Individual Differences in the Rate of Change in Cognitive Abilities during Adulthood

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Abstract

Latent growth curve models were used to examine the average rate of decline in verbal ability, spatial ability, and inductive reasoning, and whether individuals vary significantly in the rate of decline for these abilities. Cognitive abilities measured were the Verbal Meaning, Spatial Orientation, and Reasoning sub-tests from the Thurstone Primary Mental Abilities Test. A sample of 1745 participants (n = 794 males, n = 951 females) from 11 cohorts of the Seattle Longitudinal Study (SLS) was included. Utilizing a cohort-sequential growth model, longitudinal data from different cohorts were combined over the adulthood period to study change in these abilities from age 25 to age 81, a longer range than it is typically possible to study. Significant non-linear decline was found for verbal ability, spatial ability, and inductive reasoning. Significant individual variation was observed in the rate of decline for all abilities. Rate of decline over time in all abilities was related to level of ability at age 67. Cohort, gender, and level of education explained individual variation in the rate of decline for spatial ability but not for verbal or reasoning abilities. Although individual variation in the rate of decline remained significant for verbal and reasoning abilities, the rate of decline in verbal ability was predicted by cohort, and rate of decline in reasoning ability was predicted by both cohort and education.

Previous research from the Seattle Longitudinal Study (SLS) has shown that decline in cognitive abilities during adulthood is not uniform across abilities (Schaie, 1983, 1996). Crystallized abilities such as verbal meaning tend to remain relatively stable until the seventies while fluid abilities such as spatial orientation and inductive reasoning begin to decline in the sixties on average. Additionally, individual variation in the pattern of decline for these abilities may vary widely. Understanding how cognitive abilities change in adulthood and whether individual variation in the rate of change can be predicted by characteristics of the individual is important.

The cohort-sequential study design of the Seattle Longitudinal Study (Schaie, 1996) makes it possible to study change in various cognitive abilities (i.e., verbal meaning, spatial orientation, and inductive reasoning) over most of the adulthood period. The data collected in the SLS on more than 1700 individuals over 42 years using a cohort sequential design allowed us to study change in cognitive abilities over a larger age range (age 25 to 81) than is typically possible in a traditional single-cohort longitudinal study. Latent growth curve modeling was used to combine the information available from each individual to describe change in cognitive ability over adulthood and to identify predictors of the rate of change.

Three main research questions were addressed in this study using latent growth curve analysis. First, what is the pattern of change for various cognitive abilities over adulthood? It was expected that a non-linear trajectory will describe the pattern of decline significantly better than a linear trajectory. Second, do individuals vary significantly in how much they change or does everyone follow the same trajectory? Based on prior research, we expected that individual variation in the rate of cognitive decline would be found. Third, what factors predict individual variation in the rate of change in cognitive abilities over time? We investigated the relationship of three demographic characteristics (i.e., cohort, gender, and education) to the rate of cognitive decline for each of the three abilities studied.

Method

Sample

The sample for this analysis consisted of 1745 participants who were part of a larger on-going study of adult cognitive development, the Seattle Longitudinal Study (Schaie, 1996). The sample included 794 (45.5%) males and 951 (54.5%) females, and the mean education for the sample was 14.50 years (range = 4-20). All participants in the SLS were members of a health maintenance organization (HMO) in the Seattle, Washington area. The design for the present analyses required that each participant have at least two occasions of data to be included. Given that the first wave of data collection for SLS occurred in 1956 with subsequent waves of data collected every seven years in 1963, 1970, 1977, 1984, and 1991, participants in this analysis must have had at least two occasions of data within these six waves of SLS (1956-1991).

The SLS utilized a cohort-sequential study design. Data were collected on seven cohorts at the first wave of data collection in 1956. At each subsequent wave, an additional cohort was included to maintain the age range of the original sample, and a new sample of participants was added to each existing cohort (Schaie, 1996). Thus, in the present study, age refers to mean cohort age rather than individual age. As a result of this study design, a total of eleven cohorts had been studied by the 1984 wave, and participants may have between two and six waves of data by the 1991 wave. Table 1 describes the structure of the data collection for SLS and gives the sample sizes for each cohort included in the analysis sample.

Measures

Cognitive abilities were measured with the Primary Mental Abilities Test (PMA; Thurstone & Thurstone, 1949). Demographic and personal characteristics of year of birth, gender, and education were collected as part of the Life Complexity Inventory (LCI; Gribbin, Schaie, & Parham, 1980).

PMA Verbal Meaning. Verbal meaning is the ability to comprehend language. Each item on the PMA Verbal Meaning scale is a four-choice synonym test. This scale is a highly speeded test with four minutes given to complete 50 items.

PMA Spatial Orientation. This scale is a measure of the ability to mentally rotate objects in two-dimensional space. Participants are shown an abstract figure and asked to identify which of six other drawings represents the model in two-dimensional space.

PMA Reasoning. This scale is a measure of inductive reasoning. Participants are shown a series of letters and asked to give the next letter in the series.

Statistical Methods

Latent growth curve models (Meredith & Tisak, 1990; McArdle & Epstein, 1987; Muthén, 1989; Willett & Sayer, 1994, 1996) were used to model change over time in three cognitive abilities. Similar to hierarchical linear models (Bryk & Raudenbush, 1992) or multilevel models (Goldstein, 1995) used with longitudinal data, a latent growth curve analysis involves two basic models: (1) the Level 1 model, for within-person variation across time, also known as the trajectory of an individual; and (2) the Level 2 model, for between-person variation. The Level 1 model describes the individual trajectories of growth by modeling an intercept, representing performance at an initial, or other meaningful, time point, and a slope, describing change over time. Interindividual variation is incorporated into the model by allowing these terms to have random variance. The Level 2 model attempts to explain the variation in individual growth trajectories by using person-level predictors of this change.

The Level 1 model expresses change in a variable, Y_{ip}, as:

$$\boldsymbol{Y_{ip}} = \pi_{0\boldsymbol{p}} + \pi_{1\boldsymbol{p}}\boldsymbol{t_i} + \varepsilon_{\boldsymbol{ip}} \quad , \tag{1}$$

where π_{0p} is the intercept parameter, representing the value of Y for person p when $t_i = 0$, π_{1p} is the slope parameter, representing change in Y over time for person p, and ε_{ip} is the measurement error for person p at time i. Willett and Sayer (1994) showed that this model is equivalent to a measurement model with both covariance and mean structures estimated:

$$\mathrm{Y} = \Lambda_y \eta + \varepsilon_y \quad , \tag{2}$$

where Λ_y is the matrix of loadings of the Y variables on the intercept and slope parameters contained in η, and ε_y is the measurement error in the Y variables.

In a traditional LISREL model with mean structures (Jöreskog & Sörbom, 1996), the elements of Λ_y would be estimated. In these models, these elements are set to constant values to make the y-measurement model in Equation 2 equivalent to the Level 1 growth model in Equation 1. Specifically, for a linear growth model, Λ_y contains a column of ones followed by a column of linear coefficients corresponding to the t_i values (e.g., 0, 1, 2 for a three-wave study). This formulation allows the y-side measurement model to estimate the Level 1 parameters of interest, the intercept and slope of individual growth, as the latent variables contained in η.

This two-factor measurement model can also be used to fit an unspecified, rather than linear, trajectory to the data (McArdle & Hamagami, 1991; Duncan & Duncan, 1994; Duncan, Duncan, Strycker, Li, and Alpert, 1999). In this case, only two of the t_i values are fixed (in order to identify the model) and the remaining coefficients are estimated from the data. This model allows the optimal growth function to be determined from the data, and the slope factor is interpreted as a more general change factor, unless the estimated change coefficients show a linear pattern.

The full information maximum likelihood (FIML) estimation procedure implemented in Amos 3.6 (Arbuckle, 1997) was used to accommodate the various patterns of missing data. The cohort-sequential study design of the SLS incorporated several missing data patterns by design; other missing data were observed due to attrition from the study. The FIML method allows all information available from the data to be utilized in the estimation with no reduction in sample size. An additional note about Amos is that, when the data are incomplete, a function of log likelihood rather than a chi-square value is calculated. However, the difference of these values is distributed chi-square for nested models. Thus, model fit can only be assessed by comparing two nested models using a chi-square difference test.

Results

First, the developmental pattern of change in three cognitive abilities was examined to determine whether change across adulthood in these abilities was best described by a linear or a non-linear trajectory. Second, individual differences in the rate of change over time were examined. Third, because not all individuals were measured at every age included in this analysis, we also tested whether the classical assumption of equal measurement error variance across time would hold and whether measurement error variance at adjacent time points were related rather than independent. Finally, we tried to account for interindividual variation in the level of ability at age 67 and the rate of change in ability performance over time by including three time-invariant predictors (cohort, gender, and education).

Pattern of change over time

Descriptive statistics for the three cognitive abilities studied in the present investigation are presented in Table 2 for individuals assessed at ages 25 to 81 years. Verbal, spatial, and reasoning ability raw scores were re-scaled to a T-score metric to allow all abilities to be compared on the same measurement scale. Observed trajectories for a random sample of 50 participants and the curve of average ability over time for all participants were plotted to perform a preliminary inspection of the pattern of change. These trajectories are presented in Figure 1 for verbal ability, in Figure 2 for spatial ability, and in Figure 3 for reasoning ability.

