Adult Age Trends in the Relations among Cognitive Abilities

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Abstract

Adult age (24-91 years) was examined as a potential moderator of the relations among cognitive abilities in an aggregate dataset based on studies conducted at the Cognitive Aging Lab at the University of Virginia (N = 2,227). A novel approach was applied, in which the manifestations of latent ability factors were free to differ across age groups, and age trends in the interrelations among the factors tested. Contrary to the dedifferentiation hypothesis, there was no evidence for systematic increases in the magnitudes of relations among cognitive abilities. These findings highlight the utility of examining invariance at the construct level.

Keywords: Aging, Dedifferentiation, Cognitive Abilities, Intelligence, Measurement Invariance
Spearman (1904) was the first to establish that all cognitive variables are positively related to one another. He was also the first to propose moderators of the magnitudes of these relations (1927). In particular, Spearman hypothesized that ability level modifies the magnitude of ability covariation, such that ability interrelations are weaker at higher ability levels. Spearman reasoned that, at lower abilities levels, a scarcity of domain general resources constrains performance across a wide range of behaviors, whereas, at higher ability levels, domain general resources are profuse, and behavior is instead limited by the quality of domain-specific structures.

Garrett (1938; 1946, p. 373) applied Spearman’s hypothesis to childhood development, arguing that “abstract or symbol intelligence changes in its organization as age increases from a fairly unified and general ability to a loosely organized group of abilities or factors.” He termed this conjecture the “differentiation hypothesis.” Balinsky (1941) similarly examined Spearman’s hypothesis in both development and aging, and based on his cross sectional analyses of the Wechsler Bellevue standardization sample, observed that (p. 227) “less of the variance can be accounted for by a single factor through the age group 25 to 29, while more and more of the variance can be so accounted for as the higher age groups are reached.” Balinsky concluded that “there is a greater specialization up to a certain point, followed by a later reintegration of the various abilities into a flexible whole.” Hence, the hypothesis that abilities become more highly related with adult age has come to be termed “reintegration” or “dedifferentiation” (also see Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980).

McHugh and Owens (1954) supported the dedifferentiation hypothesis in a 31 year longitudinal sample of adults (the mean age at first testing was 19). Lienert and Crott (1964) found cross sectional support for differentiation followed by dedifferentiation in samples of children, adolescents, and adults, and proposed that because cognitive abilities decline with adult age, their age-based dedifferentiation could be explained by Spearman’s hypothesis that abilities are more related at lower levels. Comprehensively surveying the extant body of research at the time, Reinert (1970) acknowledged a predominance of findings in favor of age differentiation followed by dedifferentiation, but raised concerns about methodological shortcomings and uncertainties and thus concluded “the available data do not allow for a clear-cut description of life-span changes in factor structure of intelligence” (p. 479).
In more recent years, comprehensive developmental theories have specifically posited mechanisms responsible for differentiation-dedifferentiation. Cattell’s (1971, 1987) investment theory explains that in early childhood “a single, general, relation-perceiving ability” (Cattell, 1987, p. 142) is invested in the development of a number of knowledge-based capacities, but that with maturation and experience new investment patterns arise resulting in “correlational disturbances” such that individual differences in cognitive abilities become less related to one another as children mature to adulthood. A number of researchers (Baltes & Lindenberger, 1997; Li, Lindenberger, Hommel, Aschersleben, Prinz & Baltes, 2004; Lovden, Ghisletta, & Lindenberger, 2004) have elaborated on this hypothesis, suggesting that during child development learning supports ability proliferation, whereas during aging common constraints limit the expression of these diverse abilities. S-C Li’s neurocomputational model of cognitive aging (Li & Lindenberger, 1999; Li, Lindenberger, & Sikstrom, 2001) proposes that age-related increases in proportion of random variability in the central nervous system, resulting from decreased efficiency of neuromodulation, may be the basis for this common constraint on functioning. Hofer and Sliwinski (2001) have analytically demonstrated that, all else being equal, if a common constraint were manifest in correlated rates of age-associated cognitive changes, the result would be increased ability interrelations with age, i.e. dedifferentiation.

