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Organization of cognitive abilities and neuropsychological variables across the lifespan

Timothy A. Salthouse
Department of Psychology
University of Virginia

and

Hasker P. Davis
Department of Psychology
University of Colorado, Colorado Springs

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Abstract

Data from over 3,400 individuals ranging from 5 to 93 years of age were analyzed to investigate the structural organization of cognitive variables, and to use that structure to examine relations between cognitive abilities and neuropsychological variables. The results indicated that the variables could be organized into the same cognitive ability factors in both children and adults, and that in both segments of the lifespan a large proportion of the age-related influences on measures of cognitive functioning was shared across different cognitive abilities. Another set of analyses revealed that many neuropsychological variables were closely related to established cognitive abilities, although the pattern of influences varied somewhat across different age groups. Finally, variables assumed to reflect executive functioning were found to lack construct validity because there was nearly perfect overlap of the individual differences in what these variables had in common and a construct of fluid intelligence.

We used a unique data set, consisting of a wide variety of variables from a large number of individuals ranging from 5 to 93 years of age, to investigate four major questions. The first question is whether a set of 18 cognitive variables can be organized into a structure based on the relations of the variables to one another, and if so, whether the organizational structure is qualitatively similar at different periods in the lifespan. The second is whether the structure can be used to characterize the number and nature of statistically independent age-related influences operating on groups of cognitive variables. The third question is whether the structure can be used to assist in the interpretation of what specific variables represent, and to determine the extent to which the age-related influences on those variables are statistically independent of age-related influences on other cognitive abilities. The fourth question examined in this report is whether it is meaningful, on the basis of patterns of empirical relations among the variables, to use a label such as executive functioning when referring to different types of variables.

The analyses are based on data collected from a total of over 3,400 individuals between 5 and 93 years of age. Because the direction of the age relations was expected to vary across different periods in the life span, the data are divided into three non-overlapping samples. Ages 5 – 17 years are designated as the child sample, ages 18 -22 years as the student sample (because most of the individuals within that age group were college students), and ages 23 – 93 years years as the adult sample. There are obviously many other ways in which the data could be grouped but these particular categories correspond to regions of the life span with different developmental patterns, and provide sample sizes sufficiently large for meaningful correlational analyses.

With respect to the first question, prior research indicates that most cognitive variables are moderately related to one another and can be organized into a structure based on the relative strengths of the correlations among the variables. Different types of structures can be postulated for the same data, but most structures within the psychometric literature involve a grouping of variables into several correlated first-order factors. Because structures derived from correlations represent the degree to which people perform relatively high or low on sets of variables, they can be interpreted as reflections of the dimensions along which people vary.

Figure 1 illustrates the hypothesized factor structure for 18 cognitive variables from the present data set based on expectations from past research (e.g., Carroll, 1993; Salthouse, 2004; 2005; Salthouse & Ferrer-Caja, 2003). The major issue to be addressed concerning this figure is whether the portrayed structure fits the data in each age group. That is, does this organization apply in each age group, which would suggest that people in different regions of the life span differ from one another along the same dimensions. Given the large differences expected in mean levels of performance across the groups, the question of primary interest is whether there is a qualitatively similar pattern of relations among the variables in the three samples.

Place Figure 1 about here

Once an organizational structure is established for the child and adult samples, it should then be possible to use that structure to determine where effects associated with increased age operate. No age relations were expected in the student sample due to the limited age range for these participants. Because nearly all of the individual variables have significant relations to age, the primary focus in these analyses is on whether there are also age-related effects on what the variables have in common, in the form of first-order latent constructs, or on what the first-order latent constructs have in common, in the form of a second-order latent construct. Figure 2 illustrates the model used for these analyses. Of particular interest in this model is the strength of the relations from age to the second-order common factor and to the different first-order factors. These relations indicate which groupings of variables grow and decline together, and thus should be informative about the number of distinct explanatory mechanisms that may be needed to account for the influences of age on this set of cognitive variables.

Analyses similar to this with other data sets based on adults 18 and over were recently reported by Salthouse (2004) and Salthouse and Ferrer-Caja (2003). They found that negative age-related influences were evident on the second-order common factor and the first-order memory and speed factors, and a positive age-related influence was evident on the first-order vocabulary factor. These results imply that at least four different mechanisms may be needed to account for effects of aging across a wide variety of cognitive variables (i.e., one each for the influences on the common factor, and to the speed, memory, and vocabulary factors). To our knowledge, no comparable analyses have been reported on data from children.

Place Figure 2 about here

Next, the analytical model portrayed in Figure 3 was used to investigate the meaning of selected target variables, and the degree to which the age-related influences on them are independent of age-related influences on other cognitive variables. In other words, information about what a variable represents can be obtained by examining relations of different cognitive ability factors to the target variable. The rationale is that a variable can be inferred to be similar to those ability constructs to which it has a strong relation, and to be dissimilar to those ability constructs to which it is only weakly, or not at all, related. This is an indirect method of investigating the meaning of a variable, but it is more objective than judgments of face validity based largely on intuition. Ideally the analytical method would be applied with several different combinations of reference constructs, including some that represent theoretically relevant processes. Nevertheless, the use of cognitive ability factors as the reference constructs has the advantage that nearly a century of research has been devoted to refining the reliability and validity of the measures.

Place Figure 3 about here

An additional feature of the model in Figure 3 is that it provides estimates of the direct, or unique, age-related influences on the variables. Because direct influences are statistically independent of any influences operating through the cognitive abilities, they are of particular theoretical interest in that they are likely to require a separate explanatory mechanism from that needed for influences on the abilities. Analyses based on a model similar to that in Figure 3 conducted on data combined across many studies by Salthouse and colleagues were recently reported by Salthouse (2005). The major findings of those analyses were that very few of the target variables had age-related influences that were statistically independent of age-related influences on the reference cognitive abilities, and that most of the variables were related either to reasoning or speed ability. The current data set offers an opportunity to investigate the generality of the Salthouse (2005) findings because there was little overlap among the variables in the two projects, and the earlier analyses were restricted to data from adults.

The fourth major question investigated in this study concerns the construct validity of an executive functioning construct. Different types of variables are often considered to reflect the same construct, but there is seldom objective evidence to justify categorizing the variables together. One method of determining whether variables should be grouped together is based on the investigation of construct validity. There are two aspects of construct validity. Convergent validity is established when the target variables have moderate relations to one another, and discriminant validity is established when the target variables have weak relations to variables representing other constructs. Salthouse, et al. (2003) recently concluded that variables frequently used to assess executive functioning may lack construct validity because although they had significant relations to one another, the variance they had in common was very closely related to a fluid intelligence (gF) construct. Construct validity of executive functioning will be examined in this study to determine whether the earlier findings can be replicated, and are generalizable to different age groups.

Not all of the participants whose data were included in the analyses performed the same combination of tests, and thus the data set has a considerable amount of missing data. However, the missing values are attributable to the particular set of tests administered to the individual rather than to his or her level of performance on the variables, and thus the missing data can be considered to be missing at random. This property allows powerful analytical techniques to deal with the missing data such as the maximum likelihood estimation procedure incorporated within the AMOS (Arbuckle, 2003) structural equation modeling program.

Although data sets with large proportions of missing data are often considered undesirable, missing data are sometimes unavoidable, particularly when the data were originally collected for different purposes and are later aggregated into a single data set, as is the case here. However, contemporary analytical procedures take advantage of all of the available information at the time of the analysis, and thus even individuals with data on only one or two variables add to the power of the analyses.

Methods

Participants Participants were recruited from psychology classes at the University of Colorado at Colorado Springs, children and older relatives of students, and from local senior citizen organizations. All signed an informed consent form approved by the local committee for the protection of human subjects. None of the participants reported a history of head trauma with behavioral consequences, learning disability, major psychiatric illness, or illicit or prescription drug use that they thought might affect their cognition. All of the elderly participants reported themselves to be in moderate to good health, and lived independently in the community. Students received extra credit toward psychology course work, volunteers 60 years of age or older received $10 per hour, and participants 5 to 17 years of age received $5 per hour.

Procedure Participants were told that the purpose of the study was to assess different mental abilities and that they would be given a variety of tests. All testing was carried out in testing rooms at the University of Colorado at Colorado Springs, the University of Colorado Aging Center, or the participant’s home (for the convenience of some elderly participants). Each testing session typically lasted 1 to 2 hr with 5-10 min breaks each hour or when requested by the participant. In the first session participants were administered a verbal memory test and a visual-spatial memory task. The order of test administration in subsequent sessions was determined by the time length of the session, the participant's commitment to additional sessions, and the type of test to be administered. For example, two verbal tests were not given in the same session, and arduous and potentially long tests such as the N-back and Tower of Hanoi were not administered in the same session. After each testing session participants were provided feedback on their test performance.

Variables A brief description of the reference and target variables, and the source of each variable, is presented in Table 1. Inspection of the table reveals that both the reference and target variables were obtained from a mixture of standardized psychometric tests and specially designed computer-administered tasks.

Place Table 1 about here

Wechsler Abbreviated Scale of Intelligence

The WASI Manual (Psychological Corporation, 1999) provides detailed descriptions of the material and procedures for the Vocabulary, Block Design, Similarities, and Matrix Reasoning subtests. The dependent variables for this study were the raw scores for each subtest.

Rey Auditory Verbal Learning Test (RAVLT)

The Rey Auditory Verbal Learning Test (RAVLT; Rey, 1964) was administered to assess acquisition and recall of verbal material. A list of 15 concrete nouns is presented orally five times in succession at the rate of one word every 2 sec. The order of word presentation for each trial was random and the order of word presentation was the same for all participants. Participants were asked to recall the words orally at the end of each trial in any order. The numbers of words recalled on trials 1, 3 and 5 are the dependent variables in this study.

Memory Cards

This computerized test is a variation of the old television game show *Concentration* or the children's game of *Memory Cards*, in which the participant turns over two cards from a board revealing two pictures. If the pictures match they are grayed out and removed from play for the remainder of the trial, and if they do not match the pictures are again concealed, and the game continues until all the pictures are matched. Twenty-four cards are presented on the screen face down and the participant attempts to locate the matching pairs of cards by turning over two cards at a time. The cards were arranged in the same positions on each trial. Participants are administered five immediate trials and a measure of optimal choice on trials 1, 3, and 5 served as the dependent variables in the present study.

Reaction Time for Choice and Conditional Choice Decisions

The reaction time test is designed to assess speed of processing based on tasks described by Teng (1990). Participants are shown a series of visual stimuli on a computer screen and asked to respond by clicking the left or right trigger on a standard game pad. In the choice reaction time test the stimuli are arrows pointing to the left or to the right, to which the participant responds as quickly as possible with a click on the left or right trigger. In the conditional choice task when a "+" is displayed the participant clicks the trigger on the side the arrow is pointing, and when a "-" is displayed the participant clicks the trigger on the opposite side to which the arrow is pointing. The dependent variables are the mean reaction times for the correct responses.

Stroop Color-Word Interference

A version of the Stroop Color-Word interference test (Jensen & Rohwer, 1966; MacLeod, 1991) was administered in which participants were first asked to read aloud a card containing four words (red, blue, green, and yellow) printed in black ink as quickly as possible. Next, they read the same words printed in mismatched ink colors aloud as quickly as possible. For a third card, participants named the color of four dots. Finally, the mismatched color in which words are printed was to be named as quickly as possible. The times for reading the words and naming the dot colors were used as measures of speed of processing, and the time to name the color in which the mismatched word is printed was used as a measure of executive functioning.

Verbal and Spatial N-back

The N-back test is frequently used to assess working memory. In this task the participant views a continuous sequence of stimuli, and must decide for each stimulus if it matches the stimulus shown *n* stimuli back in the sequence. For the verbal n-back task letters are presented on the screen for 2 sec with an inter-stimulus interval of 2 sec, and the participant is instructed to respond to each letter by indicating whether it is the same as the letter *n* items back in the sequence. For example, in a 2-back letter condition a positive response should be made whenever the letter is the same as the one viewed two letters back, and in all other cases a negative response should be made. For the spatial n-back task four adjacent red dots are presented on the screen in one of nine locations for 2 sec, with an inter-stimulus interval of 2 sec. In the 2-back spatial condition participants should respond positively whenever the location of the stimulus is in the same position as the location two stimuli back, and for all other cases they should respond negatively. The dependent variables used in this study are the percentage of correct responses for the 2-back and 3-back verbal and spatial trials.

Wisconsin Card Sorting Test

A computerized version of the Wisconsin Card Sorting Test (WCST) was administered using the Colorado Assessment Tests software package (CATs; Keller & Davis, 1998). The appearance, arrangement, and ordering of all stimulus and response cards are identical to the manual version (Heaton et al., 1993). In the computerized version, four distinct stimulus cards (one red triangle; two green stars; three yellow crosses; four blue circles) are permanently displayed in the top third of the computer screen. Response cards with varying characteristics are drawn one at a time from a deck in the bottom third of the screen. The goal for the participant is to match the response cards to one of the stimulus cards according to one of three undisclosed sorting principles (i.e., color, form, or number). After placing a response card under a stimulus card, the participant receives feedback (i.e., “correct” or “incorrect” flashes on the screen) indicating whether or not the card has been matched according to the current sorting principle. The first “correct” sorting principle is color, followed by form, number, color, form and number. The sorting principle is changed each time a criterion of 10 consecutive correct matches is reached for a total of six possible categories. The test is completed when 10 correct responses are made to the sixth category, or when the participant has exhausted all 128 response cards.

The WCST provides a variety of measures, although most of them are highly correlated with one another. Our analyses used only the number of categories completed measure which represents the total number of times the participant achieved 10 consecutive matches for each sorting criterion.

Verbal Fluency Test (FAS)

In this test, which has been used in many psychometric and neuropsychological studies (e.g., Spreen & Strauss, 1998), participants are instructed on successive trials that they will be given three different letters (F, A, and S) of the alphabet, and are to produce all the words they can think of in one min. They are told not to use proper nouns, numbers, or variations on a common word prefix. The dependent variable used here was the total number of appropriate words generated for the three letters.

Self-Ordered Pointing Test

The Self Ordered Pointing Test (SOPT) described by Petrides and Milner (1982) is often used to assess working and strategic memory (Spreen & Strauss, 1998). The test consists of a series of 12 trials in which a set of stimulus items (abstract images) are spatially arranged in a 3 x 4 display on the computer screen. The arrangement of stimulus items varies from trial to trial over the 12 trials. On each trial the participant is required to use a mouse to click an item that had not been selected on any of the previous trials. The display then disappears for 10 sec, and reappears with the items rearranged. The participant must respond in 10 sec on each trial and cannot point at an item in the same location on two trials in a row. In this study the dependent variable is the total number of errors, which are defined as selection of a previously selected item.

Tower of Hanoi

The Tower of Hanoi puzzle, often used in studies of problem solving (e.g., Simon, 1975), consists of three pegs with either three or four disks. The participant sits in front of the computer screen and the experimenter demonstrates how using a mouse to click on a stack of disk picks up the top disk, and how it can then be moved to the target peg, and can be dropped by clicking again. The program does not allow larger disks to be placed on top of smaller disks and only one disk can be moved at a time. The participant is first given five trials to move three disks from the left peg to the right peg. These trials are followed by five trials in which the participant is required to move four disks from the left peg to the right peg. The dependent variable in this study is the total number of moves required to solve the five trials of the four-disk puzzle.

Tower of London

The Tower of London test was originally developed by Shallice (1982) to investigate problem solving in individuals with frontal lobe damage. A computerized version of the test (Keller & Davis, 1998) was used in the present study. Briefly, participants are required to move colored beads in as few moves as possible from a starting configuration to a goal configuration. Problems consist of three beads and three pegs, four beads and four pegs, and five beads and five pegs, with the problems varying in the number of direct and indirect moves required for the optimal solution. Participants completed 21 problems, and the total number of excess moves (i.e., moves beyond the minimum necessary) is the dependent variable used in the present study..

Temporal Order

The Temporal Order test (Keller & Davis, 1998) consists of a list of 10 common nouns presented one at a time for 3 sec each on a computer screen. Participants are told they can read each word aloud or simply study the word as it is presented. After the last word is presented, participants are shown the entire list in a random order and asked to arrange the words until the list matches the original order of presentation. Word order is arranged on the computer screen by the experimenter, as directed by the participant, by clicking the word and then the indicated position. After completing the ordering of the words, participants are given the opportunity to make any additional changes. Instructions at the beginning of the test mentioned that memory for the words would be tested, but participants were not told that they would be asked to remember the order in which the words were presented. A Spearman rank correlation between the actual order of words and the participant generated order of words is calculated as the dependent variable.

Visual Span Test

The visual span test used in the present study is a computerized version of the visual span test in the *Wechsler Memory Scale – Revised* (Wechsler, 1987). The two parts of this test are a forward visual span test and a backward visual span test. Eight blue blocks are arranged on the computer screen and participants are told they will flash white in a particular order and that the task was to remember the sequence. After the sequence is presented participants reproduce it by clicking the boxes in the same order. The sequence length starts at two and increases up to eight. The forward test continues until the participant makes mistakes on both of the sequences of the same length. The test is then repeated with the participant reproducing the sequence in the reverse order of presentation. The dependent variables are the number of patterns successfully reproduced for the forward and backward sequences.

Results

<u>Initial Descriptive Information</u>

Table 2 contains means, standard deviations, and correlations with the linear and quadratic (i.e., age^2) age terms for three demographic variables, 18 reference variables selected to represent five cognitive abilities, and 10 target neuropsychological variables. (In order to minimize multicollinearity between the age and age^2 terms, the age variable was first centered by subtracting the subgroup mean from all ages within the subgroup before squaring, and the correlation with the age^2 term was determined after first controlling for influences associated with the linear age term.) The student sample had the highest (or fastest) performance for all variables except for vocabulary, for which the highest level of performance was in the adult sample. Performance on all variables, except the speed variables for which better performance corresponds to lower scores, was positively related to age in the child sample, and was negatively related to age in the adult sample. The non-linear age relations on the variables were in the direction of a deceleration of the increase at older ages in the children sample, and an acceleration of the decrease at older ages in the adult sample.

Place Table 2 about here

Structural Analyses

Table 3 contains the standardized factor loadings for a confirmatory factor analysis conducted in each sample based on the model portrayed in Figure 1. The fit of structural equation models of this type can be evaluated with a number of indices. Ratios of X^2 to degrees of freedom approaching or less than 2.0, comparative fit indices (CFI) greater than .90, and root mean squared errors of approximation (RMSEA) less than .1 are often considered to represent good fits of the model to the data (e.g., Kline, 1998). Based on these criteria the fit to the data was very good for the children and adult samples, and at least moderate in the data of the student sample.

Place Table 3 about here

Additional analyses were conducted to compare the model parameters across the three groups. The first analysis constrained the unstandardized coefficients relating factors to variables to be equal across the three groups. The fit of this model was not significantly different from that for the model with freely estimated coefficients (i.e., $\Delta X^2 = 31$, $\Delta df = 24$, $p > .15$), suggesting that the factor – variable relations were similar in the three groups. A second analysis constrained the unstandardized relations among the factors to equal, but this model fit the data significantly worse than the model with freely estimated factor covariances (i.e., $\Delta X^2 = 307$, $\Delta df = 30$, $p < .01$). Inspection of Table 3 reveals that this is attributable to relatively high factor correlations in the child sample and to somewhat low correlations in the student sample.

The analyses were repeated with the child sample divided into two groups age 5 to 10 and 11 to 17, and with the adult sample divided into a 23-to-49 group and a 50-to-93 group. The sample sizes in these subgroup analyses were much smaller than in the analyses reported in Table 3 and thus the estimates were more variable, but the patterns in each group were qualitatively similar to those in Table 3.

To determine the extent to which the patterns might have been induced by relations of age to each variable, the analyses in the child and adult samples were repeated after partialling the linear relation of age from all variables. The results of these analyses are also presented in Table 3, where it can be seen that although, for children, all of the factor-variable relations and factor correlations were weaker in the age-partialled data, and for adults, most of them were weaker, in both cases the patterns were qualitatively similar to those in the original analyses.

The conclusion from the structural analyses is that the organization in Figure 1 provides a fairly accurate representation of the interrelations of the variables in all three groups. In particular, the variables appear to represent the same constructs to nearly the same degree in each group, although there is some variation in the relations among the constructs across groups.

Composite variables for each factor were created by averaging the z-scores (computed with the total sample as the reference distribution) for the variables associated with each factor. The means and standard errors of these composite variables are plotted as a function of age in Figure 4. (The sign of the composite speed variable was reversed so that higher scores represent better performance with each factor.) It can be seen that the composite scores increased with age across the period of childhood, and beginning around age 30 decreased with age across the period of adulthood except for the crystallized composite which remained relatively stable.

Place Figure 4 about here

Most of the factor correlations in Table 3 were in the moderate to high range. Rather than leaving these correlations unexplained, the relations among the factors can be postulated to be at least partially attributable to a higher-order factor, as portrayed in Figure 2. Table 4 therefore contains standardized coefficients relating the first-order factors to a second-order factor. The relations of the fluid intelligence factor with the second-order factor were very high in each sample, and the estimated coefficient was actually greater than 1.0 in the student sample. These findings are consistent with other results (e.g., Gustaffson, 2002; Salthouse, 2005) and imply that there is nearly perfect overlap of the gF factor and the second-order common factor in all three groups. It is noteworthy that unlike the children and adult samples in which every first-order factor had at least moderate relations with the second-order factor, in the student sample the speed factor was not significantly related to the second-order factor.

In the child and adult samples the fit to the data was somewhat worse for the model with a second-order common factor compared to the model with correlated first-order factors (cf. Table 3). The fit could have been improved by specifying more complex second-order models, but it should be pointed out that the difference between the two sets of models was not large (i.e., $\Delta df = 9$, and $\Delta X^2 < 30$), and the hierarchical model still had a very good fit to the data in the child and adults samples (i.e., CFI > .95, and RMSEA < .03). Both models were therefore used in subsequent analyses.

<u>Age-related influences</u>

Age-related influences were next examined on two organizational structures, the correlated-factors model and a hierarchical model with a single second-order common factor. Table 5 contains the standardized coefficients for the age relations on the correlated-factors model (top), and for a model with age either related only to the second-order common factor, or to both the second-order common factor and one first-order factor (bottom).

Place Table 5 about here

As expected because of the limited age range, in the student sample there were no significant age-related effects in the correlated-factors structure. However, all of the relations between age and the first-order factors were significant in the children and adult samples. In the children sample increased age was associated with better performance, and in the adult sample increased age was associated with lower performance, although not to a statistically significant degree for the crystallized factor.

The initial analyses with the hierarchical structure examined the relation of age on only the second-order common factor (top row). It can be seen that the age effect was large and positive in the child sample, and large and negative in the adult sample. Subsequent analyses included age relations on one first-order factor in addition to the second-order factor, with each factor considered successively. The age relations on the first-order factors were considered successively rather than simultaneously because the high correlations among the factors (cf. Table 3) and the high relations of the factors with the second-order common factor (cf. Table 4) resulted in distorted estimates due to multicollinearity when the relation on the second-order factor was considered simultaneously with a relation on more than one first-order factor. As noted in the introduction, these analyses are designed to determine where statistically independent age-related influences are operating within the hierarchical structure of cognitive variables.

None of the age relations were significant in the student sample. In the children sample there was a significant increase with age on the crystallized ability factor after controlling the variation in what all the factors have in common. This may reflect gains in knowledge that are distinct from the gains in the other abilities. There was also a significant decrease in the verbal memory factor after adjusting for the influence of age on what all of the factors have in common. However, the standardized coefficient for the relation between the verbal memory factor and the second-order common factor increased substantially from .84 (cf. Table 4) to 1.29 when age was related to the second-order common factor, and thus the negative relation between age and verbal memory could be a statistical artifact because an influence in the opposite direction is needed to offset the positive influence of age on the second-order factor.

In the adult sample there were significant relations of age on three of the first-order ability factors after controlling the variability in the second-order common factor representing what the first-order factors have in common. The positive influence of age on the crystallized ability factor can be postulated to reflect the effects of cumulative experience contributing to greater knowledge. The negative age relation on the spatial memory factor implies that in addition to effects on what the abilities have in common, increased age is also associated with poorer memory for spatial information. The positive relation between age and the working memory factor after controlling the influence of age on the second-order common factor may be a statistical artifact because the relation between working memory and the second-order factor increased from .80 (in Table 4) to 1.04 after adjusting the influence of age on what was common to all factors. Alternatively, the age-related decrease in working memory may be smaller than the decrease for other cognitive abilities and the positive coefficient could merely reflect this discrepancy.

The preceding results suggest that the correlational structure of cognitive variables and abilities is useful in understanding the nature of age-related influences on a variety of different cognitive variables. Nearly every variable was related to age in the children and adult samples, but the analyses suggest that many of the age-related effects on these variables appear to operate at a level more abstract than the individual variables, and affect what is common to different variables.

Investigating the meaning of variables

The next set of analyses used the correlated-factors structure to investigate the meaning of new variables with the model portrayed in Figure 3. Ideally an analysis of this type would include all of the reference ability factors in a single analysis, as was done in Salthouse (2005). However, the values in Table 3 indicate that many of the correlations among the factors were quite high, which leads to problems of multicollinearity and unstable regression coefficients (Cohen & Cohen, 1983). There is no completely satisfactory solution to this problem, but in an attempt to deal with it we conducted two separate analyses with different sets of ability predictors in each analysis. The ability predictors used in each analysis were somewhat arbitrary, but similar results were obtained in analyses with different combinations of variables.

Standardized regression coefficients from these analyses are presented in Table 6 for nine target variables often used in neuropsychology to assess executive functioning and related constructs. Two sets of results are of interest in this table. One consists of the relations between the cognitive abilities and the target variable because these relations are informative about what the variable represents in terms of the abilities that influence it. The other set of relevant results are the estimates of the unique relations of age on the variables. Comparisons of these relations with the age correlations in Table 2 provide an indication of the degree to which the age-related influences on the target variable are shared with age-related influences on the cognitive abilities included in the analyses.

Place Table 6 about here

The number of categories variable in the Wisconsin Card Sorting Test is a particularly interesting target variable because it is often used to assess executive functioning. This variable had moderate to strong relations to fluid ability in each sample, which is similar to the findings of Salthouse (2005) and Salthouse, Atkinson and Berish (2003) in analyses based on data only from adults. In addition, there was a significant relation with crystallized ability in the children sample, and to working memory in the adult sample, which raises the possibility that other influences on the variable change with age. There was a significant unique relation of age on the WCST variable in the adult sample after controlling the variation in crystallized, spatial memory, and working memory abilities, but not after controlling the variation in fluid, verbal memory, and speed abilities.

The FAS variable is also often used to assess executive functioning. In the children sample it was primarily influenced by crystallized ability, but in the adult sample it was influenced by verbal memory, crystallized, and working memory abilities. After controlling the variation in fluid ability, speed, and verbal memory, the unique influence of age on FAS performance in the adult sample was positive, which may represent the contribution of word knowledge which tends to increase with age across adulthood.

The SOPT variable has been postulated to reflect working memory. As one might expect, higher levels of working memory were associated with fewer errors in the self-ordered pointing task in the adult sample, but even stronger relations were apparent with fluid ability. Children with high levels of crystallized ability had significantly fewer errors on this task than children with low levels of crystallized ability.

The Stroop measure of the time to name the colors of words referring to a different color had an inconsistent pattern of influences across samples. There were no significant ability relations in the child sample, the measure was significantly related only to speed in the student sample, and it was related to speed and to crystallized ability in the adult sample. Increased age was associated with slower incongruent naming time among adults, even after adjusting for influences of age on the other abilities.

Performance in the Tower of Hanoi task is hypothesized to require planning aspects of executive functioning. Higher levels of fluid ability and spatial memory were associated with fewer moves to solution in all three samples. The Tower of London task has similar requirements as the Tower of Hanoi task, and thus it might be expected to have a similar pattern of relations with cognitive abilities. However, in the child and adult samples the Tower of London measure was significantly related to crystallized ability and not to fluid ability.

The Temporal Order variable was moderately related to verbal memory ability in each sample. It was also significantly related to spatial memory in the adult sample, and in this sample it had a unique negative age relation after controlling the variation in the crystallized, spatial memory, and working memory abilities.

The Visual Span Forward variable had moderately strong relations to fluid ability in each sample, and it was also related to working memory ability in the student and adult samples. There was a significant unique negative relation of age in the adult sample after controlling the age-related influences on crystallized, spatial memory, and working memory abilities.

The Visual Span Backward variable is often assumed to have greater working memory requirements than the Visual Span Forward variable because of the need to manipulate the information as well as retain it. Although this variable had moderate relations with working memory in each group, the relations were actually somewhat stronger with fluid ability. There were no unique age relations on the backward visual span measure after controlling the variation in the other cognitive abilities.

Many of the results just described are surprising because they imply that frequently used neuropsychological variables may represent somewhat different aspects of cognitive functioning at different portions of the lifespan. Some of the apparent variation across the three samples may be due to chance, particularly since many of the coefficients were in the same direction but because the sample sizes varied some were significantly different from zero and others were not. Nevertheless, the different patterns of results suggest that researchers should be cautious in generalizing findings obtained from one type of sample to a different type of sample.

Another noteworthy finding in Table 6 is that there were relatively few unique age-related influences on the variables, and when they did occur they were not necessarily the same in the analyses with different reference cognitive abilities. For example, in the adult sample there was no unique relation of age on the WCST variable after controlling the variation in fluid ability, verbal memory, and speed, but there was a unique relation after controlling the variation in crystallized ability, spatial memory, and working memory. These patterns suggest that the abilities contribute differentially to the age relations on the variables.

Construct Validity of Executive Functioning

The final set of analyses was designed to investigate the construct validity of an executive functioning construct in the context of structural equation models. Two aspects of construct validity were investigated; convergent validity as evidenced by moderately high loadings of the variables on the hypothesized executive functioning factor, and discriminant validity as evidenced by relatively weak correlations between the executive functioning factor and factors representing other cognitive abilities. The rationale is that if a set of variables reflect the same construct then they should have moderate relations to one another (manifested by moderate to high loadings on the construct), but the variance they have in common should not be strongly related to other constructs (manifested by weak to moderate correlations with other constructs).

Results of the analyses are presented in Table 7, where it can be seen that the fits to the data were good in each analysis. The discovery of significant relations of the variables with the hypothesized executive functioning construct is consistent with the existence of convergent validity. However, it is noteworthy that the relations are generally weaker than those found with other cognitive ability constructs (cf. Table 3), which suggests that the executive functioning construct is either broader, or possibly less coherent, than the psychometrically-based cognitive ability constructs.

Place Table 7 about here

Perhaps the most important results in Table 7 are the moderate to high correlations between the executive functioning construct and constructs representing other cognitive abilities. These results suggest that there is considerable overlap between what variables postulated to reflect executive functioning represent and what is assessed by tests of other cognitive abilities. This is particularly true for the gF construct because its correlation with the executive functioning construct ranged from .87 to .98. In this respect the executive functioning construct lacks discriminant validity in all three groups.

Analyses were also conducted in which the target variables were allowed to be related to each cognitive ability when examining any variance they might have in common. Salthouse, et al. (2003) proposed this as a particularly demanding test of construct validity because it focuses on the residual variance that remains after partialling the influences of established cognitive abilities. The results from this analysis indicated that none of the variables in any of the samples had significant relations with an executive functioning construct after controlling influences of other cognitive abilities on the variables. This finding suggests that, at least from the perspective of this particular analytical model, the executive functioning construct based on the variables in Table 7 also lacks convergent validity.

Discussion

There are both methodological and substantive contributions of the research reported here. One methodological contribution is the demonstration of the value of aggregating data and using state-of-the-art procedures, such as maximum likelihood estimation, to deal with missing data. The samples and variables in these analyses are different from those included in recent analyses reported by Salthouse (2004; 2005), but the studies are similar in yielding interpretable outcomes when the data sets contain large amounts of missing data. Furthermore, it is important to note that in other projects nearly identical results were obtained when the same analyses were conducted on complete data (Salthouse, 2005; Salthouse & Ferrer-Caja, 2003). Researchers interested in increasing the power and scope of their analyses should therefore consider aggregation of data across related studies and the use of modern analytical procedures that provide powerful methods of dealing with missing data.

A second methodological contribution is the demonstration that relations from established cognitive ability constructs to variables can help determine what variables represent. That is, one way to investigate the meaning of a variable is to determine the cognitive abilities to which it is and is not related. If people who are high in ability X perform better on variable A than people who are low in ability X, then it can be inferred that variable A likely involves some of the same processes that contribute to ability X. In contrast, if people who are high in ability Y do not differ from people who are low in that ability in their performance on variable A, then it can be inferred that the processes involved in ability Y probably do not contribute to variable A.

The target neuropsychological variables examined in this study varied in their patterns of relations with cognitive abilities, and thus they can be inferred to differ in terms of what they represent. However, an unexpected finding was that the pattern of relations between the variables and cognitive abilities was not always consistent across age groups, or with the abilities that the variables are frequently assumed to reflect. To illustrate, the WCST variable that is typically postulated to assess aspects of executive functioning was strongly related to fluid ability in every sample, but it was also related to crystallized ability in the children sample and to working memory in the adult sample. The FAS variable was related to crystallized ability in the children sample but also to verbal memory and working memory in the adult sample. The

Stroop variable was positively related to speed in the student and adult samples but not in the child sample where the trend was in the opposite direction. Finally, visual span forward was related to working memory in the student and adult samples, but not in the children sample.

Despite assumptions that certain variables represent the same construct, the results of these analyses imply that the target variables have different patterns of relations with cognitive abilities. Furthermore, the results suggest that what is ostensibly the same variable may actually reflect somewhat different aspects of functioning at different ages. (Note that this was not the case for the cognitive variables used as indicators of the reference cognitive abilities because the analyses revealed a high degree of measurement invariance across groups for those variables.) Because the implications of these findings are potentially quite important, it is desirable that the analyses be replicated and extended with other samples of participants and different combinations of variables.

One of the major substantive findings of the analyses reported here is the discovery of a qualitatively similar organizational structure of cognitive variables at different ages. These results imply that the reference variables seem to reflect the same cognitive abilities to nearly the same degree at different portions of the lifespan. At least with respect to these aspects of cognition, age differences across the lifespan appear to be more quantitative than qualitative.

A second important substantive finding was the discovery that in both children and adults the number of statistically distinct age-related influences on the variables is relatively small. Some of the age-related effects in measures of cognitive functioning both across the period of childhood and across the period of adulthood therefore appear to be fairly general, and are not restricted to processes involved in a limited set of very similar tasks. A role still exists for age-related effects that are specific to particular tasks, but the results of the analyses reported here suggest that task-specific effects are unlikely to be the exclusive, or perhaps even the dominant, age-related influence across a wide variety of cognitive variables.

Another important result of the analyses reported above is the discovery that most of the target neuropsychological variables have relatively small unique age-related influences in both the child and adult samples. Because the results suggest that there is considerable overlap in the nature of the age-related effects operating on cognitive abilities and on a number of frequently used neuropsychological variables, the implication is that many of same explanatory mechanisms may be operating in the two sets of variables.

Finally, the results of the analyses provided very little evidence for the construct validity of an executive functioning construct in any of the samples. The variables hypothesized to represent executive functioning did have significant relations to one another, and to a construct representing the variance they had in common. However, most cognitive variables are positively correlated with one another, and thus it is also important to demonstrate that the variance common to these variables was distinct from the variance hypothesized to represent other theoretical constructs. This criterion of discriminant validity was not satisfied with the variables in the current samples because the variance common to measures hypothesized to represent executive functioning had very strong relations with the variance postulated to represent other theoretical constructs. Furthermore, when the variation in the other ability constructs was statistically controlled, the hypothesized executive functioning variables no longer had significant variance in common. In each of these respects the current results are very similar to those reported by Salthouse, et al. (2003). It remains to be determined whether executive functioning is more useful in theoretical explanations than alternative constructs such as fluid intelligence, but these recent results suggest that the constructs may be difficult to distinguish empirically.

In conclusion, the results of this study provide answers to the four major questions guiding this project. First, there appears to be a qualitatively similar organizational structure of reference cognitive abilities across the lifespan. Second, relatively few statistically independent age-related influences seem to be operating on that structure, although one of the influences is on what all of the abilities have in common. Third, many variables assumed to assess distinct theoretical constructs such as executive functioning are closely related to established cognitive abilities of fluid ability and speed, and few have unique age-related influences. And fourth, in all three age groups there were very strong relations between executive functioning and fluid intelligence, which suggests that these labels may refer to the same dimension of individual differences.

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Table 1

Source and description of variables used in the analyses

Variable/Source	Description
WASI Matrix Reasoning (Psychological Corporation, 1999)	Accuracy in selecting the best completion of a missing cell in a matrix of geometric patterns
WASI Block Design (Psychological Corporation, 1999)	Time and accuracy of assembling blocks to match specified designs
WASI Vocabulary (Psychological Corporation, 1999)	Accuracy and completeness of defining specified words
WASI Similarities (Psychological Corporation, 1999)	Accuracy and completeness in stating how two terms are similar to one another
RAVLT Trial 1, 3, and 5 (Rey, 1964)	Number of words recalled on successive presentations of the same 15-word list.
Memory Cards Trial 1, 3, and 5 (Keller & Davis, 1998)	Percentage of correct choices in identifying matching pairs from a set of 24 cards located in the same positions on five successive trials.
Choice RT (Teng, 1990)	Time to press a left or right button in response to an arrow facing to the left or right.
Conditional RT (Teng, 1990)	Time to press a left or right button in response to an arrow facing to the left or right with a + or – sign indicating a compatible or incompatible response
Stroop Word Naming Time (MacLeod, 1991)	Time to read words of colors printed in black ink.
Stroop Color Naming Time (MacLeod, 1991)	Time to name colored dots.
Verbal 2-back, 3-back (Keller & Davis, 1998)	Accuracy of classifying whether letters matched the letters that occurred 2 or 3 items earlier in the sequence.
Spatial 2-back, 3-back (Keller & Davis, 1998)	Accuracy of classifying whether the positions of four red circles matched the positions of the circles 2 or 3 items earlier in the sequence.
WCST # Categories (Keller & Davis, 1998)	Number of categories with 10 consecutive correct responses in a computer-administered version of the Wisconsin Card Sorting Test.
FAS	Total number of words generated in successive 60-sec intervals beginning with the letters F, A, and S
SOPT Errors (Petrides & Milner, 1982)	Number of errors in selecting different items on successive displays of randomly arranged objects
Stroop D (Keller & Davis, 1998)	Time to name colors with a conflicting color word
Temporal Order (Keller & Davis, 1998)	Rank order correlation between original and reproduced sequence of 10 words

Table 1 continues

Table 1 continued

Variable/Source	Description
Tower of Hanoi - # moves with 4 disks	Total number of moves to solve five identical trials with 4 disks.
Tower of London - # excess moves (Keller & Davis, 1998)	Number of moves in excess of the optimum when changing one configuration of colored beads on three towers into another.
Visual Span (Keller & Davis, 1998)	Number of successive blocks accurately reproduced in either forward or backward order

Table 2

	Children				Students				Adults			
	N	Mean (SD)	Age r	Age^2 r	N	Mean (SD)	Age r	Age^2 r	N	Mean (SD)	Age r	Age^2 r
Demographic Variables												
Age	623	10.6 (3.6)	NA	NA	1065	19.6 (1.3)	NA	NA	1743	49.5 (19.8)	NA	NA
Years of Education	618	5.3 (3.6)	.98*	.06*	1000	13.8 (1.1)	.66*	-.05	1634	14.9 (1.9)	-.09*	-.08*
% Females	623	54	-.03	.04	1063	72	-.10*	.03	1706	70	-.02	-.07*
Reference Variables												
WASI Matrix Reasoning	190	24.0 (7.2)	.71*	-.29*	136	29.6 (3.0)	.09	-.05	282	25.5 (6.0)	-.54*	-.17*
WASI Block Design	130	32.3 (18.6)	.76*	-.13*	78	50.5 (12.0)	.02	.02	205	42.3 (15.0)	-.56*	-.13
WASI Vocabulary	174	44.2 (14.2)	.81*	-.20*	115	61.8 (6.8)	.22	.05	271	68.0 (8.9)	-.03	-.30*
WASI Similarities	133	30.9 (9.6)	.82*	-.25*	81	40.2 (4.0)	.15	-.15	209	40.4 (5.5)	-.34*	-.18*
RAVLT Trial 1	268	6.1 (2.1)	.57*	-.21*	459	8.1 (2.1)	.03	.02	1122	7.4 (2.3)	-.49*	-.12*
RAVLT Trial 3	269	9.6 (2.7)	.52*	-.22*	459	12.1 (2.1)	.02	-.05	1122	11.1 (2.5)	-.52*	-.12*
RAVLT Trial 5	269	11.0 (3.0)	.50*	-.27*	459	13.3 (1.8)	.04	-.06	1122	12.5 (2.3)	-.47*	-.16*
Memory Cards Trial 1	311	61.4 (13.4)	.40*	-.04	349	71.4 (13.5)	.00	.03	576	61.3 (17.0)	-.47*	-.09
Memory Cards Trial 3	311	82.2 (11.9)	.33*	-.16*	349	84.5 (12.1)	-.01	.02	576	70.7 (16.7)	-.51*	-.13*
Memory Cards Trial 5	311	90.0 (9.9)	.43*	-.11	348	93.7 (8.2)	-.08	-.02	576	80.5 (16.8)	-.57*	-.13*
Choice RT	243	598 (206)	-.66*	.16*	341	436 (119)	.01	-.03	389	489 (123)	.42*	.07
Conditional RT	243	1110 (501)	-.47*	.11	340	873 (258)	.03	-.07	389	1170 (542)	.51*	.09
Stroop Word Time	219	2.04 (1.38)	-.43*	.34*	434	1.57 (0.48)	.07	.02	897	1.71 (0.64)	.10*	.07
Stroop Color TIme	219	2.25 (1.07)	-.42*	.23*	434	1.75 (0.61)	.07	.04	896	2.04 (0.94)	.25*	.11*
Verbal 2 Back	96	80.8 (13.3)	.52*	-.12	144	93.1 (7.4)	.01	.01	251	88.0 (11.3)	-.35*	-.06
Verbal 3 Back	97	71.6 (13.2)	.53*	-.03	144	83.4 (8.7)	.00	.00	251	78.5 (9.5)	-.33*	-.08
Spatial 2 Back	73	80.9 (13.1)	.56*	-.12	103	92.1 (11.7)	.00	.14	199	88.4 (10.0)	-.34*	-.13
Spatial 3 Back	73	68.6 (13.5)	.53*	-.08	103	81.3 (11.5)	-.00	.18	199	79.0 (9.4)	-.35*	-.06
Target Variables												
WCST # Cat.	273	4.5 (1.8)	.42*	-.14	429	5.6 (1.1)	.07	.02	857	4.9 (1.8)	-.38*	-.09*
FAS	221	27.4 (10.6)	.60*	-.12	457	38.5 (9.7)	-.01	-.06	1020	40.6 (11.8)	-.16*	-.20*
SOPT Errors	166	2.1 (1.3)	-.38*	.16	219	1.4 (1.2)	.02	.01	272	1.9 (1.3)	.23*	.20*
Stroop D	224	5.8 (4.2)	-.51*	.20*	461	3.3 (1.5)	.02	.04	1023	7.4 (7.5)	.48*	.15*
Tower of Hanoi	265	160.1 (55.6)	-.31*	.08	357	126.9 (41.1)	.01	.00	465	135.3 (44.7)	.26*	.08
Tower of London	527	26.7 (25.1)	-.55*	.23*	629	9.5 (10.1)	-.03	-.02	771	11.0 (12.8)	.25*	.10*
Temporal Order	157	.72 (.26)	.51*	-.15	287	.84 (.17)	-.05	.03	685	.70 (.24)	-.44*	-.12*
VSpan Forward	277	6.9 (2.9)	.66*	-.05	379	9.9 (2.3)	.04	-.04	463	7.9 (2.6)	-.51*	-.02
VSpan Backward	274	6.1 (2.6)	.55*	-.15*	380	8.4 (2.0)	.01	-.02	462	7.2 (2.0)	-.45*	-.11*

*p<.01

Table 3
Standardized factor loadings of reference variables in three samples

Variable		Children Orig.	Children Partial Age	Students	Adults Orig.	Adults Partial Age
Fluid (gF)						
WASI Matrix Reasoning		.87+	.51+	.63+	.83+	.64+
WASI Block Design		.89*	.50*	.68*	.77*	.50*
Crystallized (gC)						
WASI Vocabulary		.94+	.48+	.75+	.68+	.87+
WASI Similarities		.94*	.51*	.55*	.88*	.69*
Verbal Memory (VMem)						
RAVLT Trial 1		.72*	.47*	.56*	.73*	.55*
RAVLT Trial 3		.91*	.76*	.89*	.93*	.79*
RAVLT Trial 5		.88+	.72+	.76+	.82+	.66+
Spatial Memory (SMem)						
Memory Cards Trial 1		.55*	.38*	.48*	.67*	.48*
Memory Cards Trial 3		.65*	.59*	.82*	.85*	.69*
Memory Cards Trial 5		.73+	.58+	.57+	.86+	.64+
Speed						
Choice RT		.88+	.55+	.52+	.75+	.53+
Conditional RT		.72*	.58*	.43*	.52*	.23*
Stroop Word Naming		.65*	.46*	.56*	.50*	.64*
Stroop Color Naming		.62*	.40*	.55*	.60*	.50*
Working Memory (WMem)						
Verbal 2 Back		.81*	.56*	.50*	.71*	.60*
Verbal 3 Back		.81*	.54*	.62*	.72*	.63*
Spatial 2 Back		.85*	.57*	.75*	.70*	.60*
Spatial 3 Back		.90+	.69+	.93+	.73+	.63+
Factor Correlations						
gF	gC	.94*	.82*	.55*	.75*	.78*
	VMem.	.84*	.72*	.32	.65*	.49*
	SMem.	.57*	.31	.63*	.65*	.40*
	Speed	-.72*	-.36*	-.27	-.67*	-.36*
	WMem	.81*	.55*	.62*	.83*	.75*
gC	VMem.	.75*	.52*	.05	.55*	.46*
	SMem.	.42*	.00	.42*	.38*	.34*
	Speed	-.71*	-.33	.16	-.47*	-.57*
	WMem	.75*	.36	.21	.50*	.40*
VMem.	SMem.	.50*	.25	.16	.59*	.37*
	Speed	-.66*	-.42*	-.17	-.40*	-.25*
	WMem	.76*	.60*	.29*	.49*	.32*
SMem.	Speed	-.60*	-.34	.01	-.36*	-.16
	WMem	.57*	.29	.34*	.57*	.45*
Speed	WMem	-.63*	-.16	-.24	-.62*	-.31*
Fit Statistics						
	X^2 / df	186/120	180/120	216/120	310/120	272/120
	CFI	.97	.97	.89	.95	.97
	RMSEA	.03	.03	.03	.03	.03

*p<.01, + indicates that the unstandardized coefficient was fixed to 1.0 to specify the metric for the factor.

Table 4
Relations of a second-order factor to the first-order factors

	Children		Students	Adults	
	Orig.	Partial Age		Orig.	Partial Age
gF	.99+	1.00+	1.08+	.99+	.98+
gC	.93*	.78*	.54*	.69*	.80*
VMem	.84*	.75*	.36*	.73*	.58*
SMem	.58*	.29	.52*	.74*	.52*
Speed	-.75*	-.42*	-.23	-.59*	-.44*
WMem	.83*	.62*	.61*	.80*	.70*
Fit Statistics					
X^2 / df	202/129	198/129	222/129	338/129	302/129
CFI	.96	.97	.90	.95	.96
RMSEA	.03	.03	.03	.03	.03

*p<.01, + indicates that the unstandardized coefficient was fixed to 1.0 to specify the scale for the factor

Table 5
Standardized age effects

	Children	Students	Adults
Correlated Factors			
gF	.82*	.05	-.68*
gC	.85*	.23	-.16
VMem	.60*	.04	-.58*
SMem	.59*	-.02	-.65*
Speed	-.73*	.08	.50*
WMem	.71*	.10	-.48*
Hierarchical			
Common	.86*	.05	-.75*
Plus One Factor			
gF	-.31	-.06	.11
gC	.24*	.27	.76*
VMem	-.54*	.03	-.04
SMem	.21	-.06	-.24*
Speed	-.25	.11	.13
WMem	-.01	.07	.29*

*p<.01

Table 6
Relation of individual variables to cognitive abilities

Variable	Children	Students	Adults
WCST (# Categories)			
gF	.94*	.32	.46*
VMem	-.36	-.01	.07
Speed	-.12	.10	.01
Unique Age	-.21	.04	-.03
gC	.55*	.00	.15
Smem	.14	.03	.06
WMem	.11	.23	.29*
Unique Age	-.18	.05	-.16*
FAS			
gF	.40	.06	.29
VMem	.13	.15	.19*
Speed	-.15	-.19	-.19
Unique Age	.11	.01	.26*
gC	.67*	.14	.33*
Smem	.18	-.03	-.08
WMem	.18	.30*	.36*
Unique Age	-.15	-.05	.04
SOPT Errors			
gF	-.76	-.19	-.44*
VMem	.21	-.18	-.10
Speed	.11	-.13	.12
Unique Age	.19	.02	-.20
gC	-.56*	-.43	-.17
Smem	-.02	-.09	-.04
WMem	-.19	-.07	-.37*
Unique Age	.23	.17	-.04
Stroop D (Name colors with conflicting words)			
gF	-.58	-.09	-.18
VMem	.12	-.03	-.15
Speed	-.18	.25*	.17*
Unique Age	-.28	-.02	.18*
gC	-.44	.04	-.42*
Smem	.04	-.10	-.17
WMem	.18	-.11	-.03
Unique Age	-.32	.03	.23*
Tower of Hanoi			
gF	-.50	-.44	-.51*
VMem	.09	-.03	-.03
Speed	.10	.07	-.01
Unique Age	.10	.04	-.12
gC	-.31	.03	.02
Smem	-.51*	-.34*	-.25
WMem	-.01	-.15	-.18
Unique Age	.22	.04	.00

Table 6 continues

Table 6 continued

Variable	Children	Students	Adults
Tower of London			
gF	-.33	-.20	-.29
VMem	-.20	-.10	-.07
Speed	-.08	.18	.09
Unique Age	-.22	-.03	-.03
gC	-.46*	.05	-.20*
Smem	-.28*	-.06	-.11
WMem	.00	-.25	-.15
Unique Age	.01	-.02	.06
Temporal Order			
gF	-.10	.07	.15
VMem	.42	.21	.33*
Speed	.06	.10	.04
Unique Age	.40	-.06	-.16
gC	.20	.02	-.00
Smem	-.03	.13	.25*
WMem	.29	.05	.15
Unique Age	.18	-.06	-.20*
Visual Span Forward			
gF	.80*	.35	.52*
VMem	-.26	.07	-.15
Speed	.09	.00	-.07
Unique Age	.24	.02	-.19
gC	.21	.01	.02
Smem	.25	.15	.07
WMem	.14	.48*	.31*
Unique Age	.26	.01	-.34*
Visual Span Backward			
gF	.99*	.33	.69*
VMem	-.31	.19	-.06
Speed	.02	-.08	.02
Unique Age	-.05	-.02	-.02
gC	.37	-.15	-.07
Smem	.05	.12	.08
WMem	.22	.33*	.53*
Unique Age	.07	.00	-.15

*p<.01

Table 7
Confirmatory factor analysis to investigate the construct validity of an executive functioning construct

	Children		Students	Adults	
	Orig.	Partial Age		Orig.	Partial Age
Executive Functioning Loadings					
WCST	.52+	.33+	.17+	.51+	.33+
FAS	.73*	.36*	.30	.42*	.45*
Stroop D	-.57*	-.19	-.29	-.62*	-.40*
SOPT	-.50*	-.33*	-.33	-.43*	-.37*
Tower London	-.63*	-.33*	-.34	-.46*	-.36*
Tower Hanoi	-.45*	-.33*	-.52	-.39*	-.30*
Correlations with other constructs					
gF	.98*	.95*	.89	.87*	.82*
gC	.94*	.80*	.36	.79*	.84*
VMem	.77*	.60*	.47	.73*	.61*
SMem	.70*	.54*	.56	.68*	.51*
Speed	-.76*	-.42*	-.62	-.65*	-.53*
WM	.78*	.52*	.60	.78*	.72*
Fit Statistics					
X^2 / df	368/231	350/231	378/231	501/231	474/231
CFI	.94	.96	.86	.94	.96
RMSEA	.03	.03	.02	.03	.03

*p<.01, + indicates that the unstandardized coefficient was fixed to 1.0 to specify the scale for the factor.

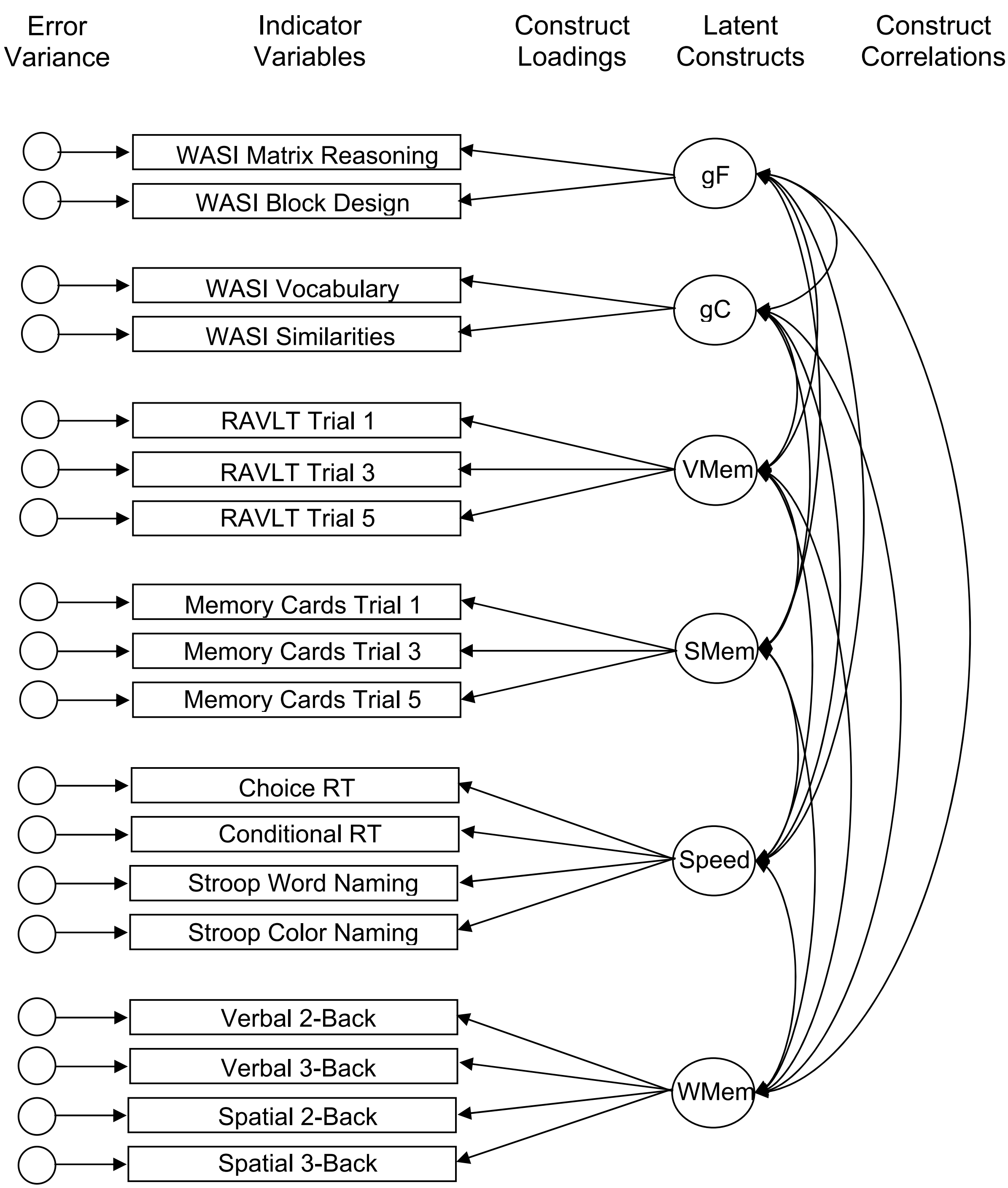
Figure Captions

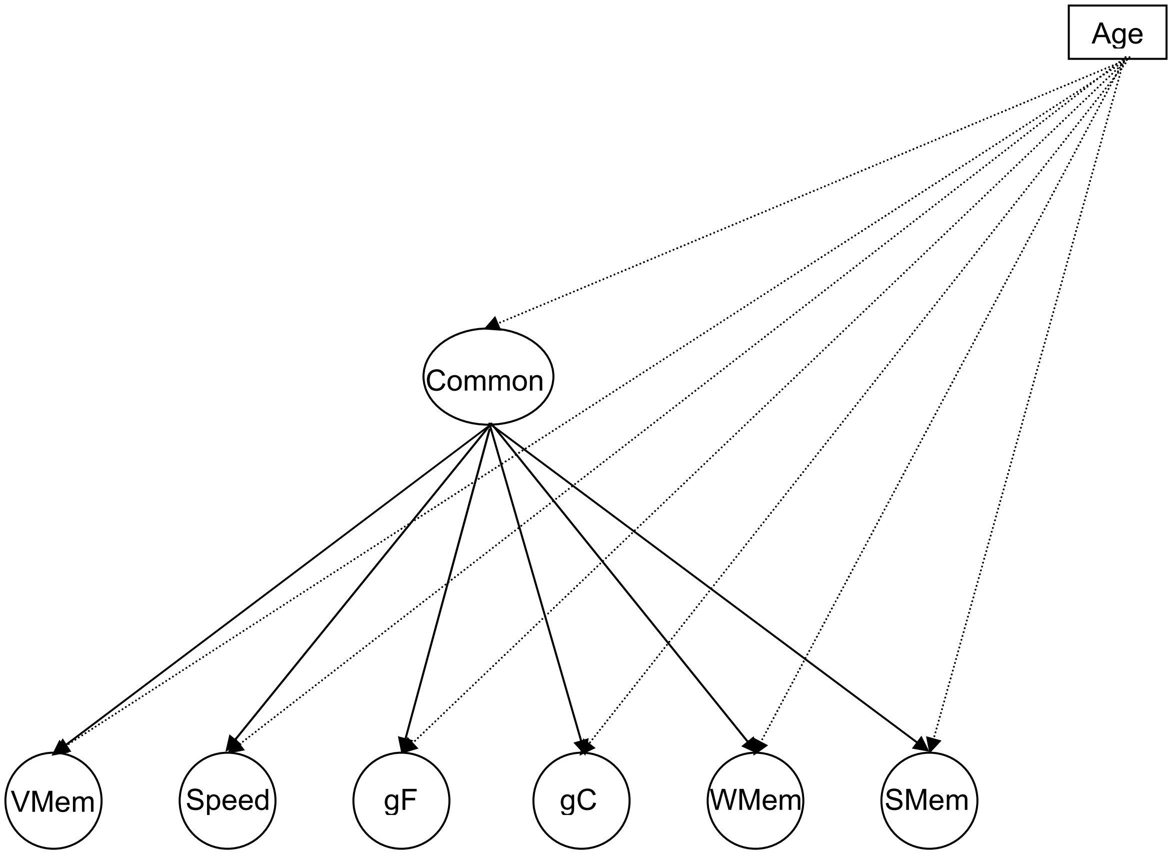
Figure 1 – Illustration of the hypothesized structural organization of 18 cognitive variables into six correlated cognitive factors.

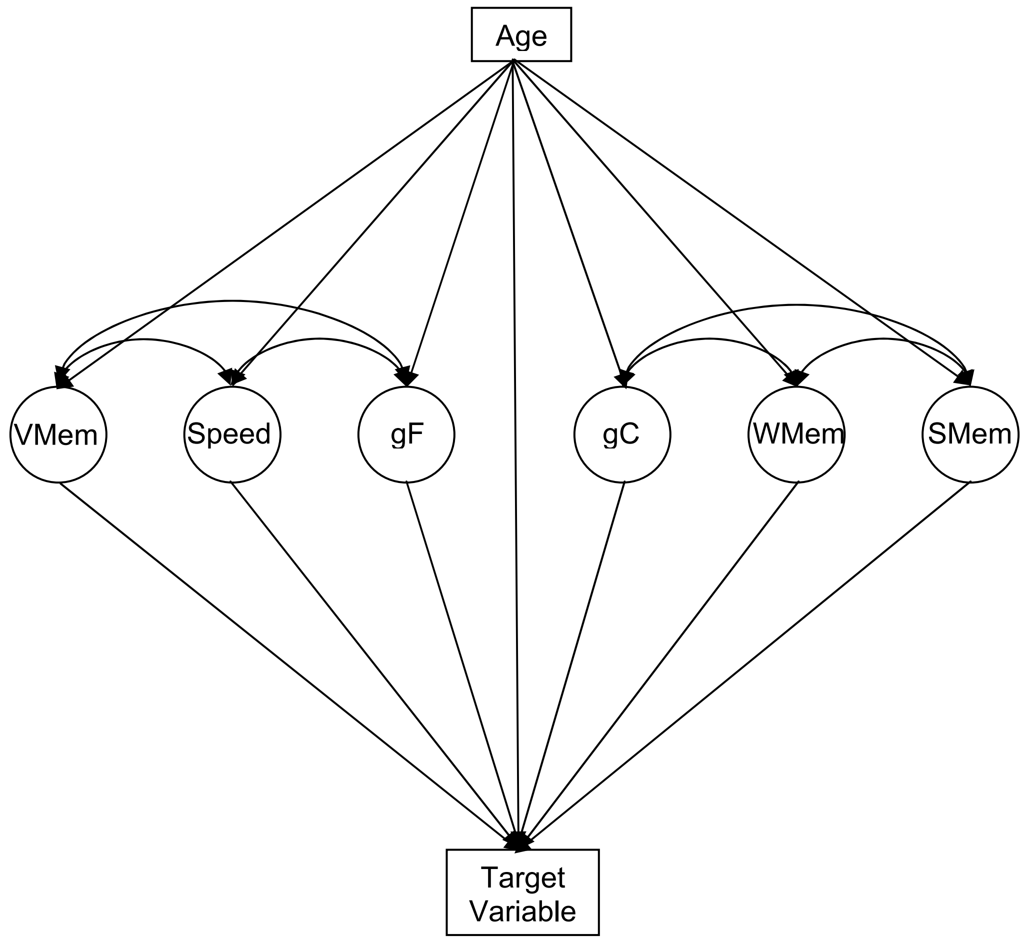
Figure 2 – Model representing possible influences associated with age on a second-order factor representing what different first-order factors have in common, and on individual first-order factors.

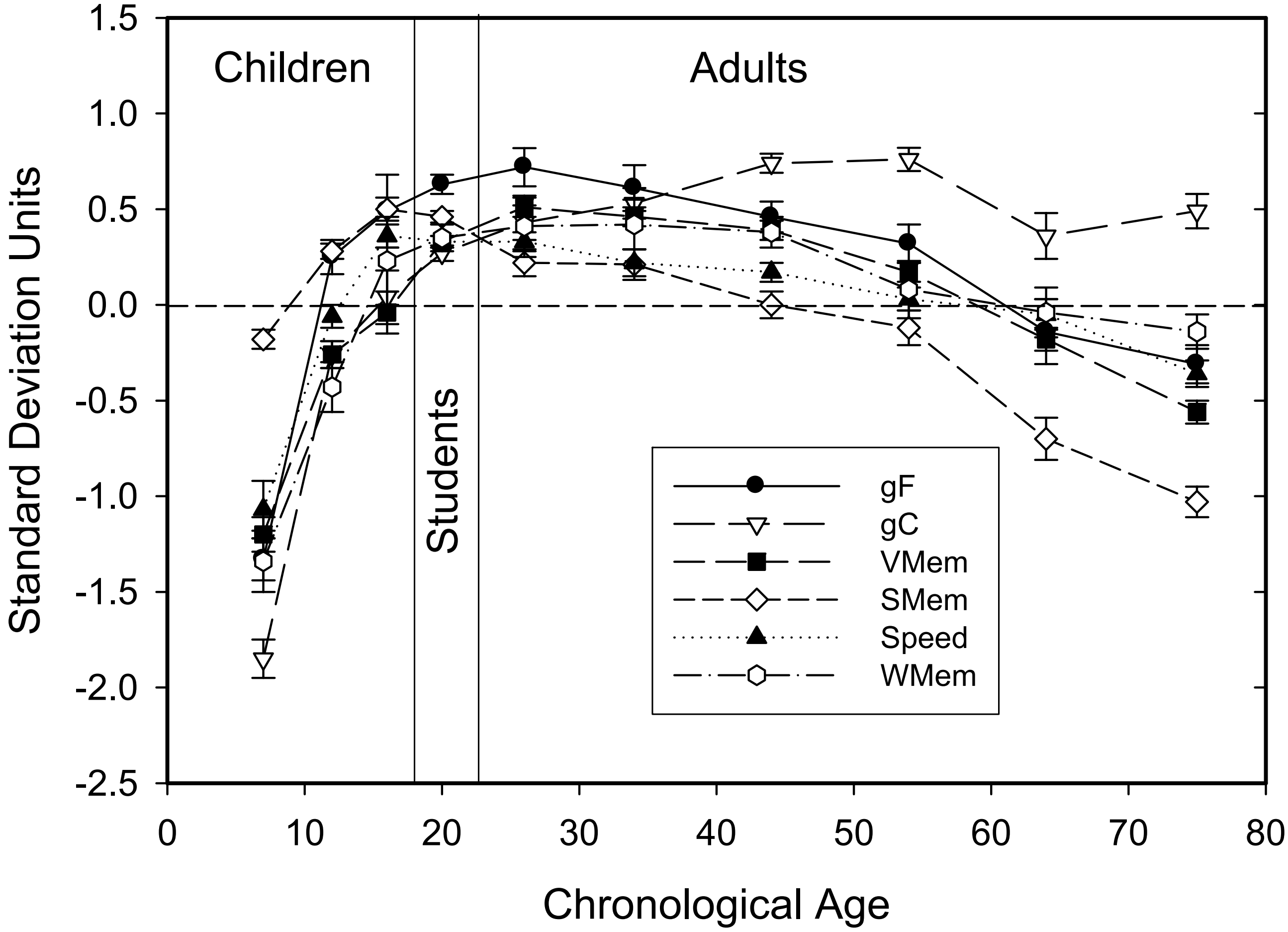
Figure 3 – Illustration of a model that allows contextual analyses to determine what a target variable represents and the unique age-related influences on the variable.

Figure 4 – Means and standard errors of composite scores for the six cognitive abilities as a function of age in the entire sample.


Error Variance
Indicator Variables
Construct Loadings
Latent Constructs
Construct Correlations
WASI Matrix Reasoning
WASI Block Design
WASI Vocabulary
WASI Similarities
RAVLT Trial 1
RAVLT Trial 3
RAVLT Trial 5
Memory Cards Trial 1
Memory Cards Trial 3
Memory Cards Trial 5
Choice RT
Conditional RT
Stroop Word Naming
Stroop Color Naming
Verbal 2-Back
Verbal 3-Back
Spatial 2-Back
Spatial 3-Back
gF
gC
VMem
SMem
Speed
WMem


Age
Common
VMem
Speed
gF
gC
WMem
SMem


Age
VMem
Speed
gF
gC
WMem
SMem
Target
Variable



1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
Standard Deviation Units
Children
Students
Adults
gF
gC
VMem
SMem
Speed
WMem
0
10
20
30
40
50
60
70
80
Chronological Age