Examination of graphs of the trajectories over time showed that change appeared to be non-linear. To provide a statistical test of whether a non-linear change model fit the data significantly better than a linear model, both linear and non-linear (i.e., unspecified growth function) models were fit to the data, and a chi-square difference test was computed. All growth models set the intercept at age 67, the age at which decline tends to begin, to provide the estimates associated with the intercept parameter with a more meaningful and interesting interpretation.

Verbal ability. Examination of the trajectories of verbal ability in Figure 1 showed that a non-linear trajectory was more likely to describe the pattern of change than a linear trajectory. To test the form of the pattern of change, the fit of a linear growth model was compared to the fit of a model that allowed the form to be estimated from the data. The unspecified growth curve model fit the data significantly better than the linear model, $\Delta\chi^2(7) = 386.256$, $p < .001$, and the change coefficients estimated in the unspecified growth model showed that the pattern of change was non-linear. As shown in Table 3, the loadings estimated in the unspecified growth model reflected the general pattern of non-linear change in verbal ability over time. The latent (i.e., estimated) change coefficients described a trend where verbal ability increased in small amounts from age 25 to age 39, then remained relatively constant through age 53, after which there was a slight decline by age 60 and a larger amount of decline between age 74 and age 81 than between any other two time points.

Both the estimated average verbal ability performance at age 67 and the average amount of change in verbal ability performance over time were significantly different than zero ($p < .001$), and the amount of interindividual variation about these average values was significant ($p < .001$). The amount of change in verbal ability performance over time was also significantly related to the individual’s level of verbal ability performance at age 67. Higher levels of verbal ability at age 67 were associated with lower rates of non-linear change over time.

Next, the assumption of equal measurement error variance over time was tested. The global test of this assumption was significant, $\chi^2(8) = 90.293$, $p < .001$, indicating that the measurement error variance for verbal ability was not constant over the nine ages studied. When error variances are not constant over time, the assumption of independent errors should also be tested by allowing temporally adjacent error terms to correlate

(Willett & Sayer, 1994). Allowing all pairs of adjacent errors to correlate showed that only the correlations between verbal ability at age 53 and 60 and between age 67 and 74 were significant. Including the two significant correlations significantly increased the fit of the model, $\chi^2(2) = 17.572$, $\underline{p} < .001$, and setting the other six correlations to zero did significantly decrease the fit of the model, $\chi^2(6) = 9.027$, $\underline{p} > .05$. Thus, the measurement error variance for the verbal ability measures over time were not equal across time or completely independent.

Spatial ability. Examination of the trajectories of spatial ability in Figure 2 revealed that that the pattern of change for spatial ability appeared to be more non-linear than linear. To test the pattern of change, both a linear growth model and an unspecified growth function model were fit to the data. A chi-square difference test showed that the unspecified growth curve model fit the data significantly better than the linear model, $\Delta\chi^2(7) = 191.561$, $\underline{p} < .001$. As shown in Table 3, the change coefficients estimated in the unspecified model described a non-linear pattern of change in spatial ability over time. The general trend showed that spatial ability had a slight increase from age 25 to age 32 but remained relatively constant through age 53 with a slight decline between age 46 and age 53, after which a greater rate of decline was observed through age 81.

Both the estimated average spatial ability at age 67 and the average amount of change were significantly different than zero ($\underline{p} < .001$), and each of these parameters had a significant amount of interindividual variation about these average values. The amount of change in spatial ability over time was also significantly related to the individual's level of spatial ability at age 67. Higher levels of spatial ability at age 67 were related to higher rates of non-linear change over time.

Next, the assumption of equal measurement error variance over time for spatial ability was tested. Allowing all error variances to vary over time significantly improved the fit of the model, $\chi^2(8) = 20.207$, $\underline{p} < .01$. This result indicated that the measurement error variance for the spatial ability was not constant over the nine ages studied. The assumption that these error variances were independent was tested next. Allowing all pairs of adjacent errors to covary did not significantly improve the fit of the model, $\chi^2(8) = 10.078$, $\underline{p} > .05$. Thus, the error variances for the spatial ability measure were found to be heteroscedastic over time but independent.

