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Development of Intellectual Abilities in Old Age:
From Age Gradients to Individuals

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Abstract

According to two-component theories, intellectual development across the lifespan is based on dynamic interactions between biology-driven fluid abilities (broad Gf, or the mechanics of cognition) and culture-driven crystallized abilities (broad Gc, or the pragmatics of cognition). In this chapter, we advocate a stronger reliance on intra-individual patterns and changes to overcome some of the conceptual and methodological problems associated with the investigation of interactions between the mechanics and the pragmatics in adulthood and old age. First, evidence about cross-sectional and longitudinal gradients of the pragmatics and mechanics during adulthood and old age is summarized. Second, we note that an improved understanding of these gradients requires efforts to decompose time/age into constituent components such as senescence, retest effects, terminal decline, cohort differences, and selective attrition. Third, the dedifferentiation hypothesis of intelligence in old age is framed in terms of mechanics/pragmatics interactions, and recent attempts to directly model these interactions using advanced structural equation modeling techniques are described. Fourth, we argue that the study of interindividual differences in a developmental context is often used to investigate substantive hypotheses that are ultimately located at the level of intraindividual patterns of changes. Therefore, interindividual-difference methods need to be complemented by the study of intraindividual variability, patterns, and changes. Intraindividual data would enable researchers to assess the amount and correlates of sample heterogeneity in patterns of performance and change, and to gauge the validity of interindividual-difference methods. The chapter ends with a discussion of methods for the study of intraindividual patterns of change.

The present chapter has two main objectives: (a) to summarize psychometric theorizing and evidence about intelligence in adulthood and old age, and (b) to promote a person-centered (idiographic) approach to the psychometric study of adult intellectual development. Both objectives can be framed in the context of two-component models of lifespan cognition. These models posit that lifespan development of intellectual abilities reflects two fundamental and dynamically interacting influences, the biological and the cultural. Historical examples of such models can be found in Tetens' (1777) differentiation between relative and absolute mental capabilities and in Hebb's (1949) distinction between intellectual power and intellectual products (Hebb, 1949). Typical contemporary examples include the theory of fluid and crystallized intelligence (i.e., Gf-Gc theory; Cattell, 1971; Horn, 1982; Horn & Cattell, 1966, 1967), the PPIK theory (Ackerman, 1996), and the decomposition of cognition into the mechanics and the pragmatics (Baltes, 1987; Baltes, Lindenberger, & Staudinger, 1998). Though the scope, terminology, and details vary considerably across the different versions, they all share fundamental assumptions beyond mapping intelligence onto two underlying components (see Baltes et al., 1998; Lindenberger, 2001).

In general, these models assume that, during ontogeny, there is an "investment" of the biological component (i.e., heredity and other factors related to neurophysiological status) into bodies of biographically acquired knowledge through processes of socialization, experience, and education (i.e., investment theory; Cattell, 1971). These investment processes lead to inter-and intra-individual differences in the acquisition and organization of procedural and declarative knowledge. The biological component and its mental correlates are held to decline after maturity. The cultural component, however, continues to increase over the lifespan as long as knowledge maintenance and knowledge acquisition outweigh losses in the biological component.

Two-component theories thus dispute the validity of a unitary general intelligence construct (i.e., g) in understanding the dynamics of intellectual lifespan development; that is, at least two broad categories of ability factors are deemed necessary to capture the basic properties of intellectual lifespan development. The first category of ability factors represents measurable outcomes of the influence of the biological component on development. It manifests itself in cognitive processes involving extrapolation, reorganization, and transformation of novel information (i.e., reasoning or Gf; Cattell, 1971; Horn, 1982; Horn & Cattell, 1966, 1967), or in broader ensembles of basic information processes including working memory, processing speed, and aspects of coordination and control of processing (e.g., Horn, 1985; Baltes, 1987; Baltes et al., 1998). Henceforth, these processes are referred to as the "mechanics" of intelligence (cf. Baltes, 1987). The second and more disparate category of ability factors refers to procedural and declarative knowledge common to a given culture (i.e., Gc), to specialized knowledge such as occupational expertise (e.g., Ackerman, 1996), and to knowledge about the meaning and conduct of life (e.g., Baltes et al., 1998). Henceforth, these applications are collectively referred to as the "pragmatics" of intelligence.[1]

In this chapter, we summarize the available cross-sectional and longitudinal evidence pertaining to the mechanic and pragmatic age gradients in adulthood and old age. In this vein, we show that improvements in the understanding of these gradients require efforts to decompose the time/age dimension into constituent components, such as terminal decline, selective attrition, retest effects, and cohort differences. In addition, recent attempts to directly model interactions between the mechanics and pragmatics in old age are described (Ghisletta & Lindenberger, 2003) and the dedifferentiation hypothesis is framed in terms of these interactions. Furthermore, we point out that theories about intellectual development are generally anchored at the intraindividual level. Therefore, the use of methods relying on interindividual differences should be complemented by methods that are better suited for assessing change in structure at this intraindividual level. We draw attention to a select toolbox of intra-person, or idiographic, psychometric methods and note that their application may allow researchers to investigate the amount and nature of heterogeneity in patterns of change, and to gauge the validity of methods based on interindividual differences.[2]

The Age Gradients of the Mechanics and the Pragmatics

Cross-sectional evidence. The Seattle Longitudinal Study (SLS; Schaie, 1994, 1996) is perhaps the most comprehensive source on adult age gradients of intelligence. From young adulthood to old age[3], the cross-sectional findings of the SLS display continuous decrements for four mechanic ability constructs; perceptual speed, inductive reasoning, spatial orientation, and verbal memory. In contrast, the more pragmatic abilities, verbal knowledge and numerical ability, show increase in young adulthood with an asymptote in middle adulthood, followed by a plateau until modest decrements are discernable in old age.

