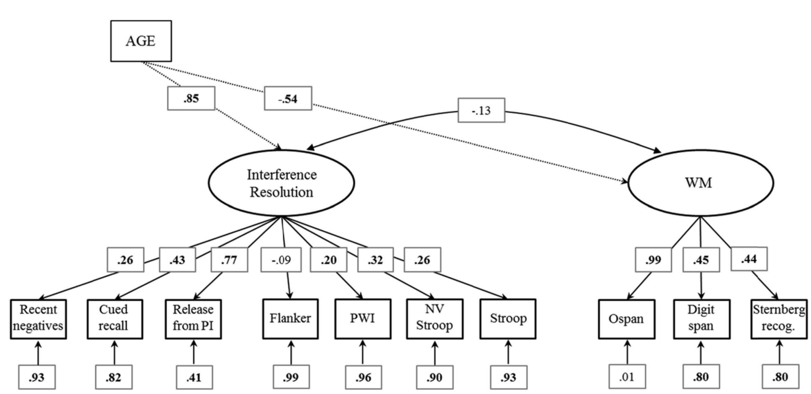

Figure 3. Final measurement model including task loadings on the interference resolution and WM latent variables, as well as the estimated effect of age on each factor. Numbers intersecting solid arrows indicate standardized construct loadings. Numbers intersecting dashed arrows indicate standardized regression coefficients for the effect of age on a given latent variable. Numbers adjacent to the smaller arrows below each individual task indicate residual error variances. Significant values are in bold.

common model, the ratio was less than 5 (162:33 = 4.91). Model 6 fit indices (see Table 5) indicate that this model fit the data well. As with the models discussed above, the flanker task loaded neither on the interference resolution nor the common factor. Furthermore, whereas the PWI and cued recall factor loadings on the interference resolution factor were in the predicted direction, they were nonsignificant ($p < .15$). These nonsignificant factor loadings may be attributable to their low reliabilities (see Table 4), which may be especially important in the context of this model's greater complexity (relative to the previous models). In contrast, all WM tasks loaded significantly on the WM factor. Table 6 shows task loadings on the common factor, as well as age effects on each latent variable. Only three tasks loaded on the common factor: Stroop, backward digit span, and cued recall. This pattern of task loadings is difficult to interpret given the two interference tasks (Stroop, cued recall) load in different directions. We hypothesize that these three task loadings reflect prepotent response inhibition requirements related to overcoming well-learned behaviors. For the Stroop task, this includes overcoming word reading (in favor of color naming); for backward digit span, this includes overcoming the tendency to repeat information back in the same order given (in favor of repeating the information backward) – in both cases, worse prepotent response inhibition results in worse performance. For the cued recall task, in contrast, this could involve overcoming the tendency to name the first semantic category item that comes to mind when presented with the recall cue. Here, worse prepotent response inhibition might lead to worse overall performance (i.e., on all trial types), and therefore smaller interference effects. This is, however, a post hoc explanation of the common factor's loadings.

Most relevant to the goals of the present study are the effects of age on the two specific and the common latent variables (see Table 6). Whereas age was a significant predictor of the interference resolution ($p = .002$) and WM factors ($p < .001$), the effect of age on the common factor was not significant ($p > .05$). This suggests that the effect of age on interference resolution and WM are best modeled by declines to these specific factors, rather than a single, common factor.

To summarize, a three-factor model with separate factors for resistance to PI, response-distractor inhibition, and WM provided a good fit to the data, with significant effects of age on each. However, a two-factor model in which resistance to PI and response-distractor inhibition were equivalent provided a comparable fit, again with significant age effects on both the single interference resolution factor, and also on the WM factor. Importantly, such age effects were found even using residual interference scores, which control for baseline performance, accounting for individual differences in information encoding and processing speed. Additionally, the results of the common factor model suggested that the effect of age cannot be attributed to the variance that is common among the interference resolution and WM tasks included herein, but is best explained by independent effects of age on specific aspects of cognition.

