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Age and Method Variance in Measures of Speed and Working Memory

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Ten measures of speed of processing were administered to 157 individuals, aged 18 to 89 years. The 10 measures comprised five pairs, each of which had a paper-and-pencil and a computer, reaction time (RT) based version of the same measure. Three measures of working memory span were also administered. Two structural equation models were fit to the speed data, one with a single latent variable, speed, and another, nested-factor model in which there were also latent variables for the two methods of measurement. The model with the method latent variables provided a better fit. Age was more strongly related to the method latent variables than to the general speed latent variable. Adding the working memory measures showed that there was also shared variance in those measures beyond the general latent variable, also related to age. The results show that any single measure of speed includes variance due to speed but also to the method of measurement. Use of a latent variable approach to speed is recommended.

Keywords: speed of processing, working memory, structural equation model

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Speed of processing has been extensively studied because it appears to play a central role in the effects of age on cognition (e.g., Park et al., 2002; Salthouse, 1996). But it has been noted that most studies use only one or a few measures of speed (for a recent example, see Borella, Ghisletta, & Ribaupierre, 2011). The most commonly used measures appear to be the Letter Comparison task and the Pattern Comparison task (Salthouse & Babcock, 1991, Exp. 2) and some version of the WAIS Digit-Symbol Substitution task (Wechsler, 1981). The most common method is a paper-and-pencil test in which the individual is to answer as many items as possible in some short, fixed time. The use of such measures is problematic as they may call not only on simple speed of processing but as well on aspects of the higher level cognitive skill that is to be accounted for. Lindenberger, Mayr, and Kliegl (1993) pointed out that the Digit Symbol Substitution test, rather than reflecting mental speed only as the rate of transmission of information, also required "a relatively complex sequence of processes that can be separated into components such as perception, working memory, secondary memory, and motor functioning" (p. 218) and, as a result the test may account for age differences in cognitive function because it reflects individual differences in "the smooth and error-free coordination of perceptual and cognitive activities in working memory" (p. 218). Hartley (2006) echoed this view of paper-and-pencil substitution tasks, noting that "performance reflects not only differences in the speed of determining the appropriate symbol digit link, but also in the organization and monitoring of the process of working across and down the page, the extent to which the pairings are kept available in working memory, the efficiency of the scan through the key if they are not, the extent to which the motor movements of responding require higher level monitoring, and other factors beyond pure speed of processing" (p. 200). Consistent with these speculations Gilmore, Royer, Gruhn, and Esson (2004) found that increasing the information content of the symbols in a substitution task—presumed to affect both encoding and memory—impaired performance. Piccinin and Rabbitt (1999) found specifically that memory for the substitution code predicted improvement over trials in a substitution task.

There is evidence that the involvement of functions other than speed affects paper-and-pencil measures besides substitution tasks. McCabe and Hartman (2008) found that the short-term memory (STM) load in the Letter and Pattern Comparison tasks differentially affected older adults. Lustig, Hasher, and Tonev (2006) found that presenting items in a block as in the paper-and-pencil measures led to differentially poorer performance in older adults than presenting items one at a time, as in most computerized tasks. They obtained a similar result for a substitution task. McCabe and Hartman reported that paper-and-pencil measures of Letter and Pattern Comparison accounted for additional variance in working memory beyond that explained by computer-based one-at-a-time measures. These results from different measures converge to support a speculation that there may well be method-related variance in paper-and-pencil measures that results in spuriously high estimates of the proportion of age-related variance in higher cognitive function accounted for by speed.

The possible presence of method-related variance was systematically evaluated in the present research. Five paper-and-pencil measures of speed were administered, including the commonly used Letter Comparison, Pattern Completion, and Digit Symbol

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Substitution tests. For each paper-and-pencil test an equivalent computer-based task was developed in which the items were presented one at a time, presumably reducing demands for higher-level task management. A structural equation modeling approach was then used to assess the extent to which age accounted for variance in the 10 measures of speed. In one model, which will be called the *speed-alone model* (see Figure 1), the 10 measured variables were modeled as loading on a single speed latent variable. In the second model, which will be called the *speed-and-method model* (see Figure 2), there was a single speed latent variable but in addition the five paper-and-pencil measures loaded on a *paper-and-pencil* latent variable. Because there have been anecdotal claims that older adults are selectively disadvantaged by computer-based activities, I also included a *computer* latent variable on which the RT measures that were collected on a personal computer loaded. Models such as this were termed *nested factor models* by Schmiedek and Li (2004).

