# 1. THEORETICAL BACKGROUND

## 1.1 Overview

The central goal of this dissertation is to achieve an adequate model representation of the structure of individual differences in cognitive abilities in old and very old age. Such models should represent the internal relations among a broad sample of cognitive tasks—i.e., have good model fit—as well as the relations to chronological age and other external variables—i.e., exhibit criterion validity. Importantly, such models should also be interpretable in relation to theories about the structure, development, and functionality of cognitive abilities in old age. To provide such a model for the analyses presented in the empirical section, the theoretical part of this dissertation brings together approaches and models used in the fields of cognitive aging and research on the structure of cognitive abilities.

The theoretical part of this thesis starts with a general overview of cognitive aging theories that evolved from two lines of research tradition: (a) psychometric research on individual differences and (b) information processing research. Then, an introduction to research on the structure of individual differences in cognitive abilities and in information-processing constructs is given to provide a background for theoretical and statistical models that will be used to structure multivariate age-related individual differences of cognitive abilities. To adequately account for the dynamic nature of cognitive development, these methods have to be complemented by other perspectives, such as changes of the factor structure across the lifespan and considerations of developmental antecedents and consequences of individual differences.

Moving from general to specific, after introducing methods, research designs, and data analysis issues in cognitive aging research, a review of recently proposed structural models is presented. These models try to tackle the question of whether cognitive aging can be explained by a general or by specific mechanisms on the basis of individual differences in age-heterogeneous cross-sectional data. By means of simulation analysis, it is shown that these methods either do not represent the internal structure of cognitive tasks adequately or are prone to produce biased results. Hence, there is a need for a different kind of structural representation. Such a representation, the *nested factor model*, is then presented. The historical roots in individual differences research of this model are presented and explanations about its theoretical and mathematical relationships to—and differences from—the existing models are given. Furthermore, different ways of relating the individual differences represented by this model to chronological age are discussed.

## 1.2 Theories of Cognitive Aging

What are the processes behind the observed age-related differences in cognitive functioning? Is there a general mechanism responsible for the manifold examples of older people performing worse on a wide range of tasks, or should one rather conceive a multitude of interrelated or even independent processes? These questions have been driving the field of cognitive aging research for many years now and a definite answer is still lacking. Competing theories have been proposed and an enormous amount of data has been collected (see Craik & Salthouse, 1992, 2000). In this section, an overview of the main theories of cognitive aging is given. These theories have evolved from different research traditions on cognition and cognitive abilities—i.e., the psychometric tradition, the information-processing experimental approaches, research on expertise, and the biological approaches that led to the now flourishing field of the cognitive neuroscience of aging. The following brief review will focus only on the information-processing and the psychometric approaches because they are central for this thesis.

### 1.2.1 Information-Processing Approaches

#### *1.2.1.1 Processing Speed*

The processing speed theory proposed by Salthouse (Salthouse, 1985, 1996) builds on earlier theoretical approaches (e.g., Birren, 1964; Birren & Fisher, 1995; Cerella, 1990) and on the ubiquitous empirical finding showing that cognitive performance slows down with increasing age (Cerella, 1985; Cerella & Hale, 1994; Salthouse, 1996). At a general level, the theory speculates that the slowing of cognitive performance in old age might be explained in terms of a reduction of processing speed at the neuronal level, leading to a slowing of basic cognitive operations, and, as a consequence, a decrease in observed performance. Focusing more specifically on information-processing mechanisms, this theory proposes that the decrease in performance can be either due to a limited time mechanism, which assumes that necessary cognitive operations are not finished within available time, or due to a simultaneity mechanism, which proposes that information needed to be simultaneously available for higher level processing is lost due to information decay before total processing is completed.

Correlational analyses with mediational models have shown measures of processing speed to be good predictors of age-associated variance in measures of memory and other constructs of higher-order cognition, such as reasoning ability (see Salthouse, 1996, for review). Recently, these mediation analyses have been extended to the use of multivariate structural equation modeling (SEM) techniques—trying to show that a single latent construct is able to explain the observed age relations of broad sets of cognitive variables (Salthouse & Czaja, 2000; Salthouse, 2001). A discussion and further development of these methods will be a central part of later sections in this thesis.