Discussion

Using multiple resistance to PI and response-distractor inhibition tasks, the present study investigated declines in interference resolution as a function of age. Age effects were examined at both the task and latent variable levels, and several important findings emerged. First, older adults demonstrated significantly exaggerated interference effects relative to young adults across all resistance to PI analyses. Second, although the results for the response-distractor inhibition tasks were not consistent across all tasks, the findings for three of the four tasks converged in showing exaggerated interference effects for older adults. Third, using SEM, we found that age independently affects interference resolution and WM mechanisms. However, we did not find evidence that age has independent effects on response-distractor inhibition and resistance to PI, as these two interference resolution mechanisms were best fit by a single factor. These points are discussed below.

Table 6
Unstandardized Estimates and Standardized Factor Loadings for the "Common" Latent Variable of Model 6 and Effect of Age on Each Model 6 Latent Variable

Variable loadings on the common factor	Estimate (*SE*), (95% CI)	Standardized factor loading
Recent negatives	0.13 (0.11), (−.09, .34)	0.16
Cued recall	−0.22 (0.10), (−.42, −.01)	−0.28*
Release from PI	−0.04 (0.11), (−.26, .18)	−0.05
Flanker	0.07 (0.10), (−.13, .27)	0.09
PWI	−0.01 (0.10), (−.21, .19)	−0.02
NV Stroop	0.15 (0.12), (−.08, .38)	0.19
Stroop	0.56 (0.17), (.23, .89)	0.72*
Ospan	−0.03 (0.11), (−.24, .19)	−0.03
Backwards digit span	−0.36 (0.13), (−.61, −.12)	−0.46*
Sternberg recognition	−0.17 (0.10), (−.37, .03)	−0.22
Effect of age on	**Estimate (*SE*), (95% CI)**	**Standardized age effect**
Interference resolution factor	1.94 (0.63), (.70, 3.18)	0.89*
WM factor	−0.80 (0.20), (−1.20, −.40)	−0.62*
Common factor	−0.80 (0.46), (−1.70, .10)	−0.62

Note. *SE* = standard error. CI = confidence interval.
* $p < .05$.

Effect of Age on Interference Resolution

The present study provided support for Hasher and Zacks (1988) inhibitory deficit hypothesis of aging, which posits that interference resolution abilities decline with age, and that these declines have consequences for other aspects of cognition. Consistent with a number of previous studies (e.g., May et al., 1999; Spieler et al., 1996), our analyses at the individual task level suggested that older adults show age-related deficits in two interference resolution mechanisms, which have previously been argued to tap theoretically distinct mechanisms, response-distractor inhibition and resistance to PI (Friedman & Miyake, 2004). Furthermore, because we used regression residuals as the interference dependent variable for each task, controlling for individual differences in baseline (i.e., no interference) task performance, these differences are likely not attributable to other mechanisms that may be sensitive to aging, such as processing speed or word or memory retrieval mechanisms. The SEM results also suggested significant effects of age on the interference resolution tasks examined herein, though further qualification is needed. Although there were significant effects of age on response-distractor inhibition, resistance to PI, and WM in the good-fitting three-factor model, a two-factor model in which response-distractor inhibition and resistance to PI loaded on a single interference resolution factor that was distinct from WM provided an equivalent fit to the data, emphasizing two important points. First, the effect of age on interference resolution was best estimated by a single interference resolution factor, as opposed to distinct response-distractor inhibition and resistance to PI factors. This raises the possibility that healthy aging affects a mechanism that is common to what have been assumed to be distinct aspects of interference resolution. Second, there were significant effects of age on both the interference resolution and WM factors, and this effect of age could not be attributed to common variance among all of the tasks included herein. This suggests that age has independent effects on multiple cognitive processes, including (but not necessarily limited to) interference resolution and WM.