Recent advances in adult developmental theory have also been met with advances in statistical methodology, and larger and more diverse multivariate cross sectional and longitudinal datasets, which have together produced mixed support for the dedifferentiation hypothesis. Cross sectional patterns consistent with dedifferentiation have been found by Baltes and Lindenberger (1997), Deary, Whiteman, Starr, Whalley, and Fox (2004)\(^1\), de Frias, Lovden, Lindenberger, and Nilsson (2007)\(^2\), and Li et al. (2004), but little or no evidence for a shift in the magnitudes of the correlations was found by Bickley, Keith, and Wolf (1995), Juan-Espinosa, Garcia, Escorial, Rebollo, Colom, and Abad (2002), Lindenberger and Baltes (1997), and Park, Lautenschlager, Hedden, Davidson, Smith, and Smith (2002). Moreover, inspection of the correlations reported in the technical manuals for the nationally representative standardization samples of several popular intelligence batteries (WAIS-III, Wechsler, 1997a; WAIS-R, WAIS-R, WAIS-

\(^1\) Although a longitudinal study, the comparisons addressing dedifferentiation were across cohorts at the follow-up measurement occasion only.

\(^2\) This study was longitudinal in the sense that correlations were computed between initial levels and between rates of change. These correlations, however, were compared across cross-sectional age groups.

Longitudinal studies have also produced mixed findings. Dedifferentiation in the form of increasing ability interrelations was not supported by Anstey, Hofer, and Luszczy (2003), Schaie, Maitland, Willis, and Intreiri (1998), or Zelinski and Lewis (2003; see for a review of key studies). In a series of longitudinal studies, Ghisletta and colleagues (Ghisletta & Lindenberger, 2003; Ghisletta & Lindenberger, 2004; Ghisletta & Ribaupierre, 2005) have found support for their hypothesis that declining process (fluid, or mechanic) aspects of cognition constrain the culture based (crystallized, or pragmatic) aspects of cognition with advancing adult age, by demonstrating that levels of process abilities predict changes in culture based abilities, more so than the converse. While these researchers have argued that this is direct evidence for their conception of dedifferentiation, it is only indirect evidence for dedifferentiation as operationalized as higher ability interrelations with adult age. Based on the extant literature, Reinert’s (1970, p. 482, citations removed) statement therefore seems to remain true that “Optimistic conclusions, however, that the question should not be any longer oriented toward ‘whether’ or ‘whether not’ but rather ‘why’ are not yet justified.”

Given the mixed support for the dedifferentiation hypothesis the goal of this study was to investigate cross-sectional age trends in the magnitudes of correlations among cognitive abilities in a large dataset with a diversity of cognitive variables, representative of ability constructs that are well established within the empirical literature (Carroll, 1993; Salthouse, 2004). Given the limitations of sample size and time lag duration in longitudinal studies, it is likely that powerful tests of dedifferentiation might best be achieved cross-sectionally. Whereas most previous studies have only included a minimal number of age-cohorts from a segment of the adult age range, we examine dedifferentiation across seven contiguous age cohorts spanning close to the entirety of the adult age range. Moreover, we take an analytic approach that allows for changing manifestations of latent abilities with age, and test for noninvariance (dedifferentiation) at the construct level. If dedifferentiation hypotheses are correct, we would expect to find increases in

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3 Cross sectional data may also be advantageous because it enables for more representative sampling due to being unaffected by attrition. Moreover, if longitudinal studies were to document increased interrelations among abilities, it would be unclear whether this reflected actual increases in ability relations or the effect of correlated retest effects. Nonetheless, longitudinal studies are advantageous in that the same people are tracked over time, allowing for more definite inferences regarded actual change.
the relations among abilities (or indicators of abilities) with increasing adult age, particularly for those abilities exhibiting the steepest age-gradients (the largest common constraints).

**Conceptual Approach**

In 1970, referring to the work of Coan, and much his own work, Nesselroade made the observation that “the universe of behaviors is not constant for different age levels and therefore the manifest nature of the factor in behavioral measures will change” (pp. 199-200). Building upon this observation, Nesselroade argued that the invariance of factor loading patterns with age, and the stability of factor scores with age, should be regarded as independent empirical questions. Nesselroade’s assertion is akin to Spearman’s (1927) theorem of “the indifference of the indicator” (Jensen, 1992), which states that the latent ability (in Spearman’s case, general intelligence) remains invariant regardless of the test used to measure it. Whereas Spearman’s theorem explained that the same ability can be manifest in different forms depending on the testing material, Nesselroade’s proposition is that the same ability can be manifest in different forms depending on the individual, group, or stage of development.