The research was extended beyond the central concern to address a corollary question. Another method that is widely used in research on aging assesses working memory capacity or span. Memory span is defined as the largest set of items that can be maintained in memory under certain circumstances. I also asked whether age accounted for variance in a latent variable indicated by working memory span tasks beyond the variance shared by speed and working memory tasks generally.

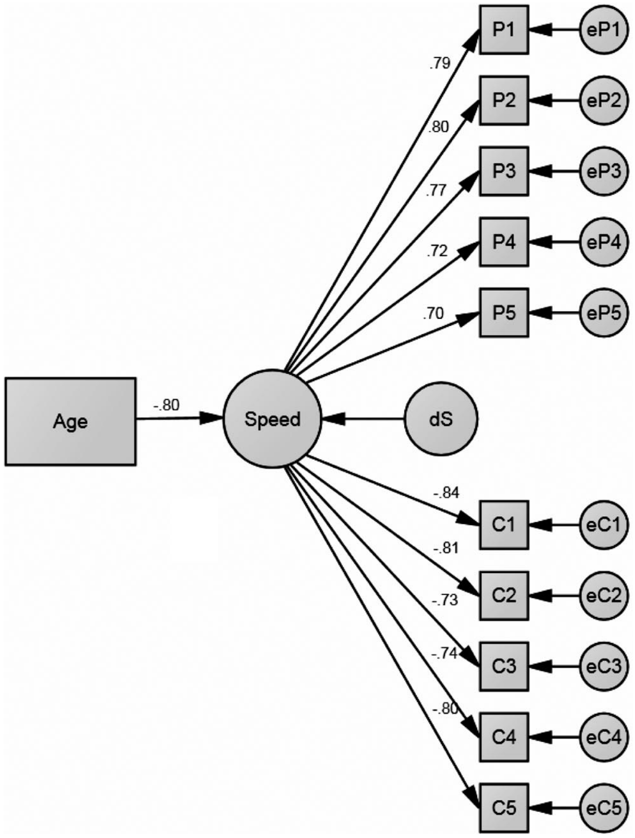

Figure 1. Speed-Alone Model with standardized coefficients and without residual correlations. Abbreviations: P1 = Pattern Completion Paper; P2 = Letter Completion Paper; P3 = Digit Symbol Paper; P4 = Arrow Task Paper; P5 = Finding Bs Task Paper; C1 = Pattern Completion Computer; C2 = Letter Completion Computer; C3 = Digit Symbol Computer; C4 = Arrows Task Computer; C5 = Finding Bs Task Computer. Correlated residuals not shown: eP2-eC4, eP2-eC1, eP3-eC2, eP3-eC1, eP4-eC5.

Method

Participants

The participants were 157 volunteers from local colleges and universities and from local retirement communities (in which retired professionals happen to be overrepresented). They ranged in age from 19 to 89 years (M = 45.66, SD = 24.41), approximately equally divided into groups of 19 to 23, 24 to 60, and 61 to 89 years. They averaged 15.76 years of education (SD = 2.67); mean measured Snellen visual acuity was 20/24.89 (SD = 7.97); mean rated health on a 10-point scale with 10 = *excellent* was 8.29 (SD = 1.45). Increasing chronological age correlated significantly with years of education, $r(155) = 0.41$, $p < .05$, and with poorer vision, $r(155) = 0.50$, $p < .05$, but was completely unrelated to reported health status, $r(155) = 0.00$.

Speed Tasks

Pattern comparison. The paper-and-pencil Pattern Comparison task consisted of pages containing pairs of line-segment patterns which were to be classified as "same" or "different" as rapidly as possible by writing the letter S or D on a line separating the two figures. One half of the pairs on each page were the same and one half were different. Pairs requiring a *different* response were constructed by altering one of the line segments in one member of the pair. The line patterns were connected lines in an invisible 4 × 4 matrix, with three, six, or nine line segments in each member of the pair. There were two separate, timed (20 s) administrations of 60 pairs. The computer version of the Pattern Comparison task used the identical stimuli, except presented one pair at a time. On each trial, a pair of figures appeared, in black on a white background, and the participant responded by pressing a key labeled S (period) or D (slash) with the first two fingers of the right hand. The stimuli remained on the screen until a response was sensed or 5 sec had elapsed. No feedback was given. The intertrial interval was 1 sec. There were two blocks of 30 trials, with an ad lib rest break between. The measure analyzed here was the mean RT on correct trials.

Letter comparison. The paper-and-pencil version was very similar to the Pattern Comparison task except that each pair consisted of strings of 3, 6, or 9 letters. Half were identical and half differed by one letter. Once again the task was to indicate whether they were the same or different by writing S or D on the line between the two strings. There were two separate, timed (20 s) administrations each with 26 comparisons. The measure was the number of items responded to correctly summed over the two forms. As with the Pattern Comparison task the computer task used the identical stimuli as the paper-and-pencil version, presented one at a time. Otherwise the procedure was identical to that in the computer Pattern Comparison task.

Digit symbol substitution. This task was adapted from the Digit Symbol Substitution test from the WAIS (Wechsler, 1981) with the task to enter the appropriate symbol for each digit ac-

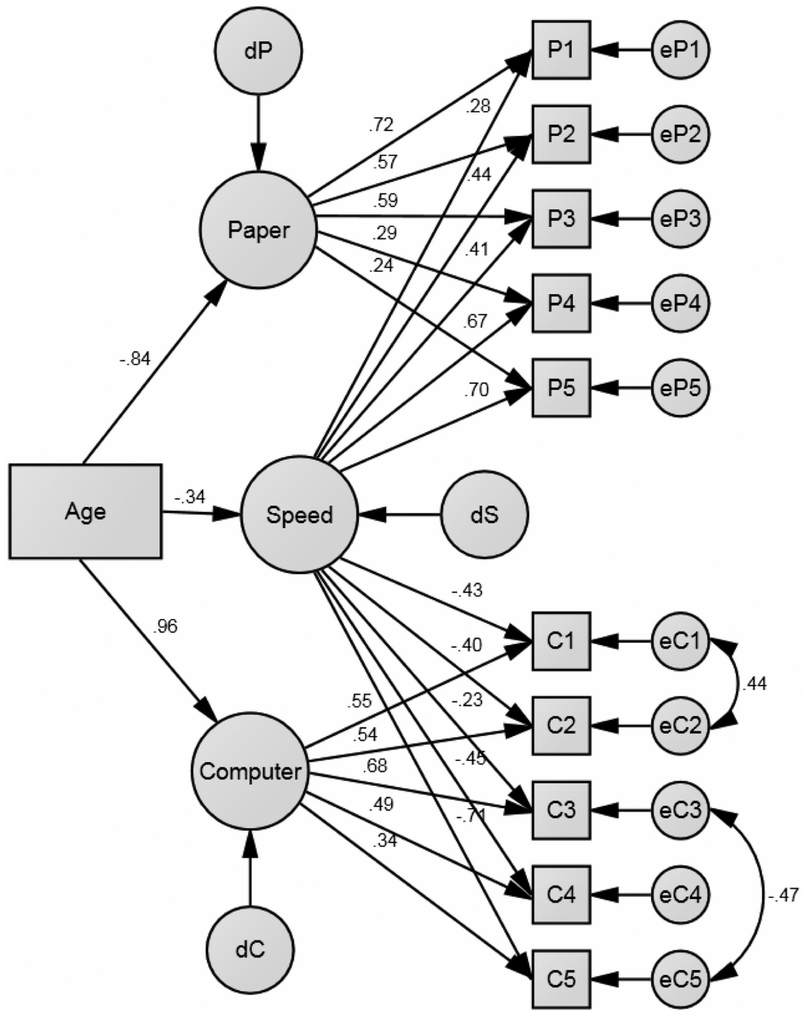

Figure 2. Speed-and-Method Model with standardized coefficients. Abbreviations: P1 = Pattern Completion Paper; P2 = Letter Completion Paper; P3 = Digit Symbol Paper; P4 = Arrow Task Paper; P5 = Finding Bs Task Paper; C1 = Pattern Completion Computer; C2 = Letter Completion Computer; C3 = Digit Symbol Computer; C4 = Arrows Task Computer; C5 = Finding Bs Task Computer.

cording to a provided translation table. The symbols used were directed arrows from the WingDings3 font (↑↓↖↗↙↘⮍↶⮌⮎) with a unique digit assigned to each. In the paper-and-pencil version, the translation table was at the top of the page. There were six rows of 10 digits with a space below to enter the translation. There were two separate timed (30 s) administrations. The score was the number of correct translations over the two episodes. The computer version used the same stimuli. Each of the symbols was assigned to a numeric key at the top of the keyboard. The set of symbols was placed above the keys, with each symbol above its corresponding key. On each trial, a fixation cross (white) was presented at the center of the screen (blue). After 1 s the cross was replaced by a digit, 0 to 9, selected from a random permutation of the 10 digits. The participant responded by pressing the key for the corresponding symbol. Five seconds were allowed for a response. Following 15 practice trials with feedback, there were 50 no-feedback trials, comprising five blocks of 10 trials, with all digits appearing once in a block. There was no break between blocks. The measure was the mean RT for correct responses.

Spatial choice reaction time (arrow directions). In the paper-and-pencil version of this task, the participant saw three columns. In each row, a string of three arrows (<<< or >>>) appeared, either in the leftmost column pointing left or in the rightmost column pointing right. The participant was to indicate whether the arrows were pointing left or pointing right by writing L or R in the middle cell. There were two timed (30 s) administrations, each with 60 rows. The measure was the number of correct responses over the two episodes. In the computer version, on each trial, there was a central fixation cross flanked, after a delay of 1 s, by a string of three arrows to the left or to the right and nothing on the other flank. Stimuli were white on a blue background. The direction of the arrows was the same as the side on which they appeared. The task was to press one of two adjacent keys to indicate whether the arrows were pointing to the left or right. There were 50 no-feedback trials following initial training of 15 trials with feedback. The measure was the mean RT for correct trials.

Verbal choice reaction time (finding Bs). The paper-and-pencil version comprised a 16 × 10 matrix of cells, each containing a B or a D with the letter and the case of the letter (upper or lower case) determined at random. The task was to cancel (draw a line through) as many Bs as possible. There were two timed (30s) administrations. The measure was the number of Bs canceled. In the computer version, each trial began with a focus (O, in white on a blue screen) for 1 s followed by the letter B or D, again with the letter and the case randomly chosen (but with the constraint that the four possibilities occurred equally often). The task was to press one of two adjacent keys to indicate whether it was a B or a D. There were 48 no-feedback trials following 16 practice trials with feedback. The measure was the mean RT for correct trials.

Memory Tasks

There were three memory span tasks. In these tasks, the participant must answer a question about each of a series of items while holding some information about the item and then attempting to recall that information at the end of the series. The number of items is called the span. There were two trials at each span. The series began at length two and continued to increase in length until the participant failed to recall the information on both trials at a particular span. For each task the stimuli were presented on a computer screen but an experimenter entered the responses to each series and determined whether to advance to the next longer span. I used weighted or partial-credit unit scoring (Conway et al., 2005). I selected this over other scoring schemes because it provided the greatest range of scores over the participants.

Reading span. In the Reading Span task (Daneman & Carpenter, 1980), sentences were presented one at a time. The participant was instructed to read the sentence aloud. The researcher entered a key press as soon as the participant finished reading, which caused the next sentence to appear. As soon as the last sentence was read, the participant saw the instruction to "recall the final words" of each sentence. The experimenter entered a key press to record the correctness of the response. The maximum set size was seven.

Computation span. In the Computation Span task (adapted from Salthouse & Prill, 1987), participants solved simple arithmetic problems involving the addition or subtraction of two single-digit numbers (with a positive answer). They gave their answers aloud, and the researcher entered the correctness of the response with a key press and the next problem was then presented. After the last problem in a set, the participant saw a question mark, which was the prompt to recall the second digit in each of the problems. Again, the recall was entered by the researcher. The maximum set size was nine.

Rotation span. In the rotation span task (adapted from Shah & Miyake, 1996), the stimulus was the letter F, presented at one of eight orientations (ranging from 0 degrees from vertical to 315 degrees from vertical). The letter could be either in normal form or mirror-image form. A sequence of these stimuli was presented. The participant's task on each stimulus presentation was to indicate with a key press whether the letter was normal or mirror image. Each letter also had a small red dot directly above the top stroke of the character. After the last letter was presented, a display showed blue dots at locations where the red dots could have appeared at the top of the letter. The participant was to use the mouse to point to and click on the locations where the red dots had appeared, in the order they were seen. The maximum set size in this task was six.

Procedure

All of the tasks were completed in a single session lasting approximately two hours. After providing informed consent, participants were asked their year of birth and the number of years of education they had completed. Then they were asked to rate their current health on a 10-point scale, on which 10 = *excellent*. All of the tasks of a particular type—paper-and-pencil speed, computer speed, and memory—were carried out in a block, with the same order of tasks within blocks for all participants. The order of the three blocks was counterbalanced across participants. During one of the breaks between blocks, the participant's visual acuity was measured using a standard Snellen chart viewed at 20 ft. Participants received a stipend of $35.

Results

The structural equation models were fit using maximum likelihood estimation with AMOS (Arbuckle, 2010). There are no agreed on standards for deciding that a model fits well, so I used and report multiple measures of fit (cf. McDonald & Ho, 2002). The first is the minimum chi-square (χ^2), which assesses the discrepancy between the observed covariance matrix and the covariance matrix estimated from the model; ideally the chi-square is nonsignificant. Because chi-square increases with the complexity of the model and the sample size, it is also useful to consider the chi-square per degree of freedom; ideally χ^2/df is less than 2. The comparative fit index (CFI, Bentler, 1990) is a function of the difference in chi-square between a fully saturated model—which would fit perfectly—and a model of complete independence. The CFI is based on the proportion of that difference explained by the tested model with some adjustment for parsimony; ideally it is greater than .90. Finally, the root mean squared error of approximation (RMSEA) is also a parsimony-adjusted index of the approximation of the data by the model; the criterion used here was that it be .07 or lower. Each of the models was first fit as hypothesized. The solutions were then examined for nonsignificant factor loadings or path coefficients and for possible modifications that would improve fit. The only modifications actually made were correlated residuals. The full correlation matrix is provided in S1.

Speed Measures Only

For the hypothesized speed-alone model the factor structure showed acceptable loadings. The fit of the model, however, was poor, $\chi^2(44) = 217.52$, $p < .001$, $\chi^2/df = 4.94$, CFI = .87, RMSEA = .16. The model was modified by introducing correlations among residuals where that would lead to a significant improvement in fit. Correlations were not permitted within the subsets of paper-and-pencil and computer speed measures, as this could account for method-related variance. With these modifications, the fit of the final speed-only model remained poor, $\chi^2(39) = 157.85$, $p < .001$, $\chi^2/df = 4.05$, CFI = .91, RMSEA =

.14. The final model, with standardized path coefficients, is shown in Figure 1. The path coefficient from age to the speed latent variable was −.80.