What mechanism might be common to response-distractor inhibition and resistance to PI, and affected by healthy aging? We hypothesize that aging affects the selection of task-relevant information in the face of competition, in line with biased competition models of cognitive control (e.g., Desimone & Duncan, 1995; Miller & Cohen, 2001; Miyake & Friedman, 2012; Munakata et al., 2011). These accounts maintain that task-relevant information is biased, or enhanced, in service of task goals, such that relevant information becomes selectable over task-irrelevant competitors. A consequence of this biasing is the effective suppression of competitors, either through absolute differences in activation (e.g., Miller & Cohen, 2001) or lateral inhibition (e.g., Munakata et al., 2011). As discussed by Kan and Thompson-Schill (2004), such selective attention mechanisms could be applied to overcome interference from information in the environment (as in response-distractor inhibition tasks) or representations in memory (as in resistance to PI tasks); in both cases, deficits in selective attention biasing mechanisms would result in larger interference effects. Applying such biased competition models to aging, we propose that older adults do not have a deficit in inhibitory mechanisms per se, but to the selective attention mechanisms that function to bias task-relevant information in the face of competition.

In line with this account, Gazzaley and D'Esposito (2007) have suggested that top-down modulation—what they consider to be the neural mechanism of selective attention—is impaired in older adults. Evidence comes from functional imaging studies finding that both young and older adults' show enhanced cortical activity when encoding task relevant information, but that older adults fail to show suppressed cortical activity in response to task irrelevant stimuli, suggesting selective difficulty deactivating (or the converse, not biasing) irrelevant information via top-down modulation (e.g., Gazzaley et al., 2008; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Gazzaley & D'Esposito, 2007; Zanto et al., 2010). Gazzaley and D'Esposito (2007) hypothesized that healthy aging affects the pattern of neural activity in response to irrelevant information, with top-down modulation being ineffectively applied to task-irrelevant information. Although these studies have focused on information encoding, and therefore avoiding interference from information that is currently present in the external environment, it can easily be extended to situations in which the interference results from representations in memory. For example, a number of studies have suggested that selection mechanisms also act on representations retrieved from memory (e.g., Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Nelson, Reuter-Lorenz, Persson, Sylvester, & Jonides, 2009). Thus, if older adults have difficulty biasing task relevant information in the face of competition, regardless of its source (environment, memory), they would show exaggerated interference in a variety of domains. Although the above discussion of the biased competition-type account does not explicitly propose a role for inhibition in age-related declines in interference resolution, the consequences of impaired selection mechanisms are nonetheless consistent with Hasher and Zacks (1988) inhibitory deficit hypothesis of aging.

Moreover, this account is also consistent with some recent behavioral work by Hasher and colleagues (Biss et al., 2012; Campbell et al., 2010; Thomas & Hasher, 2012), finding that older adults not only encode irrelevant material, but they also carry it forward such that it affects performance on later tasks, to an even greater extent than is the case for younger adults. For example, Campbell et al. (2010) recently found evidence for "hyper-binding" in older adults. They showed that when materials for a one-back working memory task were pictures with superimposed irrelevant words, older adults later showed greater preservation of the picture-word pairings than did younger adults. Also, Scullin, Bugg, McDaniel, and Einstein (2011) showed persisting sensitivity to words that were used to cue prospective memory recall for older adults but not younger adults when these cues were no longer relevant. Both of these findings suggest difficulty in deactivating irrelevant information.