Nesselroade (in press) and his colleagues (Nesselroade, Gerstorf, & Hardy, under review) have recently formalized a method for the idiographic measurement of constructs, the relations among which are invariant across individuals. In short, using multiple observations per person (time-series or p-technique data), they demonstrate how affective states that fluctuate around a fixed point in the short term (a property known as stationarity), can be manifest in different ways (i.e. by different factor loadings patterns) for different individuals, but that the pattern of interrelations among these states (the latent variable intercorrelations) remain invariant across individuals. For the current project we apply a similar approach to age groups, rather than individuals, to address Nesselroade’s (1970) proposition4.

**Analytical Approach**

Here we apply a recent method for scaling latent ability constructs (Little, Slegers, & Card, 2006) that is in line with the above stated goals in that it a) allows for the separation of information concerning the absolute magnitudes of manifest variable relations (which is

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4 Because we are interested in the relations among more stable traits (i.e. abilities) we do not take a time series approach, but rather a cross sectional approach. That is, while it is likely that cognitive performance fluctuates in the short term, the mechanisms responsible for short term stationary change are likely to be different from the determinants of absolute levels of ability that change slowly in the long term. We therefore focus this paper on interindividual relations, which may not be ergodic relative to short term intraindividual relations. However, by disaggregating our data into narrow age cohorts, we are still able to allow for potentially changing manifestations of factors with age.
specifically relevant to the dedifferentiation hypothesis) from the relative patterns by which manifest variables are indicative of the latent ability constructs; and b) does not require that an arbitrary parameter (i.e. factor loading, factor variance) be fixed (and consequently set invariant across groups), a convention that has the potential to have nonarbitrary consequences (e.g. Millsap, 2001; Steiger, 2002). The method simply requires that the average of the factor loadings for each latent factor be fixed to 1, which scales the factor variance in a metric that can be directly interpreted as the average amount of variance accounted for by the factor, or the amount of systematic variance in the system of factor indicators (in order for this parameter to be meaningful, we standardize all manifest variables to the same scale prior to analyses). Increases in factor variances across age groups would therefore be indication of dedifferentiation at the level of specific ability indicators. Dedifferentiation at the level of ability interrelations can then be examined using covariances or correlations among the factors. Because the factor loadings (which only indicate relative factor representation) are free to differ across groups, we can be sure that we are examining a broad range of the ability space, as it may be idiosyncratically manifest for each given age group (c.f. Nesselroade, 1970; Nesselroade et al. in press). We further constrain the sum of the indicators’ intercepts to 0, such that the latent mean retains the observed metric of the indicators, and is “optimally weighted” by the factor loadings. Little et al. (2006) have in fact suggested that this nonarbitrary method is ideal for use with Nesselroade’s (in press) idiographic method.

Finally, rather than merely inspecting freely estimated parameter values for the different groups (for which an objective criterion would be lacking), or testing free models against those with cross group equality constraints (which does not directly address the presence or absence of systematic trends), we statistically evaluate the extent to which parameter values systematically differ as functions of age by imposing cross-group linear and quadratic age-based constraints in the form of:


where \( P[A] \) is the parameter value for a given age group (1 through 7), \( P[4] \) is the parameter for the fourth (middle) age group (50-59 years), \( [A] \) is a 7 unit vector corresponding to age group (centered, i.e. -3,-2,1,0,1,2,3), \( [A^2] \) is a 7 unit vector corresponding to age group squared (i.e. 9,4,1,0,1,4,9), and \( L \) and \( Q \) are freely estimated coefficients (similar to multilevel model parameters; McArdle & Hamagami, 1996), corresponding to linear and quadratic effects, both
with standard errors. Significant positive linear effects would support dedifferentiation in the form of increasing parameter magnitudes with age, and significant positive quadratic effects would support dedifferentiation in the form of accelerated increases in parameter magnitudes at later ages (c.f. Frias et al., 2007).

Method

Participants

The dataset was aggregated from seven different studies conducted since 2001 at the Cognitive Aging Lab at the University of Virginia (Salthouse, in press; Salthouse, Atkinson, & Berish, 2003; Salthouse, Berish, & Siedlecki, 2004; Salthouse & Ferrer-Caja, 2003; Salthouse, Nesselroade & Berish, 2006; Salthouse, Pink, & Tucker-Drob, under review; Salthouse, & Siedlecki, in press; Salthouse, Siedlecki, & Krueger, 2006). Participants were recruited with newspaper advertisements, flyers, and referrals from other participants. To avoid an over-representation of students, the current dataset was restricted to adults 24 years of age and older. Participants 92 years of age and older were excluded because there were too few participants (N = 9) in this age range and the analyses required the sample to be broken down into narrow age groups. This resulted in a final working sample of 2,227 participants. Participant characteristics, are presented in Table 1.

One way of evaluating the selectivity of a sample involves comparing scores on a number of standardized measures to the scores for the normative sample of the WAIS III (Wechsler, 1997a) and WMS-III (Wechsler, 1997b), which were matched to the US population on a number of demographic variables including gender, ethnicity, years of education, and region of residence in the country. Age-adjusted scaled scores have means of 10 and standard deviations of 3 in the normative sample, but the scaled score means in the current sample were all above 11. Although this indicates that the individuals in this sample were functioning above the average of the normative sample, this was true to nearly the same extent at all ages as the correlations between age and the scaled scores were all quite small. Results from this dataset may therefore be most applicable to people with higher-than-average levels of functioning, but the age comparisons should be meaningful because there is little evidence that participants of different ages were differentially representative of their age groups.

Measures
All of the studies included a battery of between 11 and 13 cognitive tests (3 or 4 for each ability) selected to measure fluid reasoning (Gf), spatial reasoning (Gv), verbal knowledge (Gc), processing speed (Gs), and episodic memory (Gm). Because the pattern of missingness in the data was largely a function of the study to which participants were assigned, full information maximum likelihood estimation was used to handle missing data under the missing at random assumption (c.f. Salthouse, 2004, 2005). The specific cognitive tests are described in earlier publications (e.g. Salthouse, 2004). All variables were standardized to the IQ metric (mean = 100, SD = 15) for the youngest age group.

Reliabilities and standard deviations of the cognitive variables by age group are presented in Table 1. It can be seen that the reliabilities were all very high, and that there was little evidence of systematic trends in the magnitudes of standard deviations or reliabilities with age.

Results

All models were fit as multiple group models, with group membership determined by age at testing, as in Table 1. To avoid type I error as a result of the large number of statistical comparisons, all confidence intervals and alpha values were set to 99% and .01 respectively.

The first model fit was one in which factor loadings were constrained to be invariant across groups, and factor variances and covariances allowed to vary freely across groups (ChiSq = 2088.7, df = 790, RMSEA = .07). In a second model these factor loading equality constraints were removed, resulting in a substantial improvement in model fit (ChiSq = 1582.0, df = 724, RMSEA = .061), suggesting that the behavioral manifestations of the factors differs by age group. For the remaining models, loadings were allowed to vary freely across groups.

In order to determine whether the amount of systematic variance in the systems of factor indicators differed as functions of age, a model with linear and quadratic cross group parameter constraints on the factor variances was fit. Two linear parameter constraints were significantly different from zero and retained. The remaining linear and quadratic parameter constraints were removed (resulting in cross group equality constraints for these variances). The resulting model (ChiSq = 1629.0, df = 752, RMSEA = .061) fit better than a model in which all factor variances were constrained to equality across groups (ChiSq = 1734.0, df = 754, RMSEA = .064), and no worse than a less parsimonious model in which factor variances were freely estimated for each age group (reported above). This structure (free loadings, linear age trends in two variances) was retained for the remaining analyses.
In a final set of models, age relations in factor interrelations (correlations) were examined. Because we already had information about the magnitudes of individual differences (from the factor variances), correlations were chosen so as to focus exclusively on the degrees of correspondence between the relative orderings of individuals. A model with linear and quadratic parameter constraints on the correlations was fit, resulting in two significant linear parameters and one significant quadratic parameter. With these parameters retained, a final model (ChiSq = 1695.1, df = 809, RMSEA = .059) was constructed which fit better than a model in which correlations were constrained to equality across groups (ChiSq = 1719.5, df = 812, RMSEA = .059) and no worse than a less parsimonious model in which correlations were free to vary across groups (reported earlier).

Age trends in key parameters of the final model are presented in Figure 1. In panel A it can be seen that the means of all factors except for the Gc factor exhibit monotonic negative age trends, which based on Spearman’s hypothesis, and recent versions of the dedifferentiation hypothesis, we would expect to be accompanied by increasing interrelations. In panels B through F it can be seen that the relative loadings of the indicators on the factors drift to some extent with age, but on the whole exhibit a fair amount of stability. Finally, panels G and H show that, in contrast to the dedifferentiation hypothesis, the common variances in the systems of Gc and Gv indicators actually decrease with age, the Gv-Gc relation decreases with age, and the Gf-Gc relation is at its peak in middle adulthood. In the final model, the linear age trend in the Gm-Gc relation is no longer significant. The remaining factor variances and factor interrelations are invariant across age groups.