The steady negative age differences observed for the mechanics in the SLS study are corroborated by an enormous mass of cross-sectional evidence. In their large-scale meta-analysis, Verhaeghen and Salthouse (1997) reported age correlations of -.52 for processing speed, -.40 for reasoning, -.38 for spatial ability, -.33 for episodic memory, and -.27 for short-term memory. Importantly, significant non-linear trends were also observed, at least for reasoning, processing speed, and episodic memory, suggesting accelerating age-related decline over the adult lifespan. For the pragmatics, the cross-sectional pattern of growth during young adulthood followed by stability is present in most studies, but the age of peak performance differs somewhat across studies (e.g., Nilsson et al., 1997; Park et al., 2002; Rönnlund, Nyberg, Bäckman, & Nilsson, 2003). Figure 1, from Park et al. (2002), may serve as an example of the typical age gradients observed. The figure depicts cross-sectional age gradients based on multiple indicators for five abilities. Working memory, short-term memory, episodic memory, and processing speed display monotonic decline, whereas verbal knowledge shows increase or stability at least into the 70s. This interaction constitutes the "classic aging pattern" (Botwinick, 1977) or the "hold vs. no-hold pattern" of adult intellectual development (e.g., Hunt, 1949; Wechsler, 1955; see also Jones & Conrad, 1933).

The major source of discrepancy in available cross-sectional data concerns the onset and amount of decline in the pragmatics during the transition from young-old to old age (see Bäckman, Small, Wahlin, & Larsson, 2000 for review; cf. Salthouse, 2003). Whereas some studies report small age differences during this period (e.g., Baltes & Lindenberger, 1997; Christensen, 2001; Nyberg et al., 2003; Park et al., 2002), or are suggestive of relatively large decrements appearing within, but not before, old age (e.g., Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994, 1997), others report age-related differences starting at about age 50 (Bäckman & Nilsson, 1996; Wechsler, 1997). In any case, it seems safe to conclude that the preservation of the pragmatics often observed for groups of young-olds does not generalize to groups of old individuals (cf. Bäckman et al., 2000).

Longitudinal evidence. The longitudinal findings from the SLS study suggest a greater degree of similarity between mechanic and pragmatic age gradients. The latent construct abilities show decelerating increases across young adulthood, peaks in middle age, and accelerating declines thereafter. As a notable exception, perceptual speed shows continuous decrements beginning in early adulthood. The general pattern of rising and falling lifespan curves is discernable in most other studies (e.g., Giambra, Arenberg, Zonderberg, Kawas, & Costa, 1995; Rönnlund et al., 2003; Wilson et al., 2002; Zelinski & Stewart, 1998). For the pragmatics, the bulk of evidence suggests that the SLS observation of an onset of decline in as early as middle adulthood is rather atypical. The dominant pattern is one of remarkably stable, or even increasing, performance until young-old or old age (Christensen, 2001; Rönnlund et al., 2003; Singer, Verhaeghen, Ghisletta, Lindenberger, & Baltes, 2003; Wilson et al., 2002).

At first glance, large amounts of evidence on longitudinal developmental gradients of intelligences are available. Consider, for example, an impressive and recent study by

McArdle, Ferrer-Caja, Hamagami, & Woodstock (2002), including individuals (n = 1193) from early childhood to old age. By combining cross-sectional and longitudinal information in a latent growth curve modeling framework, the authors showed that different growth curves had to be specified for the mechanics and pragmatics of intelligence (e.g., for Gf and Gc). This evidence clearly underscores the multidirectionality of intellectual development predicted by two-component theories of cognition.

Summary. Clearly, plotting average age gradients, cross-sectional or longitudinal, as a function of chronological age serves important descriptive purposes. However, it is well known that chronological age is a fallible and incomplete index of developmental change. To substantively interpret and understand developmental gradients of cognition, it is necessary to carefully unpack the ingredients contributing to a particular score, for a particular individual, at a particular point in time. Aside from components with a relatively strong intrinsic relation to chronological age, such as maturation and senescence, cognitive developmental gradients are influenced by a wealth of additional developmental sources such as learning history, health status, distance from death, onset of pathology, and non-normative events, all of which are less closely linked to chronological age. In the following, we discuss these influences under three headings that have become increasingly familiar to researchers in the field: cohort differences, retest effects, and selective attrition.

Cohort Differences

Substantial performance improvements have been observed on various tests of intellectual functioning during the last century, for example at time of recruitment into military service (Flynn, 1987; Neisser, 1998; Raven, 2000). These “time-lagged” improvements, together with the evidence of, mostly positive, cohort gradients provided the SLS (Schaie, 1994, 1996), point to the potential severity of confounding within-cohort developmental change with between-cohort secular trends when comparing age differences at a single point in historical time. For example, when cohort gradients are linear and positive (i.e., if they favor later born cohorts at a constant rate), cross-sectional age gradients may overestimate the magnitude of true age-related changes (see Baltes, Reese, & Nesselroade, 1977, for an early illustration). Furthermore, it is conceivable that cohort differences may originate from multiple sources, that the effects may operate additively, in opposing directions, or interactively, and that they may differ in constellation and nature across cohorts and abilities. In the SLS, for example, approximately continuous improvements across cohorts born from 1907 to 1966 were found for inductive reasoning, verbal memory, and spatial orientation, amounting to around 1.5 SD for the former two abilities. In contrast, for verbal ability, numerical ability, and perceptual speed, there was an advantage for cohorts born early in the twentieth century, followed by a period of no differences in cohort effects, and then even disadvantages for later born generations. In a similar vein, when summarizing a great amount of data, Raven (2000) observed modest cohort effects on the Mill Hill vocabulary scale but substantial effects on the Ravens Progressive Matrices (see also Thorndike, 1977). Hence, if one were to adjust cross-sectional age differences for cohort effects, these gradients would probably change in ways that were more complex than a constant reduction across abilities and ages.

Retest Effects

Retest effects denote the possibility that, in repeated measures designs, prior exposure to a test or task may alter performance at retest, either through practicing task-relevant elements of skill or through a broad range of reactive effects such as general familiarization with the testing situation or (possibly negative) alterations in motivation and interest. Thus, if retest effects operate in studies of intellectual age gradients, it is important to estimate their directions, magnitudes, and correlates. For example, longitudinal findings showing a late onset of decline in the mechanics might be a result of retest effects; that is, these effects may mask decrements in the underlying ability dimensions (e.g., beyond the level practiced elements of skill; cf. Salthouse, 1991, 2000).