Importantly, the results of the latent variable modeling also suggest that age has independent effects on interference resolution and WM, suggesting a distinction between these processes. If interference resolution represents the (in)ability to appropriately select task relevant representations in the face of competition, as discussed, the WM factor may reflect WM capacity. For example, age may affect the number of representations that are in an active, accessible state in the focus of attention (e.g., Cowan, 1995, 2001), or difficulties in retrieving, refreshing, or searching for information that is outside the focus of attention, for example in the activated portion of long-term memory (Halford, Maybery, & Bain, 1988; Oberauer, 2001; Unsworth & Engle, 2007; Verhaeghen & Basak, 2005). Age-related WM deficits may also be influenced by difficulties in contextual processing, such as binding WM content to specific contexts or sources (e.g., Oberauer, 2005), source monitoring (Hedden & Park, 2003; Johnson, Hashtroudi, & Lindsay, 1993), or the recovery of contexts (e.g., Howard, Kahana, & Wingfield, 2006). Such interpretations of the interference resolution and WM factors allow for clear relationships between these constructs, in accordance with a number of previous studies (e.g., Kane et al., 2007; May et al., 1999). For example, difficulty overcoming interference from irrelevant information could result in WM clutter (e.g., Hasher & Zacks, 1988); similarly, difficulty in using content-context bindings could result in an inability to discriminate an item's source and therefore memory interference (e.g., Oberauer, 2005). Despite these relationships, the results of the present study suggest that age-related declines in only one of these mechanisms does not fully account for declines in the other (see also May et al., 1999), and therefore theories of cognitive aging must account for declines to both interference resolution and WM.

Distinct Interference Resolution Mechanisms?

As discussed above, both theoretical (Hasher et al., 1999; Kok, 1999; Nigg, 2000) and psychometric (Friedman & Miyake, 2004) work has suggested multiple types of interference resolution. The present study, in contrast, differs from the results of Friedman and Miyake (2004) insofar as we accepted the two-factor model in which response-distractor inhibition and resistance to PI were fit by a single interference resolution factor, on the grounds of parsimony, given that this simpler model provided an equivalent fit to the data as the three-factor model. However, it is important to note that the present study contained an age heterogeneous sample, as it was also designed to answer a different question than that posed by Friedman and Miyake. Furthermore, although there may be something common to each of these interference resolution mechanisms that is affected by age, as just discussed, these interference resolution mechanisms may also still involve different processes (as might be suggested by the equivalent fit of the three-factor model).

Evidence for the distinction among these processes comes from a variety of sources. In addition to finding that response-distractor inhibition and resistance to PI load on separate factors, Friedman and Miyake (2004) also found that these interference resolution mechanisms differently relate to performance on other cognitive measures in theoretically meaningful ways. For example, whereas response-distractor inhibition was related to random number generation, task switching, and a questionnaire measuring cognitive failures, resistance to PI was related to reading span and a questionnaire measuring the suppression of unwanted thoughts. In addition, response-distractor inhibition but not resistance to PI may be impaired in ADHD (Engelhardt, Nigg, Carr, & Ferreira, 2008), and furthermore, although these mechanisms involve a number of overlapping cortical regions, they also involve distinct regions (Badre & Wagner, 2004; Badre et al., 2005; Nee & Jonides, 2009; Nelson et al., 2009). One obvious distinction between the two interference resolution mechanisms examined herein is the source of interference, with response-distractor inhibition involving overcoming perceptual interference (i.e., interference from information in the external environment), and resistance to PI involving overcoming interference from information in memory (for a similar distinction, see Friedman & Miyake, 2004; Nee & Jonides, 2009).