Discussion

The major finding from the analyses reported in this project was that there was little evidence supportive of the dedifferentiation hypothesis that the relations among cognitive abilities systematically increase with adult age. In fact, of the 15 parameters representative of the magnitudes of relations among indicators of abilities (factor variances) and among latent abilities themselves (factor intercorrelations) only 4 were found to vary according to age, and these were all in directions opposite to that predicted by the dedifferentiation hypothesis. We do not have an explanation for why this was the case, but because these trends were opposite to those expected, we can be confident that dedifferentiation was not supported by these data.
The analytical method that we employed was novel in that, instead of requiring factor loadings to remain invariant, as is conventionally the case, we allowed them to vary freely according to age group. This allowed for the behavioral manifestations of the abilities to differ by age, while invariance of the relations among the unobserved factors was tested. While this premise was suggested by Nesselroade (1970) nearly 40 years ago, this is to our knowledge among the first attempts to empirically evaluate it. We do not have a specific hypothesis for why the factor loadings differed by age as they did here, however our employment of this technique ensured that the full amount of common variance was sampled in each age group (regardless of its source). This is important, because restricting the factor space only to the variance that is consistent across age groups, could have distorted the findings.

The failure to find increases in the strengths of the interrelations among variables and among constructs is inconsistent with the dedifferentiation hypothesis, and instead suggests that variables and constructs retain their distinctiveness (and perhaps become even more distinct) across nearly all of adulthood. There is considerable evidence that age-related influences on different cognitive variables are not independent (e.g., Salthouse, 2004, 2005; Salthouse & Ferrer-Caja, 2003). However, the current results suggest that even if broad or systemic influences are operating to affect average levels of functioning, they do not necessarily result in alterations in the structure or organization of cognitive abilities.
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<td>Logical Memory (Gm)</td>
<td>0.77</td>
<td>15.00</td>
<td>0.74</td>
<td>15.00</td>
<td>0.77</td>
<td>14.63</td>
<td>0.75</td>
<td>14.20</td>
<td>0.72</td>
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<td>Paired Associates (Gm)</td>
<td>0.74</td>
<td>15.00</td>
<td>0.84</td>
<td>16.50</td>
<td>0.75</td>
<td>15.47</td>
<td>0.80</td>
<td>15.59</td>
<td>0.75</td>
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<tr>
<td>Pattern Comparison (Gs)</td>
<td>0.75</td>
<td>15.00</td>
<td>0.80</td>
<td>15.77</td>
<td>0.83</td>
<td>15.18</td>
<td>0.81</td>
<td>13.48</td>
<td>0.78</td>
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<tr>
<td>Letter Comparison (Gs)</td>
<td>0.91</td>
<td>15.00</td>
<td>0.91</td>
<td>13.98</td>
<td>0.93</td>
<td>13.79</td>
<td>0.93</td>
<td>13.78</td>
<td>0.93</td>
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<tr>
<td>Digit Symbol (Gs)</td>
<td>15.00</td>
<td>17.44</td>
<td>16.37</td>
<td>15.77</td>
<td>14.56</td>
<td>15.00</td>
<td>16.85</td>
<td>17.98</td>
<td>-0.59</td>
</tr>
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</table>
Note: SS = Scaled Score. \( r \) = correlation. \( * \) = correlation significantly different from 0 at \( p<.01 \). \( r_{OE} \) = odd-even split half reliability corrected with the Spearman-Brown prophecy formula. Reliabilities for the Digit Symbol test could not be computed because it does not contain distinct items. SD = Standard Deviation. Descriptive statistics are based on raw data (with pairwise deletion to handle missing data), whereas the results displayed in Figure 1 are based on Full Information Maximum Likelihood estimation.
Figure Caption

Figure 1. Parameters plotted according to age group, as indicated by the final model (Chi Squared = 1695.1, df = 809, RMSEA = .059, CFI = .95, TLI = .95). Panel A: Age trends in factor means. Panels B-F: Age trends in factor loadings for indicators of Gf (B), Gc (C), Gs (D), Gm (E), and Gv (F). Panel G: Age trends in factor variances. Panel H: Age trends in factor intercorrelations.