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Speed and Intelligence in Old Age

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Past research suggests that age differences in measures of cognitive speed contribute to differences in intellectual functioning between young and old adults. To investigate whether speed also predicts age-related differences in intellectual performance beyond age 70 years, tests indicating 5 intellectual abilities—speed, reasoning, memory, knowledge, and fluency—were administered to a close-to-representative, age-stratified sample of old and very old adults. Age trends of all 5 abilities were well described by a negative linear function. The speed-mediated effect of age fully explained the relationship between age and both the common and the specific variance of the other 4 abilities. Results offer strong support for the speed hypothesis of old age cognitive decline but need to be qualified by further research on the reasons underlying age differences in measures of speed.

Following recent work on the influence of intellectual speed on age differences in intelligence during middle and late adulthood (Hertzog, 1989; Salthouse, 1991; Schaie, 1989), the major goal of the present study was to examine whether speed continues to be a main determinant of age-related variability in intelligence after the age of 70 years. On the basis of the speed hypothesis of cognitive aging, we expected that negative age differences in intelligence among old and very old adults would be mediated, to a large extent, by age differences in speed. A related aim of the study was to examine whether positive age gradients in crystallized cognitive abilities such as knowledge continue to exist in old and very old age after controlling for age-related differences in speed.

Cognitive aging researchers generally agree that performance on many information-processing tasks assessing cognitive or perceptual processes is slowed in old age (Hertzog, 1991; Salthouse, 1985). Proponents of the general slowing hypothesis of cognitive aging argue that this phenomenon is caused by a general decrease in processing rate with age. The reduction in rate is believed to affect most perceptual and cognitive processes and is regarded as the prime determinant of negative age changes in cognitive functioning during adulthood (Birren, 1964; Salthouse, 1985; Welford, 1984). Recent empirical evidence supporting the assumption of general slowing has come from meta-analyses of latency data examining the relation between mean latencies for groups of old adults and the mean latencies for groups of young adults (Brinley, 1965). Generally, it was found that simple linear or curvilinear functions explained a very high proportion of variance across a variety of different tasks (Cerella, 1985, 1990; Myerson, Hale, Wagstaff, Poon, & Smith, 1990; but see Mayr & Kliegl, in press).

Proponents of general slowing posit that cognitive aging reflects the depletion of a task-unspecific general resource, but they do not assume that this general resource affects all domains of cognition to the same extent (cf. Salthouse, 1985, 1988). Because of the compensatory effects of life-long knowledge accumulation, for instance, some domains of cognitive functioning may be less affected by slowing than others. Recent evidence showing that slowing is less pronounced in tasks requiring lexical decisions as compared with analogous tasks requiring nonlexical decisions is consistent with this assumption (Cerella & Fozard, 1984; Lima, Hale, & Myerson, 1991; Myerson, Ferraro, Hale, & Lima, 1992).

Psychometric research on life-span development has also stressed the fact that different domains of intellectual functioning may follow different age-graded trajectories (Baltes, 1987; Baltes, Cornelius, & Nesselroade, 1979). Specifically, the life-span theory of fluid versus crystallized intelligence (Horn, 1982; Horn, Donaldson, & Engstrom, 1981) has predicted that negative age trends are less pronounced for measures assessing interindividual differences in knowledge than for measures related to reasoning or speed. The empirical findings are generally consistent with this prediction. During middle and late adulthood, measures of intellectual speed tend to show the largest negative age differences, followed by fluid abilities such as

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spatial visualization and reasoning, which in turn are followed by more knowledge-dependent measures (cf. Salthouse, 1982). For example, the Digit Symbol Substitution subtest of the Wechsler Adult Intelligence Scale (WAIS; Wechsler, 1981), a typical measure of cognitive-perceptual speed, shows very pronounced age decrements, whereas the Vocabulary subtest of the WAIS, a typical measure of knowledge, remains stable up to late adulthood (cf. Salthouse, 1982).

The general picture of findings from the psychometric literature, pronounced negative age differences for speed and reasoning and less of a difference, or stability, for measures of verbal knowledge, is consistent with the idea that negative age trends in speed of processing may be responsible for negative age trends in other intellectual abilities. If slowing of information processing is at the core of negative age differences in cognition and if psychometric measures of speed measure interindividual differences in the rate of information processing, then negative age differences in cognitive abilities other than speed should be mediated by age-related differences in speed. For instance, negative age gradients in knowledge or reasoning should cease to exist after controlling for individual differences in speed.

Recent evidence reported by Schaie (1989), Hertzog (1989), and Salthouse (1991, 1992a, 1992b; Salthouse & Babcock, 1991) provided strong support for the *speed hypothesis* of cognitive aging. Schaie (1989, 1990) reported longitudinal and cross-sectional data from the Seattle Longitudinal Study on age differences in speed as indexed by the Identical Pictures and Finding A's tests from the Educational Testing Service (ETS) Kit of Factor-Referenced Cognitive Tests (Ekstrom, French, Harman, & Dermen, 1976) for 1,838 individuals aged 22 to 91 years. Five Primary Mental Abilities (PMA) measures—verbal comprehension, spatial orientation, inductive reasoning, number, and word fluency—served as ability markers. Age-ability correlations (i.e., linear age trends) were reduced after controlling for speed (Schaie, 1990, Table 8). In agreement with the theory of fluid versus crystallized intelligence, the speed-adjusted scores of the more crystallized measures (verbal meaning and number) increased into late life, whereas the speed-adjusted scores of the more fluid measures (inductive reasoning and spatial orientation) continued to show significant residual decrements.

Cross-sectional data reported by Hertzog (1989) also pointed to the importance of speed. Hertzog investigated the influence of speed measures on other intellectual abilities in a sample of 622 adults with an age range of 43 to 89 years. Significant negative linear age trends were observed for all abilities studied. After controlling for speed, linear and quadratic trends of age explained only between 1% and 3% of the total variance in the other ability measures. Similar to Schaie's (1989) results, speed-adjusted functions for crystallized abilities (numerical facility and verbal comprehension) evinced positive age gradients leveling off around age 70, whereas speed-adjusted gradients for fluid abilities leveled off at an earlier age and exhibited a more pronounced negative linear trend. Hertzog (1989) also reported the results of a commonality analysis to determine the proportions of variance uniquely related to age, uniquely related to speed, and shared by age and speed for each of the six ability measures. For most measures, the proportion of age-related variance shared with speed was substantial. For instance, 86% of the age-related variance in spatial relations and 89% of the age-related variance in induction was shared with speed.

Finally, Salthouse and his colleagues (Salthouse, 1991, 1992a, 1992b; Salthouse & Babcock, 1991) conducted a series of studies on the extent to which measures of perceptual speed and working memory account for age differences in complex cognitive tasks. For example, Salthouse (1991) reported the results of three independent large-scale studies covering an age range of 20 to 84 years. After controlling for speed, the age-related variance in cognitive tasks and working memory measures was reduced from a range of 17% to 31% to a range of 1% to 5%. Similar results were obtained by Salthouse and Babcock (1991), who found that simple comparison speed accounted for most of the age-related variability in complex working memory measures. In line with Schaie's (1989) and Hertzog's (1989) results, these findings suggest that measures of speed may capture central aspects of age-related decrements in cognitive functioning during adulthood.

This Study

The present study extended the investigation of speed-intelligence relationships into very old age using a close-to-representative sample drawn from the elderly population of Berlin, Federal Republic of Germany, with an equal number of individuals in six age brackets (i.e., 70–74, 75–79, 80–84, 85–89, 90–94, and 95+ years). The main goal of the study was to examine whether speed continues to explain a large portion of negative age differences in intellectual functioning after age 70.

A related objective of the study was to further examine the existence of positive age trends in crystallized abilities after adjusting for negative age differences in speed. On the basis of Hertzog's (1989) and Schaie's (1989) finding that speed-adjusted positive age gradients level off around age 70 years, it may appear unduly optimistic to expect positive speed-adjusted age gradients in a sample as old as the present one. However, as noted by Hertzog (1989, 1991), the PMA and ETS tests used by Hertzog (1989) and Schaie (1989) as indicators of crystallized abilities probably are biased toward speeded responding. Positive speed-adjusted age gradients for crystallized abilities may continue to exist after age 70 if testing conditions are less timed to avoid artifactual speed-ability covariation.

In addition to measures of intellectual speed, the abilities represented in the present study were knowledge, reasoning, memory, and fluency. Reasoning and memory, on the one hand, were chosen to represent the domain of fluid abilities, with reasoning as a typical fluid marker. Knowledge and fluency, on the other hand, were chosen to represent the crystallized domain, with knowledge representing the most widely used marker for the crystallized ability cluster. Interindividual differences in fluency tests were assumed to be knowledge dependent because fluency tests require the retrieval of instances of a semantic (e.g., animals) or phonetic (e.g., words starting with the letter *S*) category from long-term memory (cf. Salthouse, 1993). Past research has shown that adult age differences in fluency tasks tend to be small or absent (Eysenck, 1975; Fitzgerald, 1983). Given that negative age differences are generally less pronounced in crystallized than in fluid abilities, we expected that positive speed-adjusted age gradients would be more likely to occur in verbal knowledge and fluency than in reasoning and memory.

With respect to statistical methodology, we used structural equation modeling to test the adequacy of the speed hypothesis (cf. McArdle & Prescott, 1992). For the issue at hand, the two main advantages of structural modeling are that relations among latent variables are not attenuated through unreliable (i.e., construct-extraneous) variance and that predictions regarding relations among constructs can be tested explicitly. An important consequence of filtering out unreliable variance is that indirect paths (e.g., age → speed → intelligence) have a fair chance to be more prominent than direct paths (e.g., age → intelligence).

Method

Sample

The present data set is part of the Berlin Aging Study (BASE), an ongoing multidisciplinary project on old age and aging (Baltes, Mayer, Helmchen, & Steinhagen-Thiessen, in press). The BASE sample is designed (a) to be representative of the western part of the city of Berlin and (b) to oversample the very old and the male population. Specifically, it is a probability sample of community-dwelling and institutionalized individuals aged 70–100+ years. The sample was drawn from the city registration office (in the Federal Republic of Germany, every citizen is registered). The data reported here belong to the intensive data collection protocol of BASE, which comprises a total of 14 sessions covering four different disciplines (i.e., internal medicine, psychiatry, psychology, and sociology). Twenty-eight percent of the individuals who were asked to participate completed the intensive protocol.

The present sample was stratified by age and sex by randomly selecting, within each cell of the design, 13 individuals from the larger parent sample of individuals who completed the intensive protocol. As an indication of representativeness, the current sample was weighted to reflect the age and sex distribution of the over-70-year-old West Berlin population obtained from the city registration office and was then compared with West Berlin census data (Statistisches Landesamt Berlin, 1989) on the following indexes: marital status, proportion of institutionalized persons, educational level, and income. The following differences were found: Individuals in our sample were less frequently married (men, 59.3%; census, 68.1%; women, 8.3%; census, 14.8%), and men were more frequently widowed (our sample, 29.8%; census, 22.1%). The women in our sample were more educated than expected on the basis of census data (i.e., 66.5% of the women in our sample had elementary school education only, as compared with 75.4% according to census data; completion of elementary school amounted to 8 years of education). Moreover, the women in our sample were more likely to live in homes for the elderly or nursing homes (our sample, 12.6%; census, 6.5%). Finally, individuals with low incomes were less likely to be part of our sample: proportion of individuals with less than 1,000 DM (approximately $625) per month—men, 1.1%; census, 5.2%; women, 7.9%; census, 20.3%.

From the total of 156 individuals, 7 subjects with zero scores (i.e., floors) on 4 or more of the 14 tests of the cognitive assessment were eliminated from the analysis. Table 1 summarizes the characteristics of the reduced sample (i.e., $N = 149$) separately for old (70–84 years) and very old (85–103 years) individuals. In comparison with convenience samples typically used in cognitive aging research, the present sample was older, more heterogeneous, and less educated.

Table 1
Characteristics of the Effective Sample

	Age group					
	70–84 (n = 76)		85–103 (n = 73)		Total (n = 149)	
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age	77.2	4.6	92.3	4.7	85.5	8.9
Years of education	11.6	3.1	10.7	2.7	11.2	3.0
Subjective physical health[a]	2.8	1.1	3.0	1.1	2.9	1.1
Digit Symbol Substitution	30.1	9.4	20.5	11.1	25.4	11.3

[a] This was scored with a Likert-type scale ranging from 1 (*excellent*) to 5 (*very poor*).

Apparatus

A Macintosh SE30 personal computer equipped with a Micro Touch Systems touch-sensitive screen was used for stimulus presentation and data collection.

Measures

A total of 14 tests were administered to measure five different intellectual abilities: speed (Digit Letter Test, Digit Symbol Substitution, Identical Pictures), reasoning (Figural Analogies, Letter Series, Practical Problems), knowledge (Practical Knowledge, Spot-a-Word, Vocabulary), memory (Activity Recall, Memory for Text, Paired Associates), and fluency (Animals, Letter "S"). Table 2 provides a list of the measures together with estimates of internal consistency and intercoder agreement.[1]

With respect to the tests of reasoning and knowledge, items were ordered by difficulty. Testing was terminated when the subject made a certain number of consecutive false responses: three in the case of Figural Analogies, Letter Series, Practical Reasoning, Practical Knowledge, and Spot-a-Word and five in the case of Vocabulary. Item difficulty had been identified in a separate pilot study (Lindenberger, Mayr, & Kliegl, 1990). In that study, we also found that the implementation of this test termination criterion did not lead to a decrease in internal consistency. Except for the Digit Letter Test and Digit Symbol Substitution, instructions were presented in large fonts on the screen (i.e., Times Roman Bold 36). For all tests, additional information was provided verbally by the research assistant. Sample items were used with respect to tests related to speed, reasoning, and knowledge. The entire session was tape-recorded. A description of the tests in alphabetical order is given in the following paragraphs.

Activity Recall. This test was administered as the ninth test of the

[1] In a pilot study (Lindenberger, Mayr, & Kliegl, 1990) with a convenience sample of older adults ($N = 99$, age range = 63–88 years), we administered the tests of our battery together with standard (i.e., paper-and-pencil) tests of reasoning, verbal knowledge, perceptual speed, and fluency. Standard memory tests were not included in that study. Intercorrelations between standard measures and measures of the battery were highest for tests assumed to measure the same underlying construct. This pattern of convergent and divergent validity was also found when the measures of the battery were correlated with factor scores obtained on the basis of the standard measures.

Table 2
Internal Consistencies, Intercoder Reliabilities, and Path Coefficients of Tests

Ability	Test	Index α[a]	r[b]	τ[c]	β[d]
Speed	Digit Letter Test	.93	1.00	.99	.90
	Digit Symbol Substitution		1.00	.99	.88
	Identical Pictures	.91			.90
Reasoning	Figural Analogies	.89			.79
	Letter Series	.87			.76
	Practical Problems	.83			.80
Memory	Activity Recall	.59	.89	.78	.82
	Memory for Text	.59	.96	.88	.63
	Paired Associates	.87	1.00	.94	.72
Knowledge	Practical Knowledge	.79	.94	.81	.89
	Spot-a-Word	.91			.68
	Vocabulary	.80	.96	.86	.82
Fluency	Categories (Animals)		.99	.94	.84
	Word Beginnings (Letter "S")		.99	.93	.74

[a] Cronbach's alpha. Incorrect responses as well as performance on items that were not attempted were coded as zero.
[b] Intercoder reliability (Pearson product–moment correlation). This is not present for tests with computerized response entry.
[c] Intercoder reliability (Stuart's rank correlation coefficient). This is not present for tests with computerized response entry.
[d] Path coefficients of the final measurement model (i.e., Model MM2-3 of Table 3).

battery. Subjects were asked to briefly describe or to recall the name of all tests they had worked on up to that point. After subjects had named or described a task with sufficient accuracy, the research assistant asked them to recall any other task that came to their mind. Order of recall was not relevant. Answers were scored by two independent raters. A task was considered to have been recalled by the subject if there was no doubt to which task the subject was referring. Scores ranged from 0 (i.e., no task recalled) to 8 (i.e., all tasks recalled).

Digit Letter Test. This test closely resembles the well-known Digit Symbol Substitution subtest of the WAIS except that subjects had to name letters instead of writing symbols. The main motive for this change in format was to minimize peripheral (e.g., motor) task demands. The template with the digit-letter mapping was visible for the entire testing period. The test consisted of a total of 21 sheets. Each sheet contained six digits with a question mark underneath. Moving from left to right, subjects had to name the letters that corresponded to the digits. As soon as the last letter of a sheet had been named, the research assistant presented the next sheet. Digits and letters were written in large and bold fonts (Times Roman Bold 48) to minimize problems related to poor vision. Testing lasted for 3 min, with scores being taken after each minute. The score used here is based on the total number of correct responses after 3 min.

Digit Symbol Substitution. The Wechsler (Wechsler, 1955) version of the test was used. The test sheet was enlarged by 100% to reduce perceptual and motor problems. Subjects had to write as many symbols as possible within 90 s. The test was introduced on the computer screen, but actual testing took place using the regular paper-and-pencil format.

Figural Analogies. Items in this test followed the format "A is to B as C is to ?". A typical item is depicted in Figure 1. Problems were presented in the upper part of the screen, and five response alternatives were presented in the lower part. Subjects entered their response by touching one of the five answer alternatives. In part, items were adapted from a German version of the Lorge-Thorndike Intelligence tests for children (Heller, Gaedike, & Weinläder, 1976; cf. Thorndike, Hagen, & Lorge, 1954). Before the test phase, instructions and three practice items were given. If subjects were not able to solve the practice items without help from the research assistant, additional explanations were provided, and the same three practice items were presented again. After that, the test phase was initiated regardless of whether subjects had solved the practice items correctly. The test phase was terminated when subjects made three consecutive false responses, when they reached the maximum time limit (6 min), or after they had answered the last item of the test.

Fluency: Animals. Subjects had to name as many different animals as possible within 90 s. Responses were scored by two independent raters. We distinguished (a) correct responses, (b) morphological variants (e.g., "horses" after "horse"), (c) unnoticed repetitions, (d) noticed repetitions, and (e) wrong category (e.g., "rose"). In this study, all analyses were based on the number of correct responses.

Fluency: Letter "S." Subjects had to name as many different words starting with the letter *s* as possible within 90 s. Responses were scored by two independent raters. We distinguished (a) correct responses, (b) morphological variants (e.g., "summertime" after "summer"), (c) unnoticed repetitions, (d) noticed repetitions, and (e) wrong category. Scoring was based on the total number of correct responses. All words starting with the letter *s* including proper names were counted as correct responses. All analyses reported here were based on the number of correct responses.

Identical Pictures. A computerized version of the test of the same name from the ETS (Ekstrom et al., 1976) was administered. A total of 32 items was presented. For each item, a target figure was presented in the upper half of the screen, and five response alternatives were presented in the lower half. Subjects had to touch the correct figure in the lower half as fast as possible. Before the test phase, instructions and three practice items were given. Testing was terminated automatically after 80 s.

Letter Series. The test consisted of 16 items. Each item contained five letters followed by a question mark (e.g., c e g i k ?). Items were displayed in the upper half of the screen, and five response alternatives were presented in the lower half. Items followed simple rules such as +1, −1, +2, or +2 +1. Subjects entered their response by touching one of the five answer alternatives. The score was based on the total number of correct responses. Before the test phase, instructions and three practice items were given. If subjects were not able to solve the practice items without help from the research assistant, additional explanations were provided, and the same three practice items were presented again. After that, the test phase was initiated regardless of whether subjects had solved the practice items correctly. The test phase was terminated when subjects made three consecutive false responses,

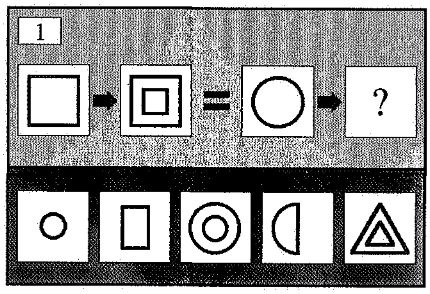

Figure 1. An item from the Figural Analogies test. (Items were presented one by one on a computer screen. Subjects entered their response by touching one of the four response alternatives.)

when they reached the maximum time limit (6 min), or after they had answered the last item of the test.

Memory for Text. A short story about a little boy who went fishing, slipped into the water, and was saved by his dog was presented both visually and auditorily (i.e., the text of the story was shown on the screen and simultaneously read aloud by the research assistant). Story presentation time was recorded on the computer and routinely checked to make sure that research assistants took about 38 s to read the story. The recall phase started immediately after presentation. Recall was cued by asking six questions regarding the content of the story. Questions referred to propositions at a high (e.g., "What was the story about?"), intermediate (e.g., "Why did the boy slip into the water?"), or low (e.g., "What was the name of the boy?") level of text hierarchy. Each response was given a score of 0 (incorrect) or 1 (correct). Responses were scored by two independent raters. The test was adapted from Engel and Satzger (1990).

Paired Associates. A list of eight pairs of concrete nouns was presented twice at a rate of 5 s per pair. Nouns referred to concrete objects and had an imagery rating above 6 on the German equivalent of the Paivio, Yuille, and Madigan imagery norms (Baschek, Bredenkamp, Öhrle, & Wippich, 1977; cf. Paivio, Yuille, & Madigan, 1968). After each presentation, recall was cued by presenting the first noun of each pair, using a different order than during encoding. Responses were scored for correctness by two independent raters. The score ranged from 0 to 16 and referred to the total number of correct responses across the two trials. Compared with separate scores for the two trials, aggregating across trials led to higher internal consistency and to higher correlations with the other memory measures.

Practical Knowledge. The test followed the format of the WAIS Information test. It consisted of 12 questions involving information supposed to be relevant for everyday life (e.g., "What is a funnel?," "What is the phone number of the emergency call?," "How much does it cost to send a letter by mail within Germany?," "What is a personal liability insurance for?"). Responses were scored for correctness by two independent raters on the basis of a scoring manual. Each response to an item received a score of 0 (wrong), 1 (partially correct), or 2 (correct). Testing time was unlimited (i.e., no maximum time was specified).

Practical Problems. The test contained 12 items depicting everyday problems such as the hours of a bus schedule, instructions for medication, a warranty for a technical appliance, a train map, as well as other forms and tables. For each item, problems were presented in the upper part of the screen, and five response alternatives were shown in the lower part. Subjects entered their response by touching one of the five answer alternatives. Some of the items were adapted from the Reading subtest of the ETS Basic Skills Test (Educational Testing Service, 1977). A single practice item was provided. The test phase was terminated when subjects made three consecutive false responses, when they reached the maximum time limit (10 min), or after they had answered the last item of the test.

Spot-a-Word. Twenty items containing one word and four pronounceable nonwords were presented successively on the screen. The task of the subject was to touch the word. Items were selected from a widely used German vocabulary test (Lehrl, 1977). Three practice items were provided, and testing time was unlimited.

Vocabulary. Twenty words were selected from the Vocabulary subtest of the German version of the WAIS (HAWIE; Wechsler, 1982). Words were presented one by one on the screen. Subjects' answers were coded by two independent raters using a refined version of the coding instructions provided by Wechsler (1982). Each response to an item received a score of 0 (wrong), 1 (partially correct), or 2 (correct). No upper limits were imposed on testing time.

Procedure

Testing was computerized and took place in the residence of the participant. Tests were administered in the following order: Digit Letter Substitution, Spot-a-Word, Memory for Text, Figural Analogies, Fluency: Letter "S," Vocabulary, Practical Problems, Digit Symbol Substitution, Activity Recall, Identical Pictures, Paired Associates, Fluency: Animals, Letter Series, and Practical Knowledge. In 77.5% of the cases, testing was completed within a single session lasting about 70 min. For the remaining participants, testing was subdivided into two separate sessions. In this case, the first session always ended with Activity Recall, and the second session contained the remaining five tests in regular sequence.

Results

Missing Data Estimation

Because of technical problems or sensory impairments, 18 individuals had missing data on some of the tests. Missing data were estimated using a regression approach. For instance, if data were missing for one of the three reasoning tests, the other two were used to predict the score on the test that was missing. Analyses reported in the following paragraphs were also done without individuals with missing data (i.e., listwise deletion of missing cases). Results for this reduced sample (n = 131) followed the same pattern as results with the full sample (N = 149).

Overview of Structural Modeling

Structural modeling proceeded in two steps. First, a measurement model was established to represent the five cognitive abilities, and the existence of linear and quadratic age trends was examined. Second, predictions emanating from the speed hypothesis were tested and compared with alternative models. For all analyses, raw data were entered into the Structural Equations Program (EQS; Bentler, 1989).[2] Model fitting was based on the variance–covariance matrix. Table 3 gives an overview of the model-fitting procedure. Throughout this article, we report the Comparative Fit Index (*CFI*) and the Non-Normed Fit Index (*NNFI*) as indexes of incremental fit (Bentler, 1989; cf. Marsh, Balla, & McDonald, 1988). As a rule of thumb, values larger than .90 on these indexes are desirable (cf. Bentler, 1989). In addition, we report chi-square values, degrees of freedom, and corresponding p values for all models that we examined (cf. Raykov, Tomer, & Nesselroade, 1991).

Measurement Model

The raw data were checked to examine whether they were consistent with the assumption of multivariate normality. Kurtosis estimates did not exceed 1 or −1 for any of the 14 measures, and the normalized estimate of Mardia's coefficient of multivariate kurtosis was 0.18. Thus, it appeared that the distributional properties of the data warranted the use of standard maximum likelihood chi-square estimation procedures.

A model with five intercorrelated factors was fit to the data. Each test served as an indicator of one factor: Reasoning was indicated by Figural Analogies, Letter Series, and Practical

[2] Before entering the data into EQS, raw scores on the Digit Letter Test were divided by 10 and Digit Symbol Substitution raw scores were divided by 2 to obtain a numerically more balanced variance–covariance matrix.

Table 3
Summary of Model-Fitting Procedure

Model	Commentary	χ^2	*df*	*NNFI*[a]	*CFI*[b]	*p* value
		Measurement models				
MM1-1	Intercorrelated factor structure	116.75	67	.954	.966	< .001
MM1-2	Allowing for three correlated residuals	100.66	64	.964	.975	.002
	Comparison with Model MM1-1	16.09	3			< .01
MM2-1	Introduction of linear and quadratic age trends	128.01	83	.957	.971	.001
MM2-2	Quadratic age trends set to zero	131.89	88	.961	.971	.002
	Comparison with Model MM2-1	3.88	5			> .1
MM2-3	Quadratic term of age removed from the model	118.29	73	.957	.970	< .001
		Structural models				
SP1	The basic speed model (see Figure 1)	130.66	82	.959	.968	< .001
	Comparison with Model MM2-3	12.37	9			> .1
SP2-1	Adding direct path from age to general ability	128.74	81	.960	.969	< .001
	Comparison with Model SP1	1.92	1			> .1
SP2-2	Adding direct path from age to knowledge	130.24	81	.958	.968	< .001
	Comparison with Model SP1	0.42	1			> .1
SP2-3	Adding direct path from age to fluency	130.35	81	.958	.969	< .001
	Comparison with Model SP1	0.31	1			> .1
SP2-4	Adding direct path from age to reasoning	130.05	81	.958	.968	< .001
	Comparison with Model SP1	0.61	1			> .1
SP2-5	Adding direct path from age to memory	130.10	81	.958	.968	< .001
	Comparison with Model SP1	0.56	1			> .1
AM1	Reasoning in the position of speed	137.09	82	.954	.964	< .001
AM2	Memory in the position of speed	136.37	82	.954	.964	< .001
AM3	Knowledge in the position of speed	139.32	82	.952	.963	< .001
AM4	Fluency in the position of speed	137.76	82	.953	.964	< .001

Note. MM = measurement model; SP = speed model; AM = alternative model.
[a] Non-Normed Fit Index, or Tucker Lewis Index (cf. Bentler, 1989; Marsh, Balla, & McDonald, 1988). [b] Comparative Fit Index (cf. Bentler, 1989).

Problems; knowledge by Vocabulary, Practical Knowledge, and Spot-a-Word; speed by Digit Letter, Digit Symbol Substitution, and Identical Pictures; fluency by Animals and Letter "S"; memory by Activity Recall, Memory for Text, and Paired Associates. No restrictions were imposed on covariances among factors. The residual variances of the indicators were freely estimated, whereas residual covariances among indicators were set to zero, reflecting the assumption that correlated measurement error was negligible. For this model (i.e., Model MM1-1 in Table 3), $\chi^2(67, N = 149) = 116.75$, $p < .001$, *NNFI* = .954, *CFI* = .966.

After inspecting the residual correlation matrix, three covariances among residuals were allowed to be freely estimated: Spot-a-Word and Vocabulary, Paired Associates and Memory for Text, as well as Digit Letter and Digit Symbol Substitution. Note that these residual covariances did not cross factor boundaries. Therefore, they did not compromise the five-factor structure of the model. The introduction of these residual correlations led to a significant increment in fit, $\Delta\chi^2(3, N = 149) = 16.09$, $p < .01$. The modified model (i.e., Model MM1-2 in Table 3) had a satisfactory *NNFI* of .964 (*CFI* = .975) and a *p* value of .002.[3]

Next, we introduced linear and quadratic trends of age (i.e., Model MM2-1 in Table 3). Quadratic age trends were com-

[3] Specifically, residual correlations were as follows: Digit Letter and Digit Symbol Substitution ($r = -.39$), Memory-for-Text and Paired Associates ($r = .18$), Vocabulary and Spot-a-Word ($r = -.28$). For all model comparisons reported in this article, we obtained analogous results when the three residual correlations were set to zero.

puted outside of EQS by regressing age squared on age and saving the residuals (i.e., the quadratic component that is orthogonal to the linear component of age). Linear and quadratic trends of age were allowed to vary freely with each of the five factors. The fit of the model was again satisfactory, $\chi^2(83, N = 149) = 128.01$, $p < .01$, $NNFI = .957$, $CFI = .971$. An inspection of the z values revealed that quadratic age trends did not differ from zero for any of the five abilities. Therefore, in the subsequent model, the five quadratic age trends were set to zero. The fit of the resulting model did not differ significantly from the previous model, $\Delta\chi^2(5, N = 149) = 3.88$, $p > .1$. For this reason, the quadratic age term was removed from the model, resulting in the final measurement model (i.e., Model MM2-3 in Table 3). For this model, $\chi^2(73, N = 149) = 118.29$, $p < .001$, $NNFI = .957$, $CFI = .970$.

The standardized covariances (i.e., latent correlations) among the five abilities and age as estimated in the final measurement model are shown above the diagonal in Table 4. Negative age trends ranged from −.53 for fluency to −.63 for speed. Factor intercorrelations were quite high, ranging from .76 (knowledge-memory) to .88 (fluency-memory). To facilitate comparisons with other studies that did not use structural modeling, raw correlations that are based on the unit-weighted composites of the z-transformed test scores are displayed below the diagonal in Table 4. The standardized path coefficients of the indicators (i.e., confirmatory factor loadings) are shown in Table 2. The magnitude of the coefficients ranged from .63 (Memory-for-Text) to .90 (Digit Letter and Identical Pictures).

Testing the Speed Hypothesis

According to the speed hypothesis, age differences in intelligence are due to age differences in speed. The structural model depicted in Figure 2 corresponds to this hypothesis. It reflects the proposition that age affects speed and that speed affects a general ability factor representing the common variance of the other four abilities. This model (i.e., speed model 1 [SP1] in Table 3) had a satisfactory fit, $\chi^2(82, N = 149) = 130.66$, $p < .01$, $NNFI = .959$, $CFI = .968$, parsimony ratio = .683. Moreover, a nested comparison revealed that the fit of this model did not differ significantly from the fit of the measurement model, $\Delta\chi^2(9, N = 149) = 12.37$, $p > .1$. Thus, the speed model adequately represented as much of the variances and covariances as the minimally constrained measurement model.

Table 4
Intercorrelations Among Abilities and Age

Factor	1	2	3	4	5	6
1. Speed	—	.82	.80	.81	.83	−.63
2. Reasoning	.71	—	.81	.87	.79	−.58
3. Memory	.66	.64	—	.76	.88	−.57
4. Knowledge	.70	.71	.59	—	.83	−.56
5. Fluency	.69	.63	.66	.66	—	−.53
6. Age	−.59	−.52	−.50	−.48	−.45	—

Note. Standardized covariance estimates of the final measurement model (i.e., Model MM2-3 of Table 3) are shown above the diagonal. Correlations that are based on unit-weighted composites of the z-transformed test scores are shown below the diagonal.

One may note that we did not model the speed hypothesis by specifying direct paths from speed to each of the four abilities. This would amount to a model without a distinct general ability factor. Such an alternative model is a special case of our speed model because it assumes that both the variance related to speed as well as the common variance of the four other abilities is adequately represented by the same latent factor. A nested comparison with our model revealed that this additional assumption was not appropriate, $\Delta\chi^2(1, N = 149) = 22.38$, $p < .01$.[4]

Next, we examined whether direct paths from age to the general ability factor or to any of the four abilities would lead to a significant increment in fit (i.e., Models SP2-1 to SP2-5 in Table 3). First, we allowed the path from age to general ability to be freely estimated. No significant increment in fit was observed, $\Delta\chi^2(1, N = 149) = 1.92$, $p > .1$, and the coefficient of the path leading from age to general ability did not differ significantly from zero ($\beta = -.10$, $z = -1.41$, $p > .1$). The same result was obtained for knowledge ($\beta = -.05$, $z = -0.68$, $p > .1$), fluency ($\beta = .05$, $z = 0.60$, $p > .1$), reasoning ($\beta = -.06$, $z = -0.80$, $p > .1$), and memory ($\beta = -.06$, $z = -0.78$, $p > .1$). In all cases, allowing the age path to be freely estimated did not lead to a significant increment in the overall fit of the model nor did the path itself differ significantly from zero. Thus, contrary to our expectations, age trends for knowledge and fluency did not become positive after controlling for speed.

Up to this point, it appears that speed excelled as a mediator of age differences in intellectual abilities. However, as noted by Breckler (1990), researchers using structural modeling procedures are often reluctant to search for equivalent models that may represent the data equally well. In the present case, one may want to explore whether any of the other four intellectual abilities would function equally well as a mediator of age differences in intelligence. Given that all five abilities correlated highly with each other and with age (see Table 4), this possibility does not appear unlikely.

To examine this issue, four additional models were considered. All four models were structurally identical with the speed model depicted in Figure 2. The only difference to the speed model was that an ability other than speed mediated the effect of age on intelligence. Speed, in turn, was used with the remaining three abilities to define the general ability factor. With the same number of degrees of freedom, the chi-square values for each of the four alternative models were higher than the chi-square values for the speed model (see Models AM1 to AM4 in Table 3); the chi-square differences ranged from 5.71 when memory was the mediator ability to 8.66 when knowledge was the mediator ability. Unfortunately, a statistical evaluation of these differences is not possible because the four alternative

[4] Technically, the nested comparison was achieved by setting the residual variance of the general ability factor to zero. As a consequence, the path from speed to general ability had to be estimated at unity, which implies an identity relation between the two factors given that general ability had no input from other variables within the model.

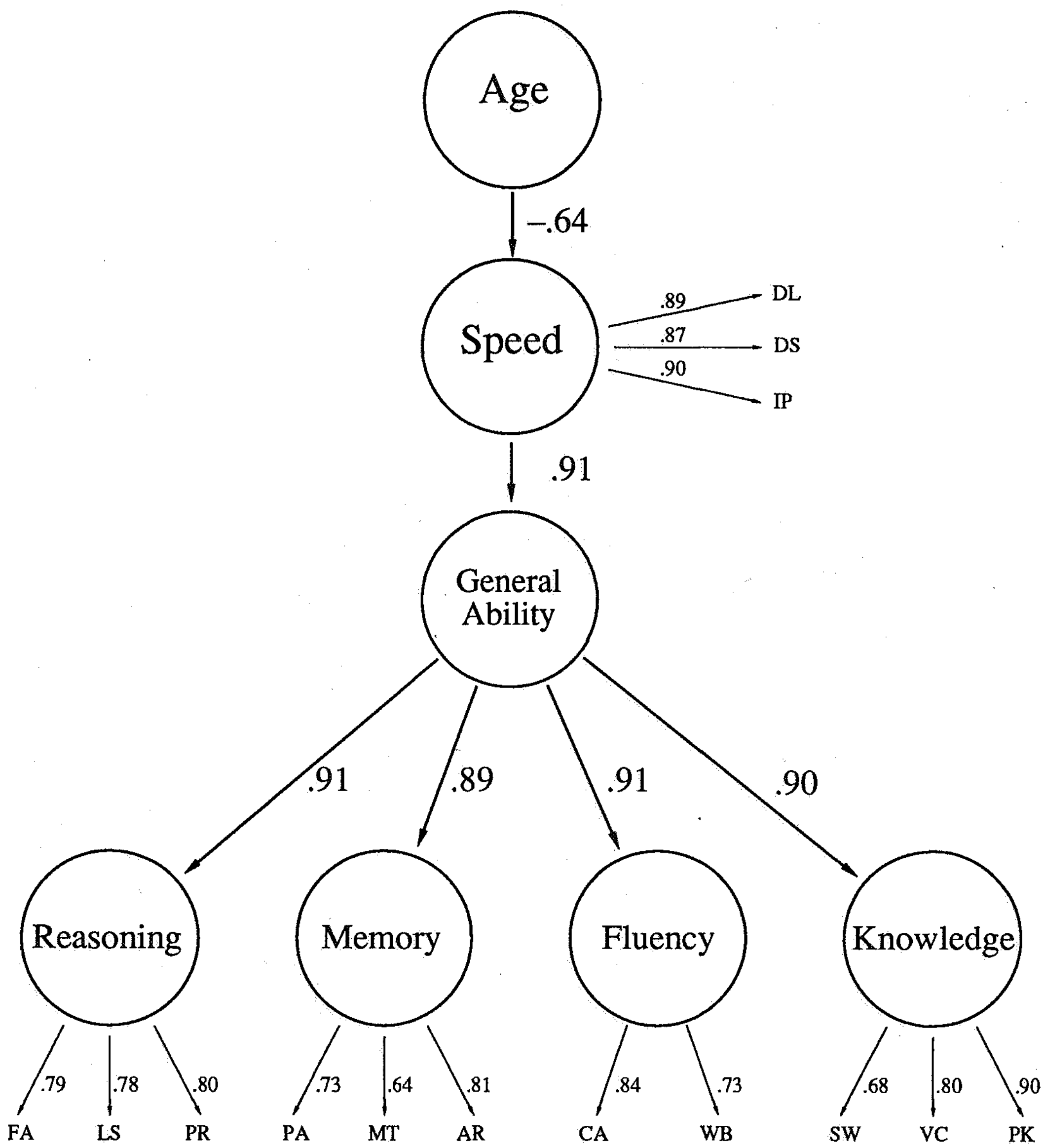

Figure 2. The speed hypothesis as a structural model. (The diagram is based on Model SP1 in Table 3. All paths were significant. DL = Digit Letter; DS = Digit Symbol Substitution; IP = Identical Pictures; FA = Figural Analogies; LS = Letter Series; PR = Practical Reasoning; PA = Paired Associates; MT = Memory for Text; AR = Activity Recall; CA = Fluency: Animals; WB = Fluency: Letter "S"; SW = Spot-a-Word; VC = Vocabulary; PK = Practical Knowledge.)

models and the speed model are not nested within each other. However, there is indirect statistical evidence in support of the speed model. First, with the other models, allowing for a direct path from age to the general ability factor representing the common variance of the remaining four abilities always led to significant increments in overall fit: increment for the reasoning model, $\Delta\chi^2(1, N = 149) = 5.83$; increment for the memory model, $\Delta\chi^2(1, N = 149) = 5.08$; increment for the knowledge model, $\Delta\chi^2(1, N = 149) = 8.11$; increment for the fluency model, $\Delta\chi^2(1, N = 149) = 8.42$ (all *p*s $< .05$). Thus, no other ability absorbed as much age-related variability in other aspects of intellectual functioning as speed. Second, although they were not nested within each other, both the speed model and the four alternative models were nested within the final measurement model (i.e., model MM2-3 of Table 3). As reported earlier, the fit of the speed model did not differ significantly from the fit of the measurement model, $\Delta\chi^2(9, N = 149) = 12.37$, $p > .1$. For the four alternative models, however, a significant difference to the measurement model was found: reasoning, $\Delta\chi^2(9, N = 149) = 18.80$; memory, $\Delta\chi^2(9, N = 149) = 18.08$; knowledge, $\Delta\chi^2(9, N = 149) = 21.03$; fluency, $\Delta\chi^2(9, N = 149) = 19.47$ (all *p*s $< .05$). Thus, despite the absence of a conclusive statistical test, the available evidence does not favor any of the alternative models over the speed model.

Commonality Analysis

We also performed a commonality analysis in the latent factor space to determine the shared and unique variance components of the main effects of age and speed as predictors of the general ability factor. To accomplish this, we first estimated a model in which age, speed, and the general ability factor defined by the other four abilities were allowed to covary freely (i.e., age, speed, and general ability were defined as intercorrelated, independent variables). Then, all parameters of this model were fixed to the estimated values except for the interrelations among age, speed, and general ability. Finally, the general ability factor was regressed on (a) age alone (i.e., speed was not included in the model), (b) speed alone (i.e., age was not included in the model), and (c) age and speed (i.e., with age and speed as intercorrelated, independent variables). Following procedures described by Hertzog (1989), the amount of variance in general ability explained by each of the three regression equations was used in conjunction to determine unique and shared variance components.[5] Taken together, age and speed accounted for 81.3% of the variance in general ability. Moreover, 42.8% of the total variance in general ability was explained by speed alone, 37.8% of the total variance was shared by age and speed, and only 0.7% of the total variance in general ability was due to age alone. Thus, 98.2% [i.e., 100 − 0.7/(0.7 + 37.8)100] of the age-related variance in general ability was shared with speed.

Additional Analyses

Rectangular versus representative age distribution. In contrast with other correlational studies on age-ability relations in old age, the sampling scheme used in our study resulted in a close-to-equal number of subjects in each of six age strata (i.e., 70–74, 75–79, 80–84, 85–89, 90–94, and 95+ years). This implies a massive oversampling of very old individuals. For instance, in a nonstratified sample of over-70-year-old West Berlin residents, about 1% of the subjects would be 95 years or older. In this study, 22 out of 149 individuals (i.e., 14.8% of the sample) fell into this age range. We believe that this oversampling of the very old allowed for a more reliable assessment of age trends in very old age. However, the sampling strategy makes it also more difficult to compare our results with studies with a random or close-to-random age distribution and to generalize them to the general population of over-70-year-old adults. Thus, it is useful to examine whether the present results are conditional on the rectangular age distribution of our sample. To explore this issue, we randomly selected from each of the six age strata the appropriate number of subjects to mimic the true age distribution of over-70-year-old West Berlin residents obtained from the city registration office. This resulted in a subsample of 86 subjects with a mean age of 79.9 years (full sample M = 84.5 years) and a standard deviation of 6.5 (full sample, SD = 8.9). Table 5 displays the standardized covariance estimates of the final measurement model (i.e., Model MM2-3 of Table 3) and the raw correlations for this age-representative subsample. Compared with the full sample (i.e., Table 4), the age-ability correlations tended to be somewhat lower in the subsample; for instance, the standardized covariance estimate for speed and age dropped from −.63 to −.51. The fit of the final measurement model (i.e., Model MM2-3 in Table 3) was again satisfactory, $\chi^2(73, N = 86) = 101.59$, $p = .015$, $NNFI$ = .945, CFI = .961, as was the fit of the speed model, $\chi^2(82, N = 86) = 109.92$, $p = .02$, $NNFI$ = .952, CFI = .962. As was true for the full sample, the difference in fit between the measurement model and the speed model was not significant, $\Delta\chi^2(9, N = 86) = 8.33$, $p > .1$. Finally, allowing for a direct path from age to general ability or from age to any of the four remaining abilities was not associated with an increment in fit: general ability, $\Delta\chi^2(1, N = 86) = 1.25$; knowledge, $\Delta\chi^2(1, N = 86) = 0.00$; fluency, $\Delta\chi^2(1, N = 86) = 0.10$; reasoning, $\Delta\chi^2(1, N = 86) = 0.34$; fluency, $\Delta\chi^2(1, N = 86) = 0.14$ (all $ps > .10$). In summary, speed functioned as a mediator of age-ability relationships in both samples, although negative age trends were more pronounced in the sample with the rectangular age distribution. Given the small number of subjects, however, these findings are only tentative and need to be replicated with larger and independent samples.

Table 5
Intercorrelations Among Abilities and Age for the Age-Representative Subsample (n = 86)

Factor	1	2	3	4	5	6
1. Speed	—	.81	.75	.79	.82	−.51
2. Reasoning	.67	—	.79	.88	.74	−.49
3. Memory	.56	.58	—	.71	.82	−.44
4. Knowledge	.68	.71	.57	—	.79	−.45
5. Fluency	.65	.59	.60	.64	—	−.47
6. Age	−.46	−.45	−.39	−.40	−.41	—

Note. Standardized covariance estimates of the final measurement model are shown above the diagonal. Correlations that are based on unit-weighted composites of the z-transformed test scores are shown below the diagonal.

Role of education. In a very heterogeneous, close-to-representative sample such as this one, one may wonder whether relations among age, speed, and intelligence interact with other subject characteristics. In the context of the theory of fluid versus crystallized intelligence, education may appear as a possible candidate for such an interaction effect because positive speed-adjusted age gradients in crystallized abilities may be more prominent among highly educated individuals. Thus, the failure to detect speed-adjusted positive age gradients in the total sample may be due to the large number of individuals with relatively low levels of education in a representative sample such as this one. To examine this issue, education and an Age × Education interaction term were added to the speed model. With respect to education, the original variable (i.e., years of education) was log transformed because it showed high values

[5] Specifically, the following equations were used: (1) $R^2_{\text{unique speed}} = R^2_{\text{speed.age}} - R^2_{\text{age}}$, (2) $R^2_{\text{unique age}} = R^2_{\text{speed.age}} - R^2_{\text{speed}}$, (3) $R^2_{\text{shared}} = R^2_{\text{speed.age}} - R^2_{\text{unique age}} - R^2_{\text{unique speed}}$.

for skewness (1.15) and kurtosis (2.23). After the log transformation, skewness was reduced to 0.34 and kurtosis to −0.24. The Age × Education interaction term was computed outside of EQS by multiplying the log-transformed education variable and age, regressing the multiplied variable on age and education, and saving the residuals (i.e., the component of the interaction term that is orthogonal to the two main effects). In the modified model, age, log-transformed years of education, and the interaction term served as independent variables. Age and education were allowed to covary; the amount of covariation was not significant ($r = -.11$, $z = -1.27$, $p > .05$). Initially, paths to the speed factor were specified for all three independent variables. Both age and education showed a significant effect (age on speed, $\beta = -.62$, $z = -8.76$; education on speed, $\beta = .22$, $z = 3.29$). The path for the interaction term was set to zero because it was not significant ($\beta = -.01$, $z = -0.08$). Next, we explored whether allowing for direct paths of the main effect of education or the Age × Education interaction term to the general ability factor or to any of the other four ability factors would lead to significant increments in fit, implying that the ability in question would be affected by one or two of these variables independent of their relationship to speed. For example, a significant positive effect of the interaction term on the two crystallized abilities may indicate the existence of speed-adjusted positive age gradients among more educated individuals. Of the 10 possible effects, only the path from the education main effect to the knowledge factor was significant ($\beta = .17$, $z = 2.99$). Thus, years of education were predictive of high levels of knowledge even after controlling for the fact that years of education were positively related to speed. This result is well in agreement with Gf/Gc theory, and it also corroborates the content validity of the knowledge factor. The interaction term, however, never approached significance. Thus, the data did not support the hypothesis that speed-adjusted positive age gradients would emerge with higher levels of education. The final model is depicted in Figure 3. For this model, $\chi^2(110, N = 149) = 178.98$, $p < .01$, *NNFI* = .946, *CFI* = .956.

Effects of gender. Although we had no specific expectations in this regard, the close-to-equal number of men ($n = 76$) and women ($n = 73$) in our sample provided for a good opportunity to test whether parameters of the speed model varied in some important way as a function of gender. To examine this possibility, the basic speed model (i.e., Model SP1 in Table 3) was recast as a two-group model. Equality constraints were imposed on the path coefficients leading from the factors to the indicators, the three nonzero residual covariances of the indicators, the variance of age, the residual variances of the factors, the path from age to speed, the path from speed to the general ability factor, and the paths from the general ability factor to reasoning, knowledge, fluency, and memory. For each of the individual equality constraints, it was inspected whether releasing the constraint was associated with a significant increment in fit using the Lagrange Multiplier test provided by EQS (Bentler, 1989). Only one significant difference between the two groups was observed, suggesting that the path from general ability to memory was somewhat higher in women ($\beta = .93$) than in men ($\beta = .89$). Given the large number of tests and the low level of significance of the difference, $\Delta\chi^2(1, N = 149) = 4.66$, $p < .05$, we will not interpret this finding. Again, allowing for direct paths from age to the general ability factor or to any of the remaining four ability factors was not associated with a significant increment in fit in any of the two groups.

Discussion

The major goal of this study was to examine the relationship between speed and intelligence in old and very old age. The data were consistent with the hypothesis that negative age differences in knowledge, reasoning, memory, and fluency are mediated through age differences in speed. In other words, we could not reject the hypothesis that age differences in intelligence are due to age differences in speed. The results of the commonality analysis further elucidated the central importance of speed. The amount of variance in intellectual functioning uniquely related to age was small (0.7%), whereas both the portion uniquely related to speed (42.8%) and the portion shared by age and speed (37.8%) were large. A direct comparison of these figures to earlier studies is difficult because of differences in samples, measures, and data analysis. Generally, however, the proportion of the variance uniquely related to age tended to be larger, and the overall amount of explained variance tended to be smaller (cf. Hertzog, 1989; Nettelbeck & Rabbitt, 1992; Salthouse, 1991; Schaie, 1989).

What are the reasons for the central role of speed in the present data set? One possibility would be that the tests used as indicators of abilities other than speed were biased toward speeded responding. This may be true with respect to the fluency tests where subjects had to name as many words of a certain category within 90 s as possible. In line with this argument, Salthouse (1993) reported that both speed and knowledge measures are predictive of individual differences in fluency. Similarly, one could also argue that the memory tests were timed because encoding time was limited. For the reasoning and knowledge tests, however, a bias toward speeded responding seems highly unlikely. With respect to the reasoning tests, testing generally was terminated for reasons other than reaching the maximum time limit. Specifically, the following proportions of subjects terminated the reasoning tests because they ran out of time: Figural Analogies, 13%; Letter Series, 30%; and Practical Reasoning, 27%. In the remaining cases, testing was terminated after subjects had made three consecutive false responses or after they had answered the last item of the test. Finally, there were no time constraints at all on the knowledge tests. If timed testing conditions were the prime reason for speed–ability correlations, then speed should correlate less with knowledge and reasoning than with memory and fluency. Clearly, this was not the case (see Table 4). In addition, speed fully accounted for the age-related variability in knowledge despite the fact that the knowledge tests were untimed. On the basis of these considerations, it is unlikely that the central role of speed in this data set was an artifactual result of speeded testing conditions.

A second reason for the importance of speed may be related to the age of the sample. All participants were older than 70 years, and about one third was older than 90 years. Recent longitudinal evidence, such as Hertzog and Schaie's (1986,

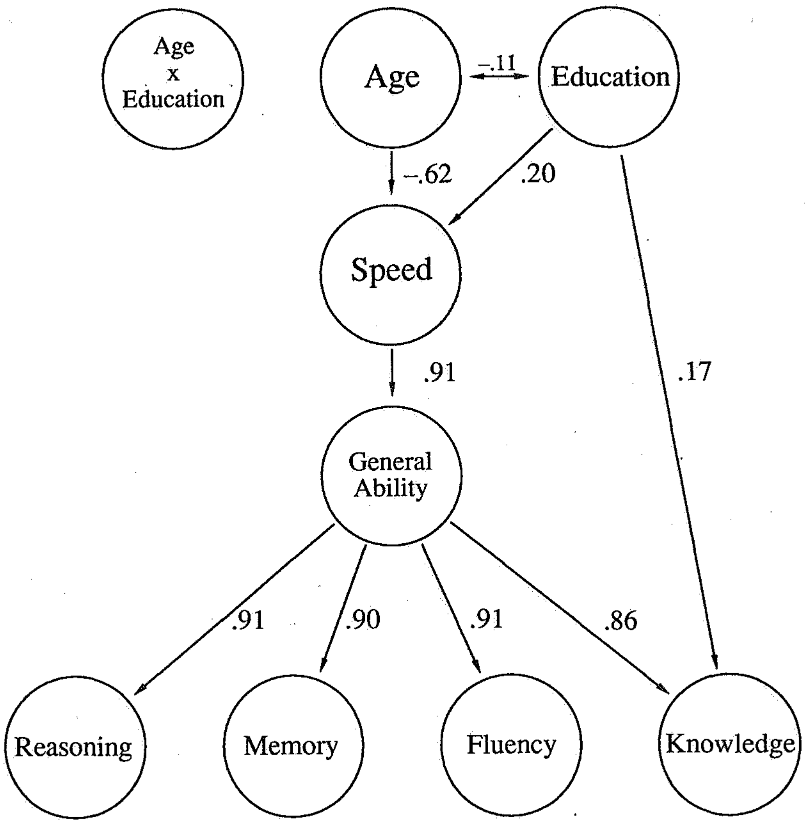

Figure 3. The role of education in the speed model. (The indicators of the ability factors are not shown in the diagram. Except for the correlation between age and education, all paths were significant.)

1988) reanalysis of the Seattle Longitudinal Study, suggests that "most individuals make a transition from a stability to a decline pattern of g development at some point between age 55 and age 70" (Hertzog & Schaie, 1988, p. 128f). By implication, this would mean that virtually all individuals in the present sample were affected by age-related decline in intellectual functioning. If negative age changes in speed mediate this decline, then the speed-mediated effect of age on intelligence should be more pronounced in an age-stratified sample of over-70-year-olds than in samples with a lower mean age and a smaller proportion of very old subjects. In this context, it is interesting to note that age-ability correlations were lower in the subsample with a representative age distribution (i.e., Table 5) than in the sample with the stratified age distribution (i.e., Table 4). Additional work with larger samples is needed to study the effect of different sampling schemes on the estimation of age gradients in cognitive functioning.

The present findings are also relevant for the life-span theory of fluid versus crystallized intelligence (Horn, 1982). According to Gf/Gc theory, age trends for intellectual abilities related to the accumulation of cultural knowledge are expected to be more positive in middle and late adulthood than age trends for abilities that are more direct measures of the "mechanics" of intellectual functioning (Baltes, 1987). The present data suggest that the difference in age gradients between fluid and crystallized abilities may be less pronounced after the age of 70 years. Simple correlations with age were negative for all five abilities, and differences in the magnitude of age-ability intercorrelations were small.[6] In addition, there was no evidence for speed-adjusted positive age trends in the two marker abilities of crystallized intelligence, knowledge and fluency, even when individual differences in education were taken into account. The only finding in favor of the Gf/Gc distinction was that years of education predicted interindividual differences in knowledge after controlling for their predictive relationship to speed (see Figure 3).

The magnitude of ability intercorrelations and the absence of significant differences in age trends between fluid and crystallized abilities are consistent with the idea that age differences in speed lead to an increasing convergence, or dedifferentiation, of the ability factor space in old age (Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980; Cunningham, 1980; Reinert, 1970; Schaie, Willis, Jay, & Chipuer, 1989). In future work, it should be examined whether correlations among abilities using the same set of measures are lower in younger age groups

[6] Age–ability correlations could be constrained to be equal without a significant loss in fit; that is, $\Delta\chi^2(4, N = 149) = 2.94$, $p > .10$, nested within Model MM2-3 in Table 2.

and whether speed occupies a less central role in younger age groups than it does in the present sample.

We want to caution against the conclusion that speed is all there is to cognitive aging (Mayr & Kliegl, in press). Our results were obtained with a small, heterogeneous, and cross-sectional sample. Larger and preferably longitudinal samples are needed to replicate the present findings and to identify the extent to which the overall pattern of results is modulated by variables such as health status, education, and social participation. For instance, positive speed-adjusted age gradients in crystallized abilities may emerge if more proximal indicators of intellectual activity level are taken into consideration. In over-70-year-old adults, years of education is a rather distal measure representing interindividual differences in the investment of fluid intelligence during relatively early phases of the life span. The existence of positive speed-adjusted age gradients in old and very old age, however, may be more contingent on one's continued interest in the acquisition of new knowledge. Therefore, the present analyses need to be extended by including measures related to job history, social participation, and current intellectual interests (cf. Hultsch, Hammer, & Small, 1993).

Moreover, the present findings are only a "snapshot" of old adults' intellectual functioning and development. As suggested by the results of past research with more select and younger samples of older adults (Baltes & Kliegl, 1992; Kliegl, Smith, & Baltes, 1990; Lindenberger, Kliegl, & Baltes, 1992), training and practice may uncover novel age-related variance in intellectual functioning. We do not know whether this variance would continue to be related to speed in much the same way as the age-related variance represented in this data set.

Finally, selective survival also complicates the interpretability of our findings. In the Federal Republic of Germany, about 70% of a birth cohort are alive at age 70 years, but only about 5% are alive at age 90 (Putz & Schwarz, 1984). Most likely, the 5% still alive at age 90 are not a random sample of the 70% still alive at age 70. In fact, available evidence shows that a high level of intellectual functioning is positively related to survival (Baltes, Schaie, & Nardi, 1971; McArdle, Hamagami, Elias, & Robbins, 1991; Manton & Woodbury, 1983; Powell et al., 1990; Siegler & Botwinick, 1979). As long as different intellectual abilities predict survival equally well, selective survival would not alter the outcome of structural analyses regarding age, speed, and intelligence. However, the situation is different if decline in some intellectual abilities is more predictive of mortality than decline in others. For instance, imagine that individuals who decline more in speed than in memory survive longer than individuals who decline more in memory than in speed. In that case, the present data would overestimate the importance of speed. Clearly, longitudinal work predicting intraindividual change in outcome intellectual abilities (e.g., Hertzog, Dixon, & Hultsch, in press; Hultsch, Hertzog, Small, McDonald-Miszczak, & Dixon, 1992) is needed for a further understanding of these issues.

If we assume, despite these reservations, that the present results are a valid representation of age-related change, what are the implications for current theorizing in the field of cognitive aging? The strong version of the cognitive slowing hypothesis claims that age-associated decrements in complex abilities are a by-product of a basic loss in processing speed. With increasing age, speed of processing becomes the critical resource that constrains the upper limits of intellectual functioning. Although our findings are consistent with this view, we believe that a different interpretation of the findings is equally plausible. According to this alternative, the speed measures were the best indicators of one or more age-associated processes affecting all intellectual abilities. In that case, the speed measures may still capture most or even all of the reliable age-related variance in intelligence, but it would be misleading to assume that negative age differences in intelligence were caused by decrements in speed of processing.

In this context, one should note that psychometric measures of speed are not a direct reflection of mental speed in terms of a content-free transmission rate of information. For example, the Digit Symbol Substitution subtest of the WAIS, one of the indicators of speed in the present study, requires a relatively complex sequence of processes that can be separated into components such as perception, working memory, secondary memory, and motor functioning (Laux & Lane, 1985). Thus, it is possible that speed tests are powerful markers of cognitive aging because they measure interindividual differences in the smooth and error-free coordination of perceptual and cognitive activities in working memory (Mayr, 1992; Mayr & Kliegl, in press; Salthouse, 1991, 1992a, 1992b; Salthouse & Babcock, 1991; cf. Baddeley, 1986, 1992).

In summary, our results show that psychometric measures of speed are powerful predictors of negative age differences in intelligence among old and very old adults. If replicated, the main merit of this finding is to constrain the search for possible sources of age differences in intellectual functioning. Thus, the question "What causes decline in diverse psychometric abilities?" can be substituted by more tractable questions such as "What causes decline in measures of speed?"

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