In contrast to the resistance to PI tasks, the results for the individual response-distractor inhibition tasks were less consistent, with the flanker task standing out as an exception to the general pattern of greater interference effects for older adults (see also Kramer et al., 1994; Wild-Wall et al., 2008); this task also failed to load on the response-distractor inhibition factor in the latent variable analysis. These findings may suggest that the flanker task measures a somewhat different construct than the other response-distractor inhibition tasks. One possibility is that response-distractor inhibition should, in fact, be broken down into the distinct constructs of a) prepotent response inhibition versus b) resistance to distractor interference, as originally hypothesized by Friedman and Miyake (2004). That is, while the present study lumped response and distractor inhibition into a single construct, the NV Stroop, Stroop, and PWI tasks may have a stronger response/restraint component given they require overcoming strong responses (naming written words, well learned directional responses), whereas the flanker task may more strongly reflect distractor interference. Interestingly, this distinction between response and distractor inhibition is also consistent with theoretical accounts that propose separate mechanisms for processing identity versus location information (e.g., Connelly & Hasher, 1993; Nee & Jonides, 2009; Nee et al., 2013), paralleling the difference between ventral and dorsal visual processing streams in posterior cortices. Whereas the response inhibition tasks included here may reflect the inhibition of identity ("what") information over a strong, competing response, distractor inhibition may differentially reflect location-based interference resolution. This suggestion is, of course, in contrast to Friedman and Miyake's (2004) findings of a single response-distractor inhibition factor; however, the dependent variables (i.e., regression residuals) used in the present study may be more pure measures of interference resolution. Of note, however, the flanker task used in the present study also had the largest proportion of congruent to interference trial types of all the response-distractor inhibition tasks included herein; as a result, the lack of age effects on this task could be attributable to less than ideal task design. The question of whether age differentially affects prepotent response inhibition and resistance to distractor interference remains an open question for future work.

Conclusions

Various theoretical accounts have proposed distinctions among interference resolution constructs (e.g., Friedman & Miyake, 2004; Hasher et al., 1999; Kok, 1999; Nigg, 2000), with Hasher and Zacks' (1988) influential account of aging proposing that age-related deficits in inhibition have consequences for other areas of cognition. However, little research has investigated whether older adults show consistent patterns of impairments across different types of interference resolution tasks (cf. Kramer et al., 1994), using multiple tasks tapping the same interference resolution construct within the same group of subjects. Here, we examined age effects on both a) resistance to proactive interference, which measures the ability to resist interference from information in memory, and b) response-distractor inhibition, which measures the ability to overcome interference from information in the external environment. In line with the inhibitory deficit hypothesis of aging

(Hasher & Zacks, 1988), the results of the present study suggest that older adults show deficits in multiple theoretically distinct aspects of interference resolution, though declines in interference resolution may result from a common cause. In addition, we found that age effects on interference resolution are independent from age effects on working memory and speed of processing, suggesting that age affects multiple cognitive domains. On one hand, then, our data were consistent with various accounts of age-related cognitive decline, which hypothesize age-related declines to specific aspects of cognition, such as interference resolution or working memory. On the other hand, the independent age effects on each of these factors suggests that age-related cognitive decline cannot be accounted for by only a single mechanism. Although it remains possible that these domains of age-related decline result from similar causes such as prefrontal volumetric changes (e.g., Raz et al., 2005) and/or alterations to dopaminergic systems (e.g., Braver & Barch, 2002), these findings suggest aging may be better understood as affecting multiple distinct aspects of cognition, each of which may affect everyday activities in a number of ways.

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(*Appendix follows*)

Appendix

Pearson Correlation Coefficients for the 10 Variables Included in the Structural Equation Modeling

Variable	1	2	3	4	5	6	7	8	9	10
1. Recent negatives	—									
2. Cued recall	.02	—								
3. Release from PI	.23*	.32*	—							
4. Flanker	.004	−.07	−.06	—						
5. PWI	.001	.16*	.17*	−.04	—					
6. NV Stroop	.06	.08	.24*	−.07	.11	—				
7. Stroop	.19*	−.02	.20*	.03	.08	.21*	—			
8. Ospan	−.23*	−.27*	−.36*	.11	−.11	−.13°	−.16*	—		
9. Backwards digit span	−.05	−.02	−.15°	.03	.03	−.12	−.26*	.45*	—	
10. Sternberg recog.	−.18*	−.22*	−.13	.06	−.05	−.05	−.12	.44*	.37*	—

Note. For interference resolution tasks, higher scores indicate worse performance (larger interference effects). For working memory tasks, higher scores indicate larger memory spans.
* $p < .05$. ° $p < .10$.

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