Retest effects have typically been regarded as threats to the internal validity of longitudinal studies. However, it is quite possible that they also operate in cross-sectional designs. For example, prior acquaintance with test taking and the nature of problem structures may be associated with systematic individual differences, thereby constituting a major ingredient in cohort effects. In this respect, longitudinal designs are theoretically superior because, with proper design precautions and analysis techniques, retest effects can be estimated and statistically controlled. In practice, however, this has rarely been done (but see Lövdén, Ghisletta, & Lindenberger, 2003; McArdle et al., 2002; Rabbitt, Diggle, Smith, Holland, & Innes, 2001; Rönnlund et al., 2003; Schaie, 1988; 1996; Wilson et al., 2002).

One method of estimating the magnitude of retest effects on the sample level is to compare the performance in a group of returnees with that of a cohort-matched and not previously tested sample of individuals (Schaie, 1988). If attrition effects (see next section) are negligible or, better still, also estimated and taken into account, then differences between samples should reflect retest effects (and error). In a recent study using this method, Rönnlund et al. (2003) examined semantic memory performance (i.e., a composite of verbal fluency and knowledge) and episodic memory performance (i.e., a composite of cued & free recall) in two population-based samples of adults from ten cohorts, 35-80 years old at baseline (total n = 1788). The measurement interval was five years. Adjusting for retest effects critically altered the observed longitudinal gradients. Average retest effects observed for episodic memory were reliable (0.15 SD). More importantly, statistical control of these effects accentuated the decline observed for older groups of individuals, and converted the continuous increments from age 35 to age 60 to a pattern of stable performance across this age period. In contrast, retest effects for the semantic memory factor were negligible (.04 SD) and did not affect the raw longitudinal curves of growth and decline in any major way. Thus, retest effects may appear even with long retest intervals such as five years, they may vary in magnitude across abilities (see also Lowe & Rabbitt, 1998; Wilson et al., 2002), and failure to explicitly model them may underestimate the magnitudes of average decline in some, but not all, instances (see also Rabbitt et al., 2001). Taken together, it is evident that retest effects, when left unanalyzed, may limit substantive conclusions based on raw longitudinal data.

Selective Attrition

A common finding in longitudinal studies is that individuals who drop out between measurement occasions perform, on average, at lower levels than returnees (e.g., Lindenberger, Singer, Baltes, 2002; Rönnlund et al., 2003; Zelinski & Burnight, 1997). Furthermore, individuals who drop out often evince greater cognitive decline during measurement intervals prior to dropout (e.g., Bosworth & Schaie, 1999; Colsher & Wallace, 1991; Siegler & Botwinick, 1979; Singer et al., 2003). Such nonrandom attrition effects (i.e., attrition is related to variables of interest) may occur for a variety of reasons that can be grouped into two additive constituents: mortality-related selectivity and experimental selectivity (Baltes & Labouvie, 1973; for computational separation see Lindenberger et al., 2002).

Experimental selectivity occurs whenever individuals who are alive but unable, or unwilling, to continue participation differ systematically from those who do participate. Mortality-associated selectivity, on the other hand, occurs whenever individuals in close proximity to death (e.g., participants that do not return because they are deceased) differ on relevant attributes from individuals with a longer distance to death. In principle, both types of selectivity may refer to attrition related to level of ability, change of ability level, or both.

Whereas experimental selectivity poses an internal validity threat to longitudinal studies, as it reflects the inability of the experimenter to randomly assign surviving individuals to a returnee status, mortality-related selectivity is a player in the population league. To capture this population-heterogeneity aspect, Kleemeier (1962) coined the term “terminal decline”, arguing that aging-related changes in old age should be distinguished from the changes associated with impending death (see also Riegel & Riegel, 1972). Specifically, changes associated with terminal decline may reflect other causal structures than aging induced changes; for example, specific cognition-influencing diseases and global breakdowns of the biological system (e.g., Berg, 1996; cf. Thaler, 2002).

Mounting evidence also points to an association between performance on intelligence tests and longevity (e.g., Small & Bäckman, 1997; Singer et al., 2003) as well as between changes in intelligence and mortality (e.g., Bosworth & Schaie, 1999, Maier & Smith, 1999; Singer et al., 2003; see Berg, 1996; Small & Bäckman, 1999 for overviews). For example, Singer et al. (2003) reported that, in a group of individuals (n = 516) aged 70 to 103 at first occasion from the Berlin Aging Study (BASE), those who died within six years after cognitive performance was initially measured (n = 277), showed lower initial performance compared to individuals who were still alive six years later (n = 229). Furthermore, greater average decrements over the four years after the first measurement occasion were observed for individuals who died during the four to six years after the initial measurement on measures of perceptual speed and knowledge, as compared to those who survived and participated in the six-year follow-up. Attrition due to factors other than mortality (i.e., experimental) was only related to initial level, and the magnitudes of both selectivity effects were greater for old than for young-old subgroups of the total sample.

Clearly, selectivity limits the generalizability of the results obtained in longitudinal studies because the observed sample is no longer representative of the original sample. Experimental selectivity poses a serious threat to the external population validity of longitudinal findings as it may affect the means, variances, covariances, and subsequently correlations of the variables under study (e.g., Little, Lindenberger, & Maier, 2000). The existence of mortality-related selectivity, on the other hand, is suggestive of profound heterogeneity in development and issues warnings against the uncritical practice of averaging individual differences in intelligence over a particular age/time (cf. Bäckman et al., 2000). For example, when rigorous health screening is applied, old age groups may not be representative of younger age groups, and the difference in sample composition may result in an underestimation of cross-sectional population gradients. That is, individuals surviving into late life who are ready to participate in cross-sectional studies may constitute a select group in terms of multiple, correlated socio-economical, biological, and cognitive characteristics. On the other hand, the magnitude of age-related decrements may also be overestimated, in particularly in old age when selectivity effects increase dramatically (because mortality risk is associated with age). That is, when averaging performance of relatively healthy individuals and individuals experiencing terminal decline, aging-related changes and dying-related changes are confounded. In this vein, there is persistent evidence for a prolonged preclinical phase of dementia (i.e., when cognitive deficits are present but have not yet have reached a diagnostic threshold; cf. Elias et al., 2000; Small, Fratiglioni, Viitanen, Winblad, & Bäckman, 2000). Because the incidence of dementia is markedly higher in old age, including an unknown proportion of individuals with preclinical signs of dementia may again overestimate the "pure" aging-intelligence relation (Sliwinski, Lipton, Buschke, & Stewart, 1996; but see Bäckman et al., 2002). And again, as is true for age-associated heterogeneity phenomena, the admixture of individuals with signs of terminal decline and preclinical dementia will increase variances and correlations, especially in age-heterogeneous samples (e.g., Bäckman et al., 2002; Sliwinski et al., 1996)

In sum, two opposing selectivity effects appear to operate in aging populations, one resulting in exaggerated age-performance relations in old age owing to preclinical dementia and impending death, and the other leading to attenuated age-performance relations because individuals in older age groups may be more positively selected than individuals in younger age groups (cf. Bäckman et al., 2000). Clearly, these considerations deconstruct the common assumption of a homogeneous population, and underscore the need to describe and explain the developmental characteristics of the individuals that compose the samples.

Summary

Apparently, understanding the developmental gradients of intellectual abilities is a tricky business. Internal validity threats impede generalization across age groups and abilities, and developmental changes appear to be heterogeneous by nature. Various influences may work simultaneously in opposing directions, and their magnitude may differ as a function of age and study. Thus, an improved understanding of the developmental gradients of intelligence requires consideration of all these factors in concert and, as a best-case scenario, within a unitary methodological framework. Recent developments in latent growth curve modeling and multilevel modeling are promising candidates for such frameworks (see Collins & Sayer, 2001; Diggle, Liang, & Zeger, 1994; Little, Schnabel, & Baumert, 2000).

Interactions between Mechanics and Pragmatics in Old Age: The Dedifferentiation Hypothesis

Couched in terms of lifespan intellectual development, the differentiation/dedifferentiation hypothesis asserts that the functional organization of intellectual abilities is relatively compressed in childhood, undergoes decompression (differentiation) during maturation (e.g., Garrett, 1946), and becomes compressed (dedifferentiated) again in old age (e.g., Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980; Reinert, 1970). As such, the hypothesis conveys a dynamic view of the structure of intellectual abilities and the underlying information-processing mechanisms. During childhood and old age, the operations and expressions of the diversity of cognitive abilities are assumed to be subject to strong and fundamental systemic constraints (i.e., the developmental status of biological substrates of intelligence). In contrast, during maturation and in adulthood, this common constraint is relaxed and other factors, such as interest, motivation, and occupational/educational opportunities, occupy more prominent roles as determinants of intellectual development, leading to greater diversity in levels of functioning in different abilities.

The dynamic view of the structure of intelligence conveyed by the differentiation/dedifferentiation hypothesis was sparked by early findings of a decrease in the amount of variance accounted for by g and decreases in correlations across different abilities from childhood to early maturity (e.g., Garrett, 1946), and by corresponding findings of increases in old age (e.g., Reinert, 1970). With respect to covariance dedifferentiation in old age, more recent empirical evidence have generally bolstered the early findings (e.g., Baltes & Lindenberger, 1997; Hultsch, Hertzog, Dixon, & Small, 1998; Li et al., in press; Mitrushina & Satz, 1991; Schaie, Maitland, Willis, & Intrieri, 1998; see Li & Lindenberger, 1999 for an overview), but some prominent exceptions are also available (e.g., Juan-Espinosa et al., 2002; Park et al., 2002). At least to some extent, the somewhat mixed evidence may emanate from methodological problems surrounding the empirical testing of the dedifferentiation hypothesis and the comparison of results across studies, including factors such as sample composition, unsuitable age groups, and restriction in range (e.g., Deary et al., 1996).

An essential corollary of old-age dedifferentiation is the hypothesis that the entire space of intellectual abilities is increasingly dominated by a common source (or an ensemble of common sources) of intellectual development. Framed in terms of the distinction between the mechanics and pragmatics of cognition, old-age decrements in pragmatic abilities are assumed to be induced by the mechanic decline (Ghisletta & Lindenberger, 2003). In other words, the biological changes reflected by decline in mechanic abilities eventually limit the expression and accumulation of pragmatic knowledge in old age when the mechanic abilities fall below certain threshold levels. At higher levels of mechanic functioning, development of the pragmatics is more dependent upon cultural-experiential factors, and less dependent upon biological factors (but see Hambrick & Engle, 2002).

This dynamic account should perhaps be distinguished from the alternative non-dynamic dedifferentiation notion of a common developmental cause operating with constant force throughout the adult lifespan. Specifically, given that individual differences in rates of aging are present, rank ordering of individuals should be increasingly saturated by aging-related variance across age/time. Accordingly, if age-related changes in different abilities are driven by a common source (i.e., if rates of aging in different abilities are associated), correlations across abilities should increase as a function of time/age (Hofer & Sliwinski, 2001; see also Li & Schmiedek, 2002). Thus, strictly speaking, the notion of an increased dominance of common constraint is not necessary to explain a pattern of covariance dedifferentiation. However, the dynamic notion has the additional benefit of being able to explain differentiation during maturation (e.g., Li et al., in press) and the phenomenon of divergence; that is, lower correlations between abilities among participants with a higher level of performance (e.g., Spearman, 1927; Deary et al., 1996). Furthermore, as will become evident below, several more recent findings support the notion of a common source that varies in strength as a function of age.

One line of evidence for the dynamic dedifferentiation account can be subsumed under the heading of <u>directionality dedifferentiation</u> (Baltes et al., 1998; Ghisletta & Lindenberger, 2003). That is, in the period from young to young-old age, the cross-sectional findings summarized above reveal steady monotonic decline in the mechanics, but stable or increasing performance levels for the pragmatics. However, in old age, negative age gradients generally prevail for both the mechanics and the pragmatics. Hence, in old age, the difference in the directionality of the age gradients vaporizes (for a longitudinal analogue see Rönnlund et al., 2003). This pattern, together with the findings of covariance dedifferentiation, is consistent with the notion that the deteriorating functional level of the mechanics starts to limit the expression of the pragmatics in old age.

So far, direct evidence pertaining to the proposition that old-age decrements in pragmatic abilities are driven by the mechanics has been lacking. Recently, Ghisletta and Lindenberger (2003) filled this lacuna by applying a recently developed dynamic (i.e., lead-lag) structural equation modeling method, the dual change score model (DCSM; McArdle, 2001; McArdle & Hamagami, 2001; McArdle, Hamagami, Meredith, & Bradway, 2000), to combined longitudinal and cross-sectional data from BASE (n = 516; age range = 70-104). Processing speed (Digit Letter and Identical Pictures) and knowledge (Vocabulary and Spot-a-Word) were used to index the mechanics and the pragmatics, respectively.

The DCSM may be considered as a variant of latent growth curve models (LGM) or multilevel models (also known as hierarchical linear models, random coefficient models, or mixed effects models). Although these models emanate from different statistical traditions and may differ in technical implementation (e.g., Lindenberger & Ghisletta, 2003), they all seem to boil down to the same underlying statistical model, and, therefore, we henceforth collectively refer to these models as LGMs (for detailed description of these models see Collins & Sayer, 2001; Diggle et al., 1994; Little et al., 2000). In general, LGMs estimate a time-based gradient for a specific group and represent individual trajectories as deviations from this gradient, thereby allowing unobserved heterogeneity in the individual trajectories to be represented, rather than to be treated as error. Extending these models to the multivariate case allows for estimation of the extent to which levels and changes are associated across different variables, at the level of latent (true) scores. The beauty of the DCSM, however, is that it extends the time/age-locked and symmetrically modeled associations between different variables (e.g., associations between slopes of change over a certain time interval) to allow for empirical testing of lead-lag relations such as the one conveyed by the dedifferentiation hypothesis. In other words, with the DCSM, the proposition that low levels of mechanic functioning limit the acquisition, expression, or maintenance of the pragmatics in old age, and thus drive (i.e., temporally precede) decline in the pragmatics, is amenable to direct empirical testing by statistically evaluating the answer to the question: Is the magnitude of the influence of level of processing speed on subsequent change in knowledge different from that of knowledge on subsequent change in processing speed?

The results reported by Ghisletta & Lindenberger (2003) clearly showed that processing speed was the leader and knowledge was the lagger within this specific system of variables; that is, processing speed at t-1 time exerted a substantially stronger influence on change in knowledge from t-1 to t than knowledge at t-1 did on subsequent change in processing speed (see Ghisletta & Lindenberger, 2003 for statistical details). In other words, declines in knowledge, when and if they occur, are temporally preceded by lower levels of processing speed (for similar results regarding younger participants see McArdle et al., 2000). It follows that, with advancing age, interindividual variance in knowledge is increasingly saturated by variance in speed, suggesting that pragmatic abilities are increasingly composed of mechanic variance.

To further dissect the pattern of dedifferentiation, we return to the Singer et al. (2003) study, described under the heading of Selective Attrition. Recall that this study included 516 individuals aged 70-103 at baseline and that this sample was followed up two times, approximately four and six years after the initial measurement. Figure 2 depicts three differently calculated age gradients for processing speed and knowledge, respectively. For our purposes, these measures may again serve as indicators of the mechanics and pragmatics of cognition. The thin black lines represent the cross-sectional gradient extracted at the first measurement occasion for the longitudinal sample; that is, for those individuals ($\underline{n}$ = 132) that subsequently survived and participated in the repeated measurement occasions. These individuals are highly select owing to both experimental and mortality-associated reasons. The dashed line describes the corresponding cross-sectional age gradient for the total initial sample (n = 516). This gradient presumably describes a sample including more participants suffering from cognition-associated health disorders and terminal decline. The thick black line represents the longitudinal convergence gradient (i.e., combined cross-sectional and longitudinal information) for the longitudinal sample.

If we start by considering the cross-sectional gradient of the total sample, it is clear the negative gradients prevail in both processing speed and knowledge. In contrast, the cross-sectional gradients describing the select longitudinal sample are more idiosyncratic: Knowledge remains stable whereas processing speed decreases. In other words, there is a pattern indicating a sample X ability X age interaction, suggesting that decline in the mechanics may be normatively age-related, whereas decline in the pragmatics, which presumably is induced by mechanic decline, may also be associated with impending death (see also Small, Fratiglioni, von Strauss, & Bäckman, 2003). The shape of the longitudinal gradient is largely consistent with this conclusion. Specifically, in very old age (> 90 years) negative gradients are evident for both processing speed and knowledge. In this age it is likely that, even in a select sample, the effects of impending death are large relative aging-induced changes. Taken together then, the pressure of biology-related factors such as specific diseases and terminal decline increase in old age and may, at least in part, act as driving forces of directionality dedifferentiation in old age. This conclusion is further bolstered by findings suggesting that health-related and biology-linked variables such as sensory functioning may be stronger related to, especially pragmatic, cognitive functioning in old age (e.g., Baltes & Lindenberger, 1997).

Intraindividual Patterns of Change

It is a truism that the primary objective for research on the aging of intelligence, and for developmental psychology in general, is to understand the nature of developmental processes at the level of individuals. Yet, standard multivariate statistics applied to hypotheses concerning development, such as standard cross-sectional and longitudinal factor analyses, are notoriously concerned with associations among variables across, rather than within, individuals. For a long time, this blatant discrepancy between concepts and methods has been noted by a loosely connected family of approaches, such as advocates of a person-oriented view on development (e.g., Block, 1971; Magnusson, 1998; Valsiner, 1984), by lifespan theoreticians and methodologists (e.g., Baltes & Nesselroade, 1979; Baltes et al., 1977), and by developmental systems theoreticians (e.g., Lerner, Dowling, & Lara Roth, 2003; see also Wohlwill, 1973; for a summary, see Li, 2003). However, the echoes of their rumbles have been overheard by mainstream developmental research. In fact, contrary to cognitivist stereotypes, it is fair to state that Skinnerian operant psychology, with its careful description and manipulation of behavioral repertoires over time, was much more germane to intra-individual research practice and theorizing than most of today's developmental endeavors (cf. Baer, 1970; Richelle, 1993).

Two interrelated insights are at the core of the intra-person developmental research agenda (see Borsboom, Mellenbergh, & Van Heerden, 2003, for a review from a general perspective). First, analyses of interindividual differences do not necessarily inform the study of how variables are related within individuals. Recently, Molenaar, Huizenga, and Nesselroade (2003) elegantly addressed this issue by applying a concept taken from mathematical-statistical theory – ergodicity – denoting a process having the same structure with respect to intra- and interindividual variances. As a rule of thumb, a process can only be ergodic when means, variances, and covariance are invariant across time. As should be evident from the findings summarized above, developmental processes related to intelligence are inherently non-ergodic. From this point of view, it seems plausible, if not likely, that analyses of interindividual differences deliver results that are unrelated to the structure of intraindividual differences. This point is analogous to the conclusion that inferring aging-related changes from cross-sectional data is made difficult by interindividual differences confounds in the form of cohort effects and selectivity.

The second message pertains to a critical assumption of standard multivariate statistics: that structural relations among variables are invariant across individuals. In light of the suspicion that developmental processes may lead to interindividual differences in intraindividual patterns of change, this assumption strikes a discordant note. Some classics are worth revisiting in this context. Baltes et al., (1977), for example, suggested that the aim of lifespan developmental psychology should be to describe and explain intraindividual differences in behavior, accompanied by the study of interindividual differences and commonalities in these intraindividual changes. The developmental path of each individual is depicted as a multivariate developmental trajectory, or, put differently, as a multivariate pattern of intraindividual change. A sharp line is drawn between studying intraindividual trajectories as the analytical building blocks and the study of the differences between them, implying that these differences might be substantial. To step down on the abstraction ladder, a similar message appears every now and then as critiques against the heavy reliance on simple aggregates across individuals in studies of learning and in studies of developmental growth (see Estes, 1956, for an early appearance; see also Hertzog, 1985). Such gradients, exemplified in this chapter by the longitudinal and cross-sectional gradients of intellectual development, contain a mix of intraindividual and interindividual variances, and mask patterns of growth that are unique to the individual (cf. Jones & Nesselroade, 1990). In the extreme case, one might end up with a gradient describing none of the individual growth curves that make up the gradient.

To illustrate, let us return to the Singer et al. (2003) study for the last time (i.e., Figure 2). As deduced from the absence of directionality dedifferentiation for the select cross-sectional sample, the pattern of dedifferentiation often observed in cross-sectional studies might be driven by a subset of individuals in close proximity to death. Put differently, the intellectual ability structure of a person entering the terminal decline phase may move toward a one-factor solution (e.g., of measures of the mechanics and the pragmatics), whereas the intellectual ability structure of a "normally aging" person of the same age may be more differentiated. Statistical parameters obtained from samples that are made up of mixtures of these two types of individuals yield a picture of intellectual development in old age that approximates, at best, an unknown proportion of the individuals constituting this mixture.

Thus, a focus on the individual, or at least on relatively homogeneous subgroups of individuals, is needed to capture the dynamic (e.g., non-stationary, time-dependent) properties of intellectual development.

Of course, if some of the causal structures are indeed mortality-related, one would expect most individuals to sooner or later evince a pattern of dedifferentiation; that is, "normally aging" and "terminally declining" individuals are not exclusive groups but denote, to some degree, different time periods of a common trajectory. The age at which this developmental transition begins will vary from person to person. Thus, an age-based analysis may actually mask developmental patterns that are truly common across individuals, because the biological timing of transition periods may differ across individuals. Age differences in the onset of adolescent growth spurts are the classical example for phenomena of this sort (Wohlwill, 1970). Thus, to discern developmental commonalities across individuals, one may need to substitute age by neurobiological and cultural-social constructs that are close to the developmental process of interest (see e.g., Li & Schmiedek, 2002; Nesselroade & Schmidt McCollam, 2000; Wohlwill, 1973).

If heterogeneity in patterns of change exists, why did standard multivariate techniques such as standard factor analysis not reveal its presence? As shown by Molenaar (1999; see also Molenaar et al., 2003), standard factor analysis is relatively insensitive to substantial heterogeneity in patterns of intraindividual change; that is, solutions based on interindividual differences may yield acceptable fits to the data, although the data correspond to individuals that are very heterogeneous in terms of the structure of their intraindividual changes.

In conclusion: To enhance the validity of our knowledge about intellectual aging, one would like to see increased use of methods that separate intraindividual variability and change from interindividual differences, as well as methods that have the potential to reveal heterogeneity and transition periods in patterns of aging. At the risk of sidestepping many useful approaches, we describe three broad avenues that might lead in these directions.

Person-oriented approach with Pattern-Based Methods

Instead of focusing on associations between variables, pattern-based methods focus on relationships among individuals, with the aim to group individuals on the basis of similarity. Similarities and dissimilarities among individuals are based on the profile of values on the variables under study. In terms of Cattell's (1952) data box, the general idea is to turn the conventional orientation of the cross-sectional data matrix 90 degrees, factoring people over variables (i.e., Q technique), rather than factoring variables over people (i.e., R technique). Popular examples of model-based variants include categorical factors, such as latent-class analysis and its longitudinal extension, latent transition analysis. When the observed variables are continuous, the corresponding technique is called latent profile analysis. Exploratory pattern-based methods include configural frequency analysis (von Eye, 1990) and variants of cluster analysis. Bergman, Magnusson, & El-Khouri (2003) may be consulted for a comprehensive overview of the methods and the theoretical rationale behind a pattern-oriented approach, accompanied by an accessible description of the technical implementation of the exploratory (e.g., non-model based) alternatives.

The advantage of using a pattern-based approach lies perhaps not so much in statistics as in a closer match between the theoretical model and the measurement model. Specifically, in principle, there is no variance accounted for by the pattern-oriented approach that cannot be explained by a standard variable-oriented factor approach (e.g., Horn, 2000). However, pattern-based methods may offer a more direct reflection of the theoretical suspicion that development not only may produce quantitative interindividual differences, but also qualitatively different developmental paths for different individuals. In other words, these methods may provide a more direct way of focusing on the individual and, therefore, a way of grasping the extent and nature of sample heterogeneity in patterns of change.

A further advantage of this approach is the capacity to structure and explore unobserved population heterogeneity. Specifically, whereas many standard multivariate approaches offer ways to represent heterogeneity by including interaction terms or by employing multi-group factor models, the pattern-based approach offers a viable alternative for structuring unknown sources of heterogeneity and exploring its correlates.

Although the pattern-based approach offers a natural avenue for establishing homogeneous subgroups, the analysis of change is not easy to manage with this approach (see Bergman, 1998; Bergman et al., 2003). Typically, classifications are carried out at each time, followed by the study of individuals' group membership over time with the aim to find typical and antitypical (cf. von Eye, 1990) transition paths across the groups established at each cross-section (e.g., Bergman et al., 2003). Panel designs lend themselves to this kind of analysis; for example, group transitions may map onto a stage-sequential theoretical model. However, often, at least with regard to intellectual development in old age, transition might be a relatively slow and gradual process that deserves more direct and intense study. The next approach seems promising in this regard.

<u>LGMs allowing for Differences in the Parameters between Subgroups.</u>

This approach merges the variable-oriented LGM approach used to structure change with the model-based pattern-oriented methods described above. Categorical latent variables are used to describe groups of changing individuals that are homogenous within and heterogeneous across groups. The notion is that each group corresponds to a subpopulation with its own set of parameters. These features are then combined with the conventional growth modeling approach, which provide the parameters. To recapitulate, LGM is an attractive approach to analyze longitudinal data, relating an observed variable to time or to some time-related variable such as age. However, a mean growth curve is estimated under the assumption that all individuals in the sample are drawn from the same population and a continuous latent variable is used to capture any heterogeneity in individual trajectories of growth.

The combination of the two approaches offers a way to gauge the validity of the mean growth curve. By using an outcome variable measured at multiple time points, a latent class model is formed in which the latent classes correspond to different growth curves of the outcome variable. In other words, individuals are assigned to different groups based on their longitudinal trajectory. For example, one group of individuals may have a linear growth and another may have a quadratic growth. Individual differences in the trajectories within the groups are captured by growth factor variances for each group (as in traditional LGM). Muthén and Muthén (2000; see also Muthén, 2001) provide accessible overviews of this framework and Raudenbush (2001) describes similar techniques within the multilevel modeling tradition.

Multivariate, Replicated, Single-Subject, Repeated Measures Designs

The methods described so far are useful tools for analyzing typical data sets in studies of intellectual aging; that is, data sets including many individuals, relatively few variables, and, at best, a few measurement occasions. In contrast, the approach described now requires a profound shift in research design, as well as in data analytical procedure. As argued above, this radical shift may well be necessary to better understand the structural dynamics of intellectual aging. Specifically, the designs and data-analytic techniques described in this section are based on the intensive longitudinal study of single individuals. The degree of generalizability across individuals can be assessed after patterns of change have been analyzed at the intraindividual level. Nesselroade (e.g., Nesselroade & Schmidt McCollam, 2000; Jones & Nesselroade, 1990) and Molenaar (e.g., Molenaar et al., 2003) are strong advocates of this general approach. Because it offers a way to clearly separate intraindividual and interindividual differences, more widespread applications are desirable.

Empirically, the main feature of this approach is to collect many variables many times within several individuals. Factor analysis may be performed on the longitudinal data to explore how groups of variables are related across time for a single individual; that is, P-technique factor analysis may be employed (variables over occasions). Molenaar (1985) suggested a combination of multivariate time series analysis and P-technique factor analysis, called dynamic factor analysis, to examine lagged relations among variables within persons (see Kim & Nesselroade, 2003 for a recent application).

When the individual's structure of intraindividual change have been clearly understood without being contaminated by interindividual differences, individuals with similar patterns of intraindividual change can be aggregated into homogeneous groups on the basis of statistical tests (Nesselroade & Molenaar, 1999). In this way, generalization across individuals can be approached and interindividual differences in intraindividual processes can be explored.

Concluding Remarks

To capture the complexities of intellectual development in old age, one can neither treat individuals as if they do not differ among each other only because they happen to be born at a similar point in time, nor construe intelligence as a unitary and static construct. In younger adulthood, the biology-based mechanics and the culture-based pragmatics of intelligence display relatively loose couplings and display different age gradients. In late senescence, decline in mechanics limit pragmatic functioning, perhaps due, at least in part, to terminal decline. The onset and nature of this transition are likely to differ from person to person. General regularities in patterns of change are likely to exist, but can only be discerned with certainty after intraindividual time-dependent structures have been observed, analyzed, and compared. Thus, improved understanding of intellectual development in old age requires a multivariate, dynamic, and individual-oriented perspective.

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Footnotes

[1]The overwhelming majority of studies on intellectual development in old age have used verbal knowledge as a marker of the pragmatics. This fact will be reflected in this chapter, although we join those (e.g., Hunt, 2000) arguing for the use of a wider range of pragmatic markers.