#### *1.2.1.2 Working Memory and Executive Functions*

The term "working memory" denotes a cognitive system that is capable of storing several items of information in one or more short-term memory stores, while simultaneously processing this, or other, information (Baddeley, 1986, 2001; Just & Carpenter, 1992). Declines in working memory capacity have been proposed as causes for the observed age-associated decrements in cognitive performance (Craik, 1983; Craik & Byrd, 1982). Declines of working memory performance with advancing age are an established finding in the literature (Craik & Jennings, 1992). The strong relation of working memory to reasoning ability reported for adult samples (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Cristal, 1990; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002) make this construct a plausible candidate for the explanation of age-related declines in fluid intelligence. Indeed, studies on predicting reasoning and problem solving abilities in old age show that large portions of the age-associated variance in these intellectual abilities are shared with age-associated differences in working memory (Salthouse, 1991).

An issue regarding the processing speed and working memory accounts of cognitive aging is whether one of the two has causal priority over the other. In other words, whether the decrease in processing speed limits working memory capacity, or vice versa. The *levels of dissociation* framework proposed by Kliegl, Mayr, and colleagues (Kliegl, Mayr, & Krampe, 1994, 1995; Mayr, Kliegl, & Krampe, 1996) may help to integrate these two theoretical propositions. Building on findings of experimental dissociations of age differences on tasks of different complexity, this framework proposes that the effects of aging are organized in an ordered fashion with a discontinuous transition from one level of complexity to the next. On the one hand, sequential complexity—the number of independent serial processing components of a task—can be assumed to be influenced mainly by basic processing speed. On the other hand, coordinative complexity, which requires results of intermediate processing steps to be kept in active memory, is closely related to working memory functioning (Mayr et al., 1996).

Another problem with the working memory hypothesis is that currently there is only limited understanding of a central function of working memory, namely the conscious control of thought and action. In Baddeley's model, a *central executive* (similar to the *supervisory attentional subsystem*, Norman & Shallice, 1986) serves to monitor and coordinate the functioning of the other working memory subsystems. The functions assigned to the central executive are closely related to the abilities to inhibit thought and action and to avoid interference of parallel or serial cognitive processes, which are central to other cognitive aging theories (e.g., Hasher & Zacks, 1988). However, the large number of paradigms used in the research on inhibition, interference, and attentional processes as central mechanisms of cognitive aging (see McDowd & Shaw, 2000, for review) often reveal inconsistent findings. Clearly, further research and theoretical integration are necessary.

### 1.2.2 Psychometric Approaches

In the psychometric tradition of cognitive aging research, most prominent are two-component theories that build on the theory of fluid and crystallized intelligence by Cattell and Horn (*Gf–Gc* theory; Cattell, 1971; Horn, 1982). According to the *Gf–Gc* theory, the two broad ability domains of fluid and crystallized intelligence show differential age gradients. Fluid abilities, which are mainly measured by tasks of inductive and deductive reasoning, are more vulnerable to loss in brain efficiency; whereas crystallized abilities, which reflect knowledge in all kinds of domains, are proposed to be better maintained. This maintenance of acquired knowledge has been proposed to be due to an overdetermination in the networks in which knowledge is stored. It is assumed that these knowledge networks allow for many possible ways of retrieving information so that sufficiently efficient access to knowledge might be maintained into old age (Horn & Hofer, 1992).

In addition to these differential age-related processes, Cattell's (1971) *investment theory of intelligence* proposes a developmental dynamic between fluid and crystallized abilities. According to this theory, knowledge accumulates by a process of fluid abilities being invested over time into the acquisition of crystallized abilities. What is recognized as crystallized knowledge at a certain developmental stage of an individual is, in part, the product of an earlier investment of fluid abilities to understand, structure, and elaborate information in different knowledge domains.

Because the efficiency of fluid abilities declines with age, the investment theory implies that the acquisition of new knowledge should become more difficult with aging. This is also a central aspect of the theory of the mechanics and pragmatics of cognition (Baltes, 1987). This two-component model of lifespan intellectual development builds upon the *Gf–Gc* theory but broadens its conceptual scope to include the ontogenetic dynamics between the biological basis of cognitive abilities and the role of cultural influence on the acquisition of bodies of knowledge and expertise. The model links the interplay of fluid and crystallized factual abilities with the dynamics of biology and culture across the adult and the aging part of the lifespan. Specifically, it is postulated that a decreasing role of evolutionary selection benefits in biological functioning contributes to an increased need for culture, which is paralleled by a decrease of the efficacy of cultural factors in supporting cognitive performance and development (Baltes, 1997). These basic processes lead to the prediction that the mechanics of cognition decline during aging, while the pragmatics are better maintained. The pragmatics even keep the potential of gains, though for the price that an increasing amount of investment becomes necessary due to the decreased efