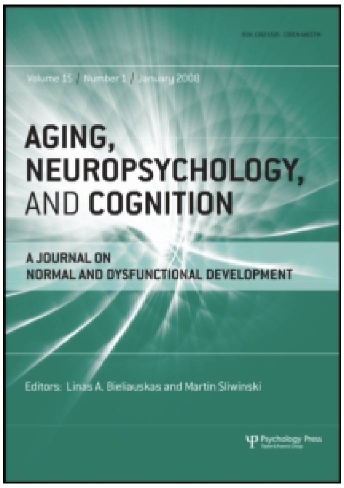

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Tianyong Chen[a]; Deming Li[a]
[a] Key Laboratory of Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing, China

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The Roles of Working Memory Updating and Processing Speed in Mediating Age-related Differences in Fluid Intelligence

TIANYONG CHEN AND DEMING LI
Key Laboratory of Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing, China

ABSTRACT

This study was conducted to investigate the relative roles of working memory updating (updating) and processing speed in mediating age-related differences in fluid intelligence. A sample of 142 normal adults between 18 and 85 years of age performed a set of updating, processing speed, and fluid intelligence tasks. Hierarchical regression analyses indicated that the proportion of unique age-related variance in updating measures was related to the complexity of speed measures. There was a larger proportion of unique age-related variance in updating measures after controlling for the variance in simpler speed measures. Moreover, structural equation modeling showed that updating mediated almost all the age-related effects on fluid intelligence. These results suggest that updating, but not speed, is the critical mediator between age and fluid intelligence. In addition, the speed mediation of age-related differences in fluid intelligence as indicated by previous studies is at least partially derived from the executive component of speed measures.

For a long time, processing speed theory (see Salthouse, 1996, for a review) has been one of the dominant theories in the field of cognitive aging research. This theory emphasizes the fact that the processing speed is generally slower in older adults than in younger adults, and postulates that this reduction in speed leads to impairments in higher-order or fluid cognition. However, in recent years, the attention of cognitive aging research appears to be drawn towards the concept of executive function, which is broadly defined as control processes responsible for the monitoring, controlling, and integration of other cognitive operations. Note that executive functions are

Address correspondence to: Deming Li, Institute of Psychology, Chinese Academy of Sciences, Beijing, China. E-mail: lidm@psych.ac.cn

often associated with the frontal lobes, and there is sufficient neuroanatomical evidence indicating that frontal lobes are more vulnerable to age-related deterioration compared to other brain areas (Raz, 2000, 2004), some researchers proposed frontal (or executive) decline hypothesis of cognitive aging, which predicts that increasing age is associated with a greater decline in measures of executive functions than with declines in general cognitive abilities. Furthermore, declines in executive functions may account for age-related differences in higher-order performance (Rabbitt et al., 2001; West, 1996; Woodruff-Pak, 1997).

Working memory updating (updating) is one of the most frequently postulated executive functions in recent literature (e.g., Collette & Van der Linden, 2002; Friedman et al., 2006; Miyake et al., 2000; Salthouse et al., 2003). This updating function involves constantly monitoring incoming information relevance for the task at hand, and then appropriately modifying the content of working memory by replacing old, no longer relevant information with newer, more relevant information (Morris & Jones, 1990). Previous research has classically explored the updating process with running memory task, which requires participants to watch strings of items (letters or digits) of unknown length, and then to recall a specific number of recent items in sequence. Morris and Jones (1990) have shown that updating is not the passive maintenance of memory loads, but the dynamic aspects of real-time processing in working memory. That is to say, updating belongs to the executive component of working memory.

Previous studies have suggested that working memory, especially its executive component, has a strong relationship to fluid intelligence (Conway et al., 2002; Engle et al., 1999; Kane et al., 2005; Kyllonen & Christal, 1990). Furthermore, a recent paper directly examined the relations between several executive functions (including updating) and intelligence, and found only updating was highly correlated with intelligence measures (Friedman et al., 2006). Engle et al. (1999) and Friedman et al. (2006) suggested that the link between working memory (or updating) and fluid intelligence is the demand for controlled attention to maintain goal-relevant information in the face of concurrent processing and distraction. In the aging research field, it has been found that updating operations are more vulnerable to age than storage capacity when performing a running memory task (Van der Linden et al., 1994). Altogether, because working memory (especially its executive component, updating) has a verified strong relationship to both age and fluid intelligence, it is reasonable to assume that age-related decline on fluid intelligence may be primarily due to updating impairment, and this assumption is indubitably consistent with the executive decline hypothesis of cognitive aging.

However, it is regrettable that, as a good indicator of executive component of working memory, updating has been investigated relatively rarely in relation to fluid intelligence and in the field of cognitive aging research. An exception is the study of Salthouse et al. (2003), which found various executive functions, especially updating, mediated almost all the age-related effects on fluid intelligence. However, in that study, they did not directly compare the relative roles of updating and processing speed in mediating age-related differences in fluid intelligence. In previous studies, Salthouse preferred to adopt general slowing to explain age-related decline in cognition, and assumed that processing speed is a primitive construct that influence the cognitive system without themselves being reducible to other psychological constructs (Salthouse, 1996; Verhaeghen & Salthouse, 1997). That is to say, when processing speed is considered, the mediation of age-related effects on fluid abilities through executive construct are much smaller than those through speed construct (e.g., Salthouse & Miles, 2002), or most of the relations between executive construct and both age and other cognitive abilities are shared with other variables, especially speed variables (e.g., Salthouse et al., 1998). These studies, together with others (e.g., Bryan et al., 1999; Fisk & Warr, 1996), induced us to feel that there has been little evidence to support executive decline hypothesis in cognitive behavior studies, especially where processing speed is considered.

While numerous empirical reports have been found to support the processing speed theory, it is important to note that some studies have suggested that the relations between processing speed and fluid intelligence, and the speed mediation of age-related variance in other cognitive abilities, were varied when choosing different speed measures. For instance, Conway et al. (2002) showed that when choosing speed tasks requiring minimal demands on working memory, they did not find a significant unique relation between processing speed and fluid intelligence. Verhaeghen (1999) found that age-related difference of recognition performance could be well accounted for by perceptual speed, but to a lesser extent by inspection time.

Different types of measures have been used to assess the processing speed of an individual (see Salthouse, 2000, for a review). For instance, reaction time (e.g., choice reaction time) is one of the most frequently used speed measures, which is generally assumed to require four processing stages (i.e., stimulus encoding, stimulus identification, response selection, and motor execution). Psychophysical speed (e.g., inspection time) is supposed as an even simpler or purer measure of central processing speed than reaction time (Nettelbeck & Wilson, 1985), which normally involves only two processing stages (i.e., stimulus encoding and stimulus identification). Compared with reaction time and psychophysical speed, perceptual/motor speed measures (usually on paper-and-pencil tests, e.g., digit–symbol substitution test) are more complex, which generally involve some other cognitive processes. For instance, a digit–symbol substitution test typically involves visual searching, attention switching, and working memory resources (i.e., the more digit–symbol pairs were maintained internally, the more items were completed in a given time). Therefore, we assume that some widely used speed measures (i.e., perceptual/motor speed) in cognitive aging studies are not pure measures of processing speed, and involve some executive operations.

The purpose of this study was to investigate the relative roles of updating and processing speed in mediating age-related differences in fluid intelligence, and to find empirical evidence for the executive decline hypothesis. Different from previous studies, which usually take processing speed as cognitive primitives, this study will adopt three types of speed measures (i.e., inspection time, reaction time, and perceptual/motor speed), which is assumed to involve different level of working memory resources.

METHOD

Participants

The participants were 142 normal adults between 18 and 85 years of age. Four additional participants took part in the study, but they failed to complete all the tasks. Descriptive characteristics of the sample are presented in Table 1. All gave informed consent and were paid RMB 50 to participate.

Measures

All participants completed a set of working memory updating, processing speed, and fluid intelligence tasks. Task administration was either computerized or paper-and-pencil. Parameters for the computer-administered tasks were selected on the basis of several pilot studies to maximize sensitivity and reliability. All the tasks were programmed with E-Prime (Psychological Software Tools). The screen of the computer was apart from participants approximately 50 cm.

TABLE 1. Means (and Standard Deviations) of Demographic Characteristics of the Participants.

	Age			
Variable	18–39	40–59	60–85	Total
N	54	41	47	142
Age	28.1 (6.8)	50.3 (6.0)	69.8 (6.3)	48.3 (18.8)
% Female	50	71	57	58
Health rating[1]	4.6 (.6)	3.9 (.8)	3.7 (.8)	4.1 (.9)
Near vision[2]	1.11 (.20)	1.23 (.21)	1.36 (.30)	1.23 (.26)
Education	14.8 (2.1)	13.4 (2.3)	14.6 (2.7)	14.4 (2.4)
Vocabulary[3]	13.9 (1.2)	13.6 (1.1)	14.6 (.9)	14.0 (1.2)
Digit symbol[3]	15.1 (2.3)	14.7 (2.6)	15.2 (2.7)	15.0 (2.5)

Notes: [1] Self-rating on a scale from 1 (poor) to 5 (excellent). [2] Near (corrected) vision in Snellen ratios (e.g., 40/40 = 1.0). [3] Age-adjusted scores based on the norms from the Wechsler Adult Intelligence Scale, Chinese revised version (Gong, 1982).

Fluid Intelligence Tests

Raven's Advanced Progressive Matrices (Raven, 1962). In this test participants attempted to determine which pattern best completed the missing cell of a matrix. Two sample problems were followed by the 18 odd-numbered items from the Advanced Progressive Matrices. Participants were allowed 10 min to work on the 18 test problems.

Cattell's Culture Fair Scale (Cattell & Cattell, 1960). This test is composed of four separate and timed paper-and-pencil subtests (i.e., Series, Classifications, Matrices, and Conditions). Participants were allowed 2.5–4 min to complete each subtest after two or three examples. When time expired for a subtest, participants were instructed to stop working on that subtest and begin the next. At no point were the participants allowed to go back to work on previous subtests. The test score was the sum of all correct answers, across all four subtests.

Paper Folding (Ekstrom et al., 1976). In this test the participants attempted to determine which of five patterns of holes would result from the displayed sequence of folds and hole punch. There were 12 problems and the time limit in the test was 10 min.

Spatial Relationship (Bennett et al., 1997). In this test the participants were to select which of four three-dimensional objects corresponded to an unfolded two-dimensional drawing. Ten minutes were allowed to solve 20 problems.

Processing Speed Tasks

Digit Symbol (Wechsler, 1981). This is a classical perceptual/motor speed task. In this test participants were to substitute nine different symbols with the corresponding numbers from 1 to 9; while he/she was performing this task, the substitution code remained visible on the test page. The score was the number of correct substitutions made over a 90-s period.

Digit Copying (Li et al., 2001). This is a computerized perceptual/motor speed task. Participants were to respond to single digit by pressing the key on the numeric keypad with index finger only. The digit (0 through 9, approximately 1.7° in size) was displayed on the central of the screen until a response was registered, after which a 500-ms delay occurred before presentation of the next stimulus. Four practice trials were followed by 20 trials. The score was the average reaction time of correct responses.

Pattern Comparison (Salthouse & Babcock, 1991). This is a computerized reaction time speed task. On each trial, a pair of pattern was presented in the center of the screen. Participants were instructed to verify whether the pair was the same or different, and press corresponding key on the keyboard as quickly and accurately as possible. After practicing on two trials with patterns consisting of three, six, and nine line segments, respectively, the participants performed three blocks of 32 pairs each.

Chinese Character Comparison (locally developed). This is another reaction time speed task. Stimuli in this task consisted of 32 pairs of Chinese character string, which consisted of one, two, or four high-frequency Chinese characters (two to four strokes), respectively. On each trial, a pair of Chinese character string was presented in the center of the screen. Participants were instructed to verify whether the pair was the same or different, and press corresponding key on the keyboard as quickly and accurately as possible. After practicing on two trials with Chinese character strings consisting of one, two, and four characters, respectively, the participants performed three blocks of 32 pairs each.

Inspection Time: figure (after Nettelbeck & Rabbitt, 1992). In the first inspection time task, the target consisted of two vertical lines, one approximately 44 mm long, the other approximately 32 mm long, separated by 10 mm and aligned at the top by a horizontal line. The longer line occurred equally often on the left or right of the screen. Each trial began with the presentation of a fixation cross with 500 ms duration, followed after 360 ms by the target (variable duration), which remained on the screen until replaced by a pattern mask, shown for 360 ms. The mask consisted of two thicker vertical lines, which extended for approximately 52 mm and thus completely overwrote the original stimulus. Participants were asked to press a button corresponding to the location of the longer line (left or right). The intertribal interval was 500 ms.

Initial training for the inspection time task began with a demonstration illustrating the target-mask sequence and response requirements, followed by 10 trials at target exposure duration of 500 ms. This procedure was then repeated by 400 ms, with a criterion of eight correct responses successively to began the task. Then, an adaptive staircase procedure was used for determining inspection time. The first stimulus was projected for 300 ms. Presentation times remained identical until either the participants made a mistake (then presentation time was incremented by 20 ms) or made six correct answers in a row (then presentation time was decreased by 20 ms). The shortest presentation time used was 20 ms (refresh rate of the screen was 10 ms). Throughout the task, it was emphasized that accuracy, not quickness of responding, was important. The procedure continued until six peaks and valleys in presentation time were found; the first reversal was disregarded. The average value of these peaks and valleys was the participant's score.

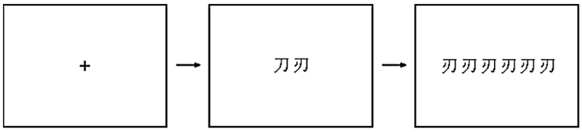
Inspection Time: Chinese character (locally developed). In the second inspection time task, the target consisted of a pair of Chinese character, which the only difference between them was one character having one more stroke. It should be noted that erasing the more stroke of the other character made the character with a less stroke. Both characters were approximately 7 mm high, and separated by 10 mm. The pattern mask consisted of 6 one-more-stroke characters in a row, which overlapped the original character pair exactly. Participants were asked to press a button corresponding to the character with one more stroke, which occurred equally often on the left or right of the screen. Displays of the series of events in the task were illustrated in Figure 1. The details of the procedure were the same with the first inspection time task.

Working Memory Updating Tasks

Digit Updating (Chen et al., 2002). In this task (adapted from Morris & Jones, 1990), several digits from 1 to 9 were presented serially for 1750 ms per digit (presented 1250 ms and blank 500 ms). The task was simply to recall the last three digits presented in the list. To ensure that the task required constantly updating, the instructions required the participants to rehearse out loud the last three digits by mentally adding the most recent digit and dropping the fourth digit back and then saying the new string of three digits out loud. For example, if the digits presented were “7-6-2-1-4” the participants should have said, “7-76-762-621-214” and then recalled “214” at the end of the trial. It should be noted that every digit had only one syllable in Chinese. The number of digits presented (5, 7, 9, or 11) was varied randomly across trials to ensure that participants would follow the instructed strategy and constantly update their working memory representations until the end of each trial. After practicing on two trials with five and seven digits, respectively, the participants performed two blocks of eight trials each. The dependent variable was the proportion of trials recalled correctly both for the digits and the sequence.

Keep Track (after Yntema, 1963). In this task participants were first showed all categories and the exemplars in each to ensure that they knew to which category each word belonged. Each trial began with an initial display of the names of three target categories at the bottom of the screen. A

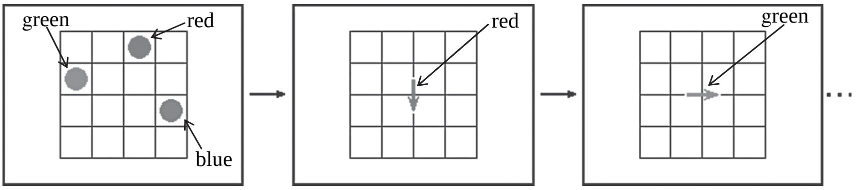
Figure 1. Displays of the series of events in the Inspection Time task (Chinese character).



sequence of words including two or three exemplars from four categories (three target and one non-target) was then presented for 1300 ms each with an interstimulus interval of 300 ms, followed by six numbered exemplars of each target category, for which participants were instructed to recalled the last-presented member of three target categories, and pressed the corresponding number key. To ensure that the task required constantly updating, the instructions required the participants to rehearse out loud the three last-presented exemplars. The number of exemplars presented (6, 8, 10, or 12) was varied randomly across trials to ensure that participants would update the exemplar of relevant category at each time until the end of each trial. After practicing on three trials with six exemplars, the participants performed two blocks of eight trials each. The categories in the practice block were head, festival, rooms, and weather (the last one is non-target category). Categories for the first block were fruits, furniture, birds, and cities, and categories for the second block were vegetables, clothing, insects, and countries. The proportion of words recalled correctly was the dependent variable.

Matrix Updating (locally developed). Displays of the series of events in the task were illustrated in Figure 2. Stimuli in this task consisted of a 4 × 4 matrix approximately 11° wide, and cells about 2.2° on each side. Three color-dots (i.e., red, green, and blue) were centered in one of the cells respectively, and had a diameter of approximately 2°. The matrix with color dots was displayed for 4000 ms, and then several color arrows pointing either left, right, up, or down were successively presented at the central of the matrix for 1500 ms each with an interstimulus interval of 500 ms. These color arrows indicated that the dot with the same color moved one cell in the direction of the arrow. At last, the participants were required to point out the current locations of the three color-dots by mouse click. The number of arrows presented (three, four, or five) was varied randomly across trials to ensure that participants would update the location of relevant color dot at each time until the end of each trial. After practicing on two trials with three and four arrows, respectively, the participants performed two blocks of six trials each. The dependent variable was the percentage of correct decisions.

FIGURE 2. Displays of the series of events in the Matrix Updating task.



Procedure

Participants were tested individually in a quiet, well-illuminated room. All assessments were taken in two sessions, administered during a 2-week period. Participants were encouraged to have a break whenever they felt tired. The stimuli in each of the tasks were balanced for relevant parameters (e.g., an equal number of arrows with different color), and the order of the trials within each task was pre-randomized and then fixed for all participants.

RESULTS

The results are presented in three sections. First, descriptive statistics and reliability estimates of the measures are presented. Second, a series of hierarchical regression analysis are presented to verify whether the age differences in updating are at least partially independent of the age differences in processing speed. Third, a series of structural equation models are presented to examine the mediated effects of age on fluid intelligence through processing speed and updating.

Descriptive statistics of fluid intelligence and processing speed measures are presented in Table 2. Also in this table are reliability estimates of the measures. It can be seen that all the estimated reliabilities were greater than .80. The data are separated into three age groups for purposes of illustration, but most of the analyses were based on treating the samples as continuous with respect to age. As expected, there were significant relations between age and fluid intelligence and speed variables. Older participants performed poorer on fluid intelligence assessments and slower on speed tasks.

TABLE 2. Means (and Standard Deviations) of Fluid Intelligence and Processing Speed Measures.

	Age				
Variable	18–39	40–59	60–85	Est. rel.	Age *r*
Ravens	10.7 (2.4)	7.1 (2.0)	5.8 (2.3)	.81	–.59*
Cattell	27.5 (4.6)	19.5 (3.3)	16.4 (3.8)	.86	–.59*
Folding	9.2 (2.2)	6.8 (2.2)	5.6 (2.2)	.82	–.69*
Spatial	11.9 (4.4)	6.4 (2.7)	6.1 (2.2)	.89	–.78*
DIGSYM	68.3 (9.7)	54.1 (10.7)	43.6 (11.9)	–[1]	–.70*
DIGCOP (ms)	797 (126)	925 (148)	1185 (235)	–[1]	.71*
RT: fig (ms)	1260 (213)	1519 (224)	1692 (325)	.99	.62*
RT: char (ms)	1522 (232)	1885 (233)	2234 (315)	.99	.79*
IT: fig (ms)	92 (19)	105 (24)	114 (27)	–[1]	.40*
IT: char (ms)	132 (32)	170 (33)	205 (46)	–[1]	.68*

$*p < .01$.

Note: [1]No reliability estimates available in this task. All other reliability estimates were calculated by adjusting split-half (odd-even) correlations with the Spearman–Brown prophecy formula.

Descriptive statistics of updating measures are presented in Table 3. Also as expected, increased age was associated with a decrease in the percentage of correct responses in updating tasks, suggesting a decline in the ability of constantly updating the content of working memory. The data were further analyzed by evaluating accuracy of separate difficult levels. As expected, accuracy was lower in more difficult level, and the age differences were also slightly larger in more difficult level than in easier level. Because the overall percentage correct variable had the highest reliability, it was used as the summary measure of updating performance in subsequent analyses.

Although there was a significant age-related influence on the updating variables, further analysis was needed to verify whether the age-related influences on updating variables were unique after statistically controlling for the influences of speed variables (Salthouse, 2001). That is to say, this section involves obtaining evidence that the age-related differences in the updating variables were at least partially independent of the age-related differences in speed variables. In order to compare our results with those of Salthouse (2001), composites of three types of speed were derived by averaging the two *z*-scores of each type of speed measures. Table 4 summarizes the proportions of variance associated with age in the target variable, and in residuals created by controlling the variance of three types of speed composites. A series of hierarchical regression analyses showed that there was a considerable reduction of the age-related variances in updating variables after controlling each of the

TABLE 3. Means (and Standard Deviations) of Working Memory Updating Measures.

	Age				
Variable	18–39	40–59	60–85	Est. rel.	Age *r*
Digit updating					
% Correct	79.5 (18.2)	51.4 (17.5)	41.1 (21.5)	.91	–.65*
Length 5, 7	95.1 (11.5)	80.5 (17.5)	66.5 (22.1)	.82	–.57*
Length 9, 11	63.9 (29.6)	22.3 (22.8)	15.7 (24.5)	.88	–.62*
Keep track					
% Correct	85.9 (11.9)	73.4 (11.3)	64.7 (9.8)	.80	–.65*
Length 8	91.5 (10.2)	84.3 (13.2)	72.5 (13.7)	.47	–.56*
Length 10	84.6 (15.7)	74.2 (13.3)	67.6 (15.9)	.43	–.46*
Length 12	81.6 (16.6)	61.8 (20.6)	54.1 (16.5)	.67	–.56*
Matrix updating					
% Correct	85.1 (13.4)	64.0 (15.2)	54.2 (14.0)	.90	–.71*
3 Arrows	96.6 (6.8)	85.2 (17.1)	78.7 (15.8)	.62	–.50*
4 Arrows	84.3 (16.8)	62.2 (18.0)	50.4 (21.1)	.74	–.63*
5 Arrows	74.4 (22.5)	44.5 (23.3)	33.5 (15.9)	.77	–.68*

*$p < .01$.

Note: All reliabilities estimated by adjusting split-half (odd-even) correlations with the Spearman–Brown prophecy formula.

TABLE 4. Total and Unique Age-Related Variance in Working Memory Updating Variables.

		Age-related variance		
Target variable	Total	After perceptual/ motor	After reaction time	After inspection time
Digit updating	.423	.045	.106	.145
Keep track	.426	.053	.082	.148
Matrix updating	.498	.052	.119	.152
Average	.449 (100%)	.050 (11.1%)	.102 (22.8%)	.148 (33.0%)

three types of composite speed variable. However, the reduction was the largest for perceptual/motor speed, lesser for reaction time, and the least for inspection time. It should be noted that the average proportion of unique age-related variance on the updating variables was 33.0% after control of the composite inspection time variable, compared with 11.1% for perceptual/motor speed in this study, and 12.6% for perceptual speed in a series of previous studies (see Salthouse, 2001, for details).

The last section of analyses examined to what extent measures of speed and updating mediated the relationship between age and fluid intelligence. We used a model equivalent to that of Salthouse and Miles (2002), which is illustrated in Figure 3. Although the measures used to construct the latent variables are not presented in Figure 3, the standardized coefficients for the relations between the latent variables and the observed variables were all greater than .64, with median of .83. This information, together with the good fits of the models to the data (see Table 5), implies that there was a good convergent validity of each construct (i.e., speed, updating, and fluid intelligence). Furthermore, the relations between speed construct and updating construct, were quite small (.11 to .24), indicating that there was a good discriminate validity between these two constructs after statistically controlling for the influences of age.

FIGURE 3. Structural model with standardized coefficients for relations among age, processing speed, working memory updating, and fluid intelligence. Significant path coefficients are in bold. The values presented from left to right are for perceptual/motor speed, reaction time, and inspection time, respectively.

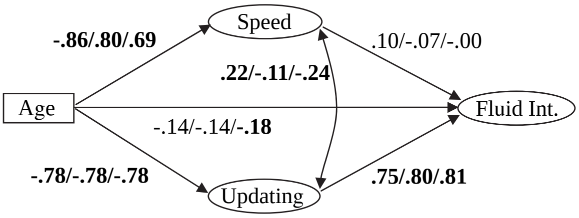


TABLE 5. Fit Indices for Structural Equation Models

Speed variables	Model	*df*	χ^2	CFI	RMSEA
Perceptual/motor	1	30	30.93	1.00	.015
Reaction time	2	30	49.35	.99	.068
Inspection time	3	30	28.18	1.00	.000

Note: Ratios of χ^2/df less than 2, CFI value close to 1.0, and RMSEA less than .08 are usually considered indications of good fit of the model to the data.

Inspection of the values in Figure 3 also shows that the path coefficients from age to both speed and updating were large, indicating that increased age was associated with slower processing speed and poorer updating efficiency. However, it seems that it was updating, but not speed, involved in the mediation of age-related differences in fluid intelligence. That is to say, whenever which type of speed measures was considered, the speed–intelligence coefficient was small and not significant, but the updating–intelligence coefficient was large and significant. Furthermore, when perceptual/motor or reaction time was taken as the speed mediator, the age–intelligence coefficient was also not significant. Similarly, the direct effect of age on fluid intelligence was very small (–.18) as considering inspection time. In addition, we tested whether the model with the path from age to fluid intelligence and the path from speed to fluid intelligence provided a significantly better fit than the model without the paths. This test was clearly not significant whenever which type of speed measures was considered, $\chi^2_{\text{diff}}(2) = 5.14$, 2.08, and 5.42, respectively, all p values $> .05$, supporting the conclusion that updating mediated almost all the age-related effects on fluid intelligence.

DISCUSSION

The purpose of this study was to investigate, in normal adults, to what extent updating and processing speed contribute to age-related differences in fluid intelligence, and whether the contribution of updating is unique after statistical control of the variance in different speed measures (i.e., perceptual/motor speed, reaction time, and inspection time). The results consistently show that, increased age was associated with reductions in updating ability, and lower efficiency in performing updating measures was associated with poorer performance on fluid intelligence tests. This pattern suggests that updating appears to play an important role in the mediation of age-related differences in fluid intelligence. Also note that, while the relationship between updating and fluid intelligence is strong and significant (path coefficient is greater than .75), the speed construct does not significantly predict fluid intelligence after the influence of updating was considered. Therefore, these findings appear to provide empirical evidence to support the executive decline hypothesis of cognitive aging.

However, as noted in the introduction, the results from previous research have been inconsistent with respect to the existence of a unique age-related decline in executive function, compared with decline in general cognitive ability (e.g., Bryan et al., 1999; Fisk & Warr, 1996; Salthouse et al., 1998). In the present study, a series of hierarchical regression analyses indicated that the proportion of unique age-related variance in updating measures is related to the complexity of speed measures. Specifically, there was a considerable proportion (33%) of unique age-related variance in updating measures after controlling for the variance in the simplest speed measures (i.e., inspection time).

This finding stands in contrast to the results of classic cognitive aging studies, which found very little unique age-related influences on updating (see Salthouse, 2001, for details). We interpret this finding to mean that the more complex the speed task is, the more it relies on executive or working memory resources, and then the more shared age-related variance between speed and executive variables. Therefore, the current results suggest that the tasks used to measure processing speed in those classic studies may have tapped into executive processes to some extent, and the speed mediation of age-related differences in fluid intelligence is at least partially derived from the executive component of speed measures.

As an executive function, updating is supposed to be closely linked to the frontal lobes (Collette & Van der Linden, 2002; Smith & Jonides, 1999). A large number of neuroimaging studies have suggested that there is a unique decline in frontal lobes with normal aging (see Raz, 2000, 2004, for reviews). For instance, Raz (2000, p. 17) indicated that “Regional differences in the magnitude of age effect on the brain may be subtle in comparison with the global deterioration, yet they are noticeable in white and gray matter alike”. Taken together, the results reported here, as well as the neuroimaging reports, suggest that both general slowing and unique executive decline exist in normal cognitive aging process.

Finally, we would like to address the validity and reliability of the updating measures. It has been suggested that there is an impurity problem with many tests of executive functioning (i.e., involving non-executive component). In addition, the task impurity problem is further compounded by the low reliability problem (Miyake et al., 2000; Rabbitt, 1997). Previous studies preferred to use latent variable analysis and structural equation modeling to resolve these problems. However, we feel not only advanced statistical methods, but also more works to improve on the quality of each measure, are needed to achieve high validity and reliability. For instance, Morris and Jones (1990) have indicated that the running memory task requires two independent components: updating (executive component) and memory load (non-executive component). Therefore, in order to improve the validity and reliability of updating tasks, we decrease the memory load of the task by reducing the number of items to be recalled (i.e., only three items in this study), and increase the executive component of the task by requiring participants rehearsing out loud constantly. Furthermore, in pilot studies, we have found three-item memory load is appropriate for nearly all participants. If the memory load is increased (e.g., four items), most participants would fell it's too difficult to follow, and then it promotes preferential utilization of other strategies. That is, participants prefer to reduce the frequency of updating (e.g., updating every other item), or frequently restart updating process immediately after failed at the middle of the trial. These strategies are indubitably considered having a bad influence on the validity and reliability of updating measures. This study also locally developed a Matrix Updating task, which is proved to be highly effective to assess updating ability.

In conclusion, the current project clearly suggests that updating, but not speed, is the critical mediator between age and fluid intelligence. In addition, the speed mediation of age-related differences in fluid intelligence as indicated by previous studies is at least partially derived from the executive component of speed measures.

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