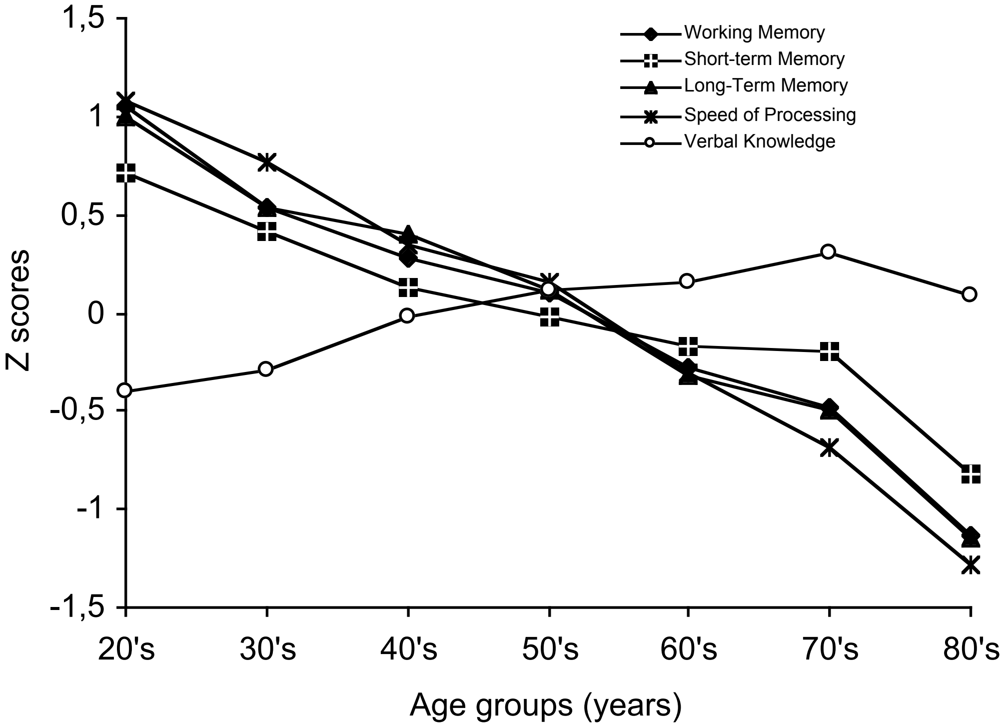
[2]In this chapter, we discuss intellectual development in adulthood and old age from a psychometric perspective. This perspective is complementary, rather than opposed to other perspectives, such as cognitive-behavioral (e.g., Zacks, Hasher, & Li, 2000; see Pascual-Leone & Johnson, this volume, for an example concerning childhood development), neurocognitive (e.g., Reuter-Lorenz, 2002), or neurophysiological (e.g., Raz, 2000).

[3]Because any valid developmental stages are both generation- and person-specific (e.g., Baltes & Smith, 2003), partitioning the lifespan into substantive stages based on chronological age is likely to be a hopeless endeavor. Therefore, when nothing else is explicitly stated, we use the labels “young” (20-40), “middle-age” (40-60), “young-old age” (60-80), and “old age” (>80) only as means to replace chronological age with words.

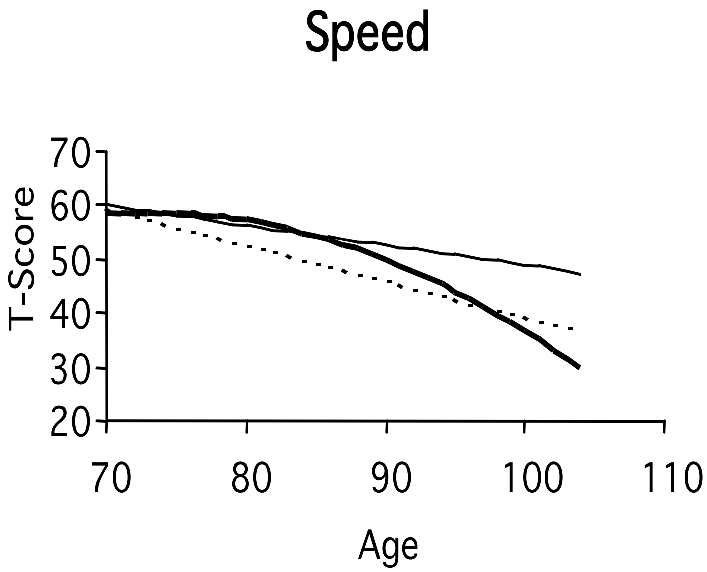
Figure Captions

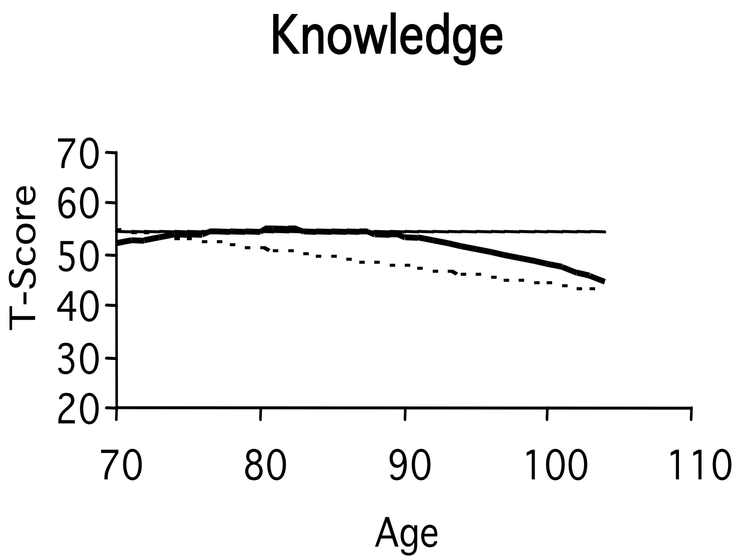
Figure 1. Cross-sectional age gradients for composite measures of working memory, short-term memory, long-term memory, speed of processing, and verbal knowledge (n = 345). Each composite is constructed from three tests. Copyright © 2002 by the American Psychological Association (APA). Adapted with permission from Park et al. (2002).

Figure 2. Three differently calculated age gradients for processing speed and knowledge, respectively. The thin black lines represent the cross-sectional gradient extracted at the first measurement occasion for the longitudinal sample (n = 132). The dashed line describes the corresponding cross-sectional age gradient for the total initial sample (n = 516). The thick black line represents the longitudinal convergence gradient (i.e., combined cross-sectional and longitudinal information) for the longitudinal sample (n = 132). Adapted from Singer et al., (2003).



Working Memory
Short-term Memory
Long-Term Memory
Speed of Processing
Verbal Knowledge
Z scores
1,5
1
0,5
0
-0,5
-1
-1,5
20's
30's
40's
50's
60's
70's
80's
Age groups (years)


Speed
70
60
50
40
30
20
T-Score
70
80
90
100
110
Age


Knowledge
70
60
50
40
30
20
T-Score
70
80
90
100
110
Age