For the speed-and-method model, examination of the factor structure also showed acceptable loadings. The hypothesized model provided a poor fit to the data, $\chi^2(32) = 111.44$, $p < .001$, $\chi^2/df = 3.48$, CFI = .94, RMSEA = .13. When correlated residuals were introduced, the fit improved significantly, $\chi^2(29) = 52.41$, $p = .005$, $\chi^2/df = 1.81$, CFI = .98, RMSEA = .07. The final model, with standardized path coefficients, is shown in Figure 2. The path coefficients from age to the method-related variance were −.84 for the paper-and-pencil latent variable and .96 for the computer latent variable. In contrast to the speed-alone model, the path coefficient from age to speed dropped to −.34. The speed-alone and speed-and-method models are nested, so they can be compared directly. The speed-and-method model represents a clear and significant improvement in fit over the speed-alone model, $\Delta\chi^2(10) = 105.44$, $p < .001$.

Speed and Memory Measures

Next, a working memory latent variable with three measured variables was introduced into the final speed-and-method model, as shown in Figure 3. The latent variable, Speed, was renamed General to reflect the newly introduced measures. The factor loadings for working memory were weak but significant. The fit of the model was good, $\chi^2(58) = 83.82$, $p = .015$, $\chi^2/df = 1.44$, CFI = .98, RMSEA = .05, and no further modifications were indicated. The path coefficient from age to the working memory latent variable was −.67; the other structural path coefficients remained essentially unchanged.

Discussion

Consistent with previous research, there was a speed factor that was strongly and negatively related to age. Note that the paper-and-pencil measures were weighted positively and the computer measures were weighted negatively. More paper-and-pencil items completed and shorter response latencies produced higher levels of the latent variable, speed. Increased age resulted in lower speed. Three orthogonal method factors were identified, each strongly related to age. The paper-and-pencil factor and the working memory factor were negatively related to age. Greater age resulted in fewer correct items. The computer factor was positively related to age with greater age resulting in longer response latencies. When these factors were introduced along with the general factor, the relation between age and the general factor was substantially attenuated.

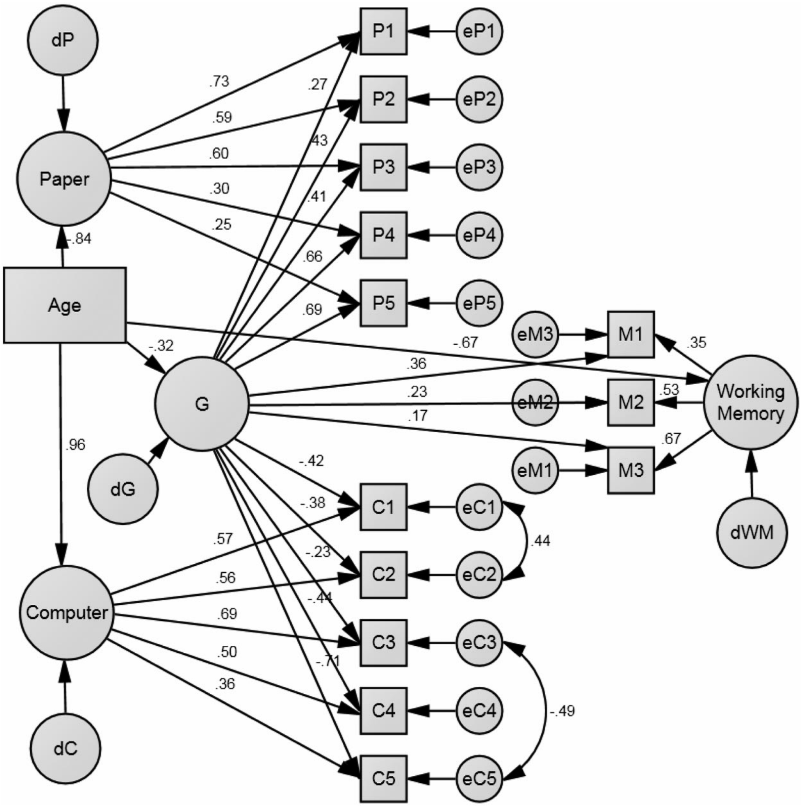

Figure 3. Speed and Working Memory Method Model with standardized coefficients. Abbreviations: G = General; M1 = Reading Span; M2 = Computation Span; M3 = Mental Rotation Span; P1 = Pattern Completion Paper; P2 = Letter Completion Paper; P3 = Digit Symbol Paper; P4 = Arrow Task Paper; P5 = Finding Bs Task Paper; C1 = Pattern Completion Computer; C2 = Letter Completion Computer; C3 = Digit Symbol Computer; C4 = Arrows Task Computer; C5 = Finding Bs Task Computer.

The results show that, beyond general speed, there is unique variance due to the method by which speed is measured—by paper-and-pencil measures or by computer measures—and that age is strongly related to that method variance. Moreover, age is more strongly related to those sources of variance than it is to the general speed factor as measured by all 10 speed indicators. What might be responsible for the relationship of age to the method variance? Importantly, this must involve different mechanisms for the two types of measures. Any common mechanism would have been captured by the shared variance in the speed factor. As speculated earlier, paper-and-pencil task performance may reflect age-related changes in coordinating perceptual, cognitive, and motor activities in working memory (Lindenberger et al., 1993). Alternatively, as a reviewer suggested, there may be an age-related shift in response strategy. Participants were told only to complete as many items as possible without making mistakes. There was no penalty for errors (except that they did not count) and, so, none was mentioned. Younger adults might capitalize on this by working more rapidly, gaining more in additional items than they lost in errors. Older adults may give more weight to errors and, so, may proceed more slowly. On computer tasks older adults may also adopt a cautious strategy unlike younger adults. A speed–accuracy trade-off would be such a strategy. Inconsistent with this possibility, there was no evidence for a speed–accuracy trade-off in individual differences: Among participants over 50, the average correlation between RT and proportion correct across the five tasks was −.28 whereas for younger adults it was −.08. For the older adults the negative correlation is consistent with individual differences in ability such that more able individuals have both shorter latencies and greater accuracy. It may simply be that use of a computer is relatively unfamiliar to some older adults and they may be both slower and more error prone in carrying out appropriate actions that may be nearly reflexive to younger adults.

The results also showed that there was unique variance in working memory beyond that shared across cognitive tasks and that variance, too, was strongly related to age. Thus, there is unique, age-related variance in a method that is different from both pencil-and-paper and computer tasks. It is true that with 10 measures of speed and only three of working memory, the shared variance in the general factor would be weighted toward speed. This can be seen in the relatively low loadings of the working memory indicators on the general factor. As a result, the working memory latent variable may reflect more than method variance.

There is a long and rich tradition of exploring the extent to which age-related variance in higher cognitive function can be explained by cognitive primitives, reviewed by Hartley (2006). In a recent example, Borella, Ghisletta, and Ribaupierre (2011) found that age-related variance in text comprehension was substantially accounted for by working memory which, in turn, was accounted for by speed of processing (see also DeDe, Caplan, Kemtes, & Waters, 2004; Kwong See & Ryan, 1995; Van der Linden et al., 1999). It might appear that the present research would permit just such an analysis, examining whether speed of processing mediates the effect of age on working memory. Unfortunately, it does not. The present design is one that was classified by Lindenberger, von Oertzen, Ghisletta, and Hertzog (2011) as cross-sectional age variance extraction (CAVE) with all measurements taken at the same point in time. Hofer, Flaherty, and Hoffman (2006) have shown that, because of the general decrease with age in performance across many measures, CAVE overestimates the effect of any presumed mediator. In fact, Lindenberger et al. (2011) have shown that with a deliberate selection of data points not only can apparent mediation occur even when no longitudinal relationship exists but indeed any apparent relationship can occur with any possible pattern of longitudinal change. There is nothing in theory to prevent such an artifact. Because the present research used a CAVE approach, the issue of mediation is rendered moot.

There are important implications to these results. The way speed is measured matters. The common practice of using a single measure confounds variance related to true speed with method variance. The safest avenue would be a latent variable approach with manifest measures of speed from each of the two categories, paper-and-pencil and computer-based. This would not only isolate the purely speed-related variance but it would also give the distinct advantage of error-free measurement of the construct.

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