<u>Reasoning ability</u>. As with verbal and spatial ability, examination of trajectories of the reasoning ability and average reasoning ability over time presented in Figure 3 showed that a non-linear trajectory was more likely to describe the pattern of change in spatial ability than a linear trajectory. A chi-square difference test showed that the unspecified growth curve model fit the data significantly better than the linear model, $\Delta\chi^2(7) = 199.393$, $\underline{p} < .001$. As shown in Table 3, the change coefficients estimated in this model described a non-linear function of change in reasoning ability over time. The general trend showed that reasoning ability was relatively stable from age 25 to age 53. Reasoning ability then declined slightly more by age 60 after which the rate of decline increased but remained relatively constant until age 81.

Both the estimated average reasoning ability at age 67 and the average amount of change were significantly different than zero ($\underline{p} < .001$), and each of these parameters had a significant amount of interindividual variation around these average values. The amount of change in reasoning ability over time was also significantly related to the individual’s level of reasoning ability at age 67 ($p < .05$). Higher levels of reasoning ability over time were associated with higher rates of change over time.

Next, the assumption of equal measurement error variances over time was tested. Allowing all error parameters to vary freely did not significantly improve the fit of the model to the data, $\chi^2(8) = 15.336$, $p > .05$. Therefore, it was concluded that the assumption of homoscedasticity of error variances over time was met for the reasoning ability test. Because the error variances were homoscedastic, the correlation of adjacent error terms was not tested.

Comparison of growth parameters across abilities

Because the verbal, spatial, and reasoning scores were all in the same metric, comparisons of the growth parameter estimates shown in Table 3 can be made across abilities. One comparison of interest is that, although all are significant, the estimate for individual variation in rate of change was larger for verbal ability than for spatial and reasoning abilities. As Figure 1 shows, this larger variation may be due to greater individual differences in the point where decline began in contrast to spatial and reasoning abilities, where the pattern of decline was more uniform.

Second, the higher verbal ability at age 67 was related to lower rates of change while higher spatial and reasoning ability at age 67 were related to higher rates of change over time. This difference may be related to the difference in the shapes of the curves for the different abilities. The curve for verbal ability increases from age 25 to age 39 and then levels out until approximately age 60 while the curves for spatial ability and reasoning ability were relatively more stable from age 25 to age 60. Last, for all curves, the difference between change coefficients is much greater between age 74 and age 81 (as expected) than between any of the other ages. In addition, this decline appears to be smaller for reasoning ability than for verbal and spatial ability.

Predictors of growth

Significant interindividual variation was found in the intercept and change parameters estimated in the growth models for verbal, spatial, and reasoning ability. Three predictors, specifically cohort, gender, and education, were included in the model to account for this variation. Parameter estimates from the growth models with predictors are shown in Table 4.

Birth cohort, gender, and education were significant predictors of level of ability at age 67 for verbal, spatial, and reasoning abilities ($p < .001$). Being in a later birth cohort and having a higher level of education were both associated with higher levels of ability at age 67. Women had significantly higher levels of verbal and reasoning ability at age 67 than men, but men had significantly higher spatial ability at age 67 than women.

The relationship of these predictors with rate of change in ability over time was less strong than with level of ability at age 67. Rate of change in verbal ability was predicted significantly only by birth cohort ($p < .001$); earlier birth cohorts had higher rates of change in verbal ability over time. However, rate of change in spatial ability was significantly predicted by all three variables ($p < .05$). Being in a later birth cohort and having fewer years of education were related to higher rates of change in spatial ability, and women were predicted to have lower rates of change than men. Rate of change in reasoning ability was predicted significantly by birth cohort ($p < .05$) and by level of education ($p < .01$), but not by gender. Earlier birth cohorts and higher levels of education were related to higher rates of change in reasoning ability.

Although the addition of these three predictors reduced the amount of interindividual variation observed in the intercept and change parameters, these variance parameters, with the exception of the variance in the rate of change in spatial ability, were still significant. Thus, while individual differences in the rate of change in spatial ability were explained by cohort, education, and gender, the rates of change in verbal and reasoning ability were not.

Discussion

The pattern of change in verbal, spatial, and reasoning abilities over adulthood was shown to have a non-linear trajectory when all longitudinal data available from the Seattle Longitudinal Study was used. These trajectories differed between the three abilities in the degree of non-linearity and in the amount of decline seen in the later years. As expected, the fluid abilities of spatial and reasoning ability showed more decline between age 67 and 81 than verbal ability. Because verbal meaning is a crystallized ability, the amount of decline with age is typically smaller. Decline in verbal ability would have been even smaller if the measure were not a speeded test.

Individual variation in the rate of change was significant for verbal, spatial, and reasoning abilities in the unconditional growth models without predictors. Cohort, education, and gender were able to explain this significant individual variation in the rate of change for spatial ability and predicted both level of spatial ability at age 67 and rate of change in spatial ability over time. These predictors did not explain the interindividual variation observed in the rate of change for verbal and reasoning abilities. Also, while these variables were able to predict level of verbal and reasoning ability at age 67, rate of change in verbal ability was only predicted by cohort and rate of change in reasoning ability was predicted by cohort and education but not by gender. Further research needs to be conducted to identify predictors of individual variation in verbal and reasoning ability beyond that accounted for by cohort, gender, and education. Time-varying predictors such as indicators of socioeconomic status and life satisfaction may have more explanatory power than these time-invariant demographic variables.

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Table 1.

Structure of Seattle Longitudinal Study data collection design (N = 1745)

Cohort	Average Birth Year	Average ages when assessed[a]	SLS Wave	n
1	1889	67, 74, 81	1956, 1963, 1970	62
2	1896	60, 67, 74, 81	1956, 1963, 1970, 1977	111
3	1903	53, 60, 67, 74, 81	1956, 1963, 1970, 1977, 1984	135
4	1910	46, 53, 60, 67, 74, 81	1956, 1963, 1970, 1977, 1984, 1991	234
5	1917	39, 46, 53, 60, 67, 74	1956, 1963, 1970, 1977, 1984, 1991	277
6	1924	32, 39, 46, 53, 60, 67	1956, 1963, 1970, 1977, 1984, 1991	288
7	1931	25, 32, 39, 46, 53, 60	1956, 1963, 1970, 1977, 1984, 1991	236
8	1938	25, 32, 39, 46, 53	1963, 1970, 1977, 1984, 1991	170
9	1945	25, 32, 39, 46	1970, 1977, 1984, 1991	116
10	1952	25, 32, 39	1977, 1984, 1991	64
11	1959	25, 32	1984, 1991	52

[a] Due to the cohort-sequential study design, participants in each cohort were assessed at varying numbers of the ages listed.

Table 2.

Means and Standard Deviations for Verbal, Spatial, and Reasoning Ability

Cohort Age		Cognitive Ability		
		Verbal	Spatial	Reasoning
25	M	54.93	56.52	59.04
	SD	7.32	10.80	7.34
	n	187	187	187
32	M	55.82	56.93	58.40
	SD	6.84	9.23	7.43
	n	393	393	393
39	M	55.79	55.60	56.60
	SD	7.16	9.38	7.68
	n	566	566	566
46	M	55.72	54.74	55.46
	SD	7.34	9.46	7.75
	n	704	704	704
53	M	54.90	53.12	53.66
	SD	7.77	8.93	8.05
	n	791	791	791
60	M	53.37	51.13	51.50
	SD	8.15	8.65	8.04
	n	798	798	798
67	M	50.19	48.22	48.02
	SD	8.81	8.40	8.17
	n	773	773	774
74	M	46.46	45.54	44.79
	SD	9.16	8.08	7.62
	n	560	560	559
81	M	42.50	41.87	42.43
	SD	9.38	7.99	6.96
	n	259	258	257

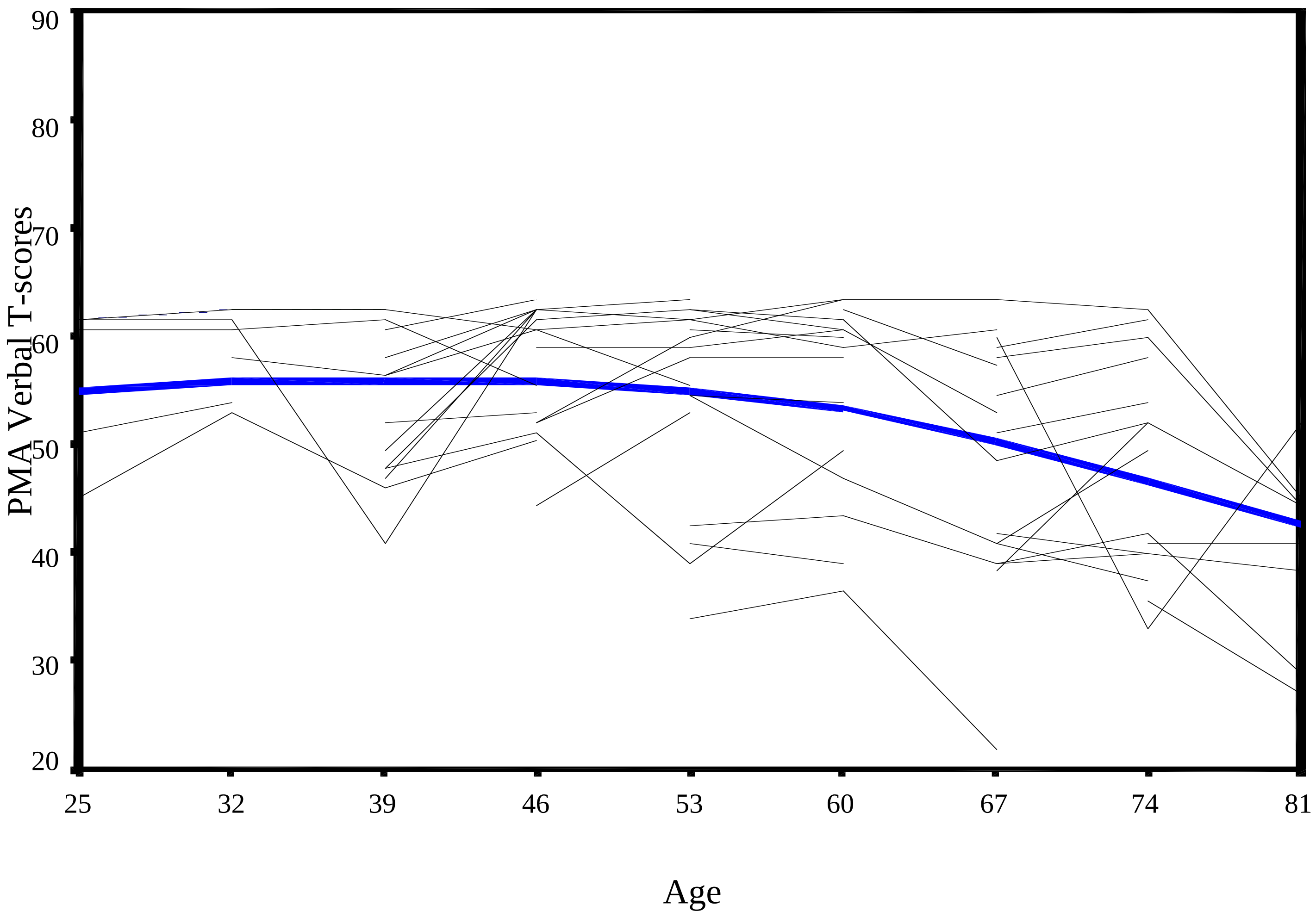

Figure 1. Verbal Ability Trajectories for Random Sample of 50 Participants and Average Verbal Ability over Time

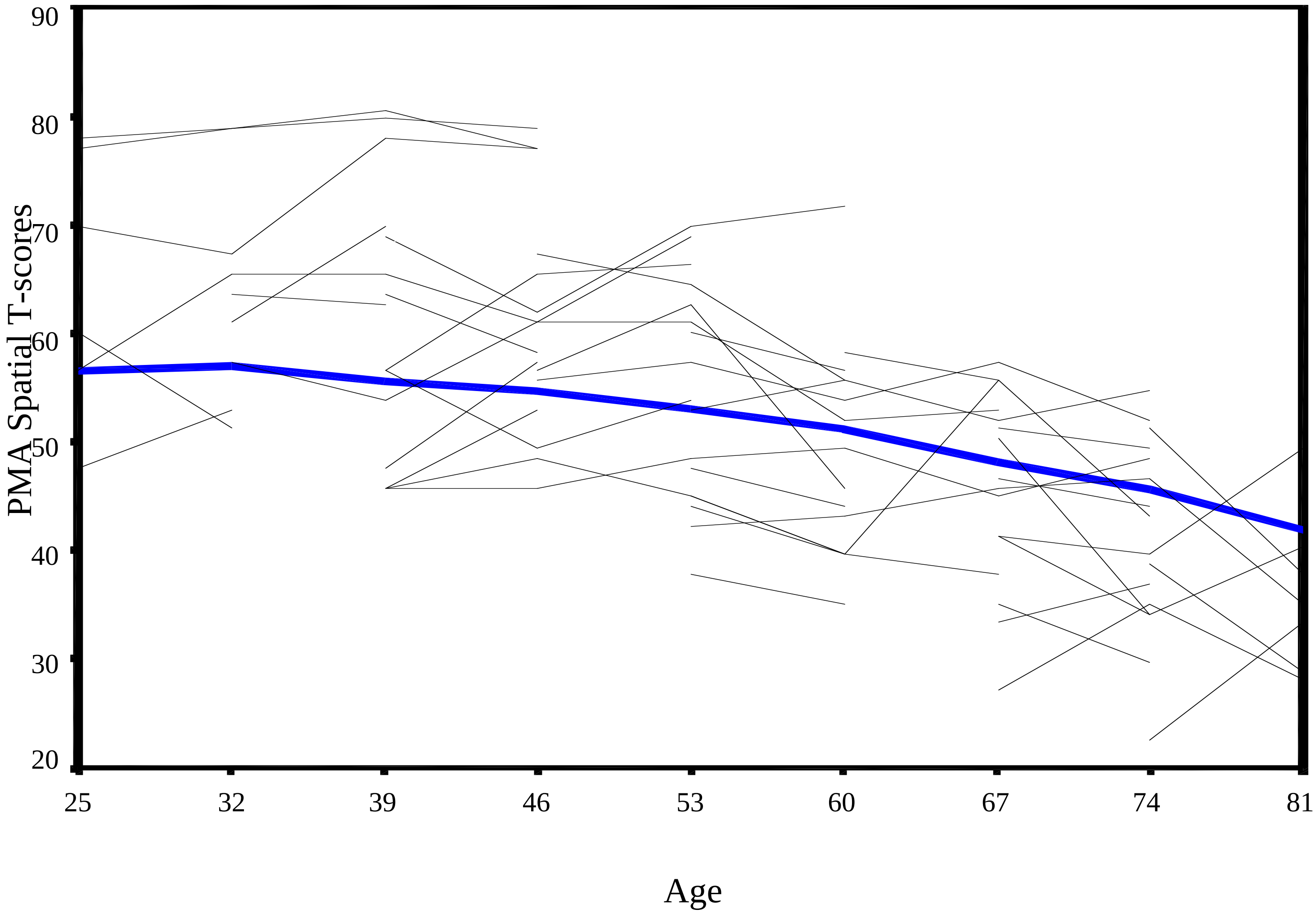

Figure 2. Spatial Ability Trajectories for Random Sample of 50 Participants and Average Spatial Ability over Time

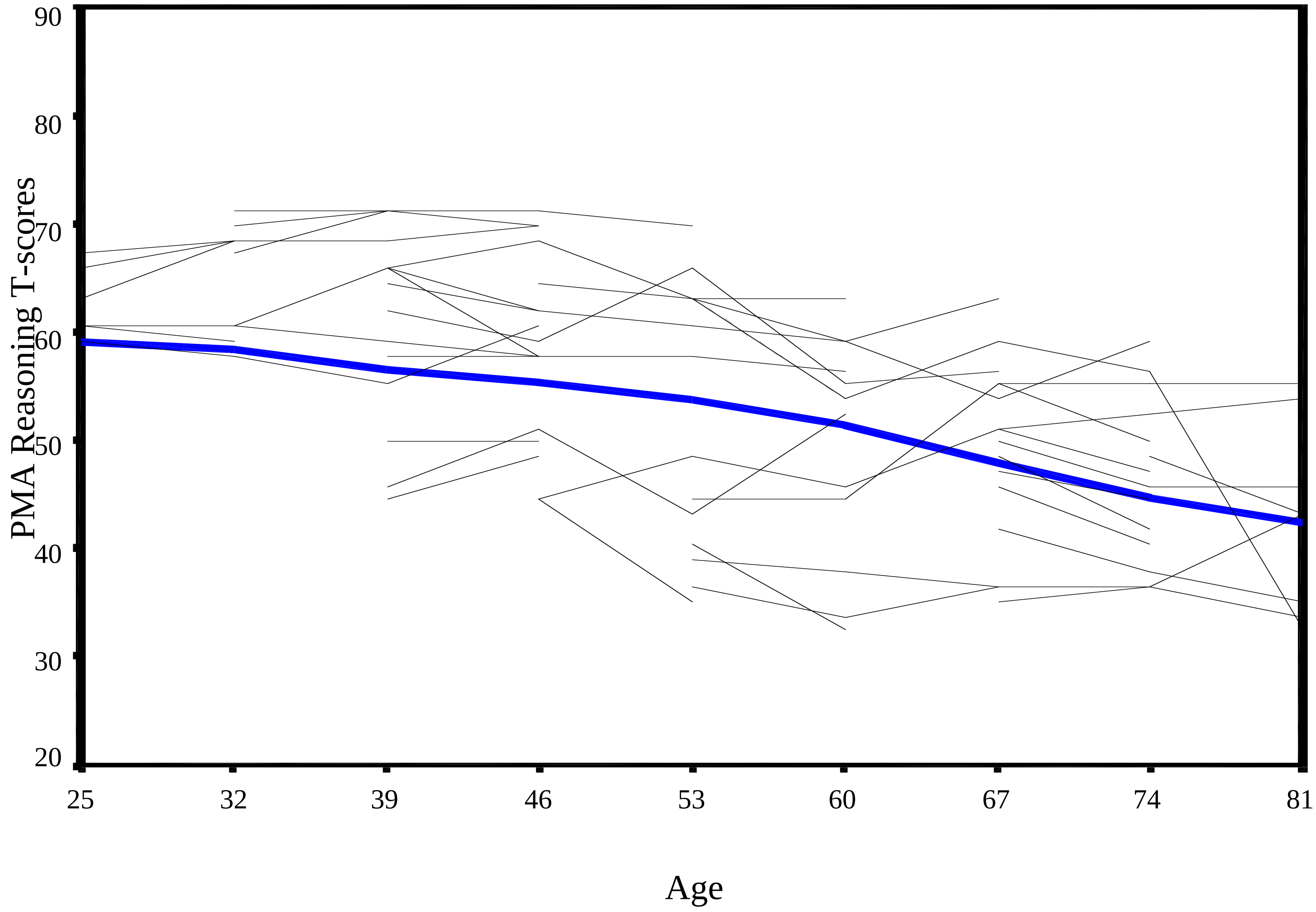

Figure 3. Reasoning Ability Trajectories for Random Sample of 50 Participants and Average Reasoning Ability over Time

Table 3.

Parameter estimates for latent growth models for verbal, spatial, and reasoning abilities with intercept at 67

	Verbal		Spatial		Reasoning	
Parameter Estimate Description	Linear Model[a]	Unspecified Model	Linear Model[a]	Unspecified Model	Linear Model[a]	Unspecified Model
Mean ability at age 67	50.97***	51.12***	48.97***	49.09***	49.66***	49.75***
Mean rate of change	1.02***	2.90***	1.30***	2.19***	1.24***	2.64***
Variance of ability at age 67	63.15***	52.59***	56.77***	50.49***	58.82***	50.95***
Variance of rate of change	1.38***	4.01***	0.45*	1.24**	0.59***	1.58***
Covariance of ability at age 67 and rate of change	-5.71***	-4.37***	-0.86	1.99**	-2.53***	1.34*
Change coefficient at age 25	6.00†	0.52**	6.00†	1.80***	6.00†	1.55***
Change coefficient at age 32	5.00†	0.87***	5.00†	2.18***	5.00†	1.62***
Change coefficient at age 39	4.00†	1.10***	4.00†	2.14***	4.00†	1.55***
Change coefficient at age 46	3.00†	1.14***	3.00†	2.02***	3.00†	1.45***
Change coefficient at age 53	2.00†	1.04***	2.00†	1.60***	2.00†	1.23***
Change coefficient at age 60	1.00†	0.76***	1.00†	1.07***	1.00†	0.88***
Change coefficient at age 67	0.00†	0.00†	0.00†	0.00†	0.00†	0.00†
Change coefficient at age 74	-1.00†	-1.00†	-1.00†	-1.00†	-1.00†	-1.00†
Change coefficient at age 81	-2.00†	-2.15***	-2.00†	-2.82***	-2.00†	-1.87***
Error variance	16.78***	15.07***	24.65***	23.12***	13.57***	12.77***

[a] Signs on parameters related to change were reversed for presentation. † Fixed parameter. * $\underline{p} < .05$; ** $\underline{p} < .01$; *** $\underline{p} < .001$.

Table 4.

Unspecified two-factor latent growth models for verbal, spatial, and reasoning abilities with predictors

Parameter Description	Verbal	Spatial	Reasoning
Mean ability at age 67	52.11***	51.62***	49.84***
Mean rate of change	0.80***	2.21***	1.76***
Variance of ability at age 67	36.09***	44.74***	33.51***
Variance of rate of change	1.73**	0.65	1.14**
Covariance of ability at age 67 and rate of change	-1.60*	2.32***	1.45*
Change coefficient at age 25	2.56***	1.07***	0.79**
Change coefficient at age 32	1.88***	1.57***	1.09***
Change coefficient at age 39	1.34***	1.69***	1.14***
Change coefficient at age 46	1.16***	1.65***	1.15***
Change coefficient at age 53	1.24***	1.37***	1.06***
Change coefficient at age 60	0.92***	1.03***	0.82***
Change coefficient at age 67	0.00†	0.00†	0.00†
Change coefficient at age 74	-1.00†	-1.00†	-1.00†
Change coefficient at age 81	-2.08***	-3.02***	-1.93***
Cohort → Ability at age 67	1.43***	0.95***	1.56***
Cohort → Rate of change in ability	-0.67***	0.10*	-0.10*
Education → Ability at age 67	1.01***	0.27***	0.78***
Education → Rate of change in ability	0.05	-0.06*	0.10**
Gender → Ability at age 67	1.43***	-3.52***	1.73***
Gender → Rate of change in ability	0.13	-0.45*	0.24

† Fixed parameter. * p < .05; ** p < .01; *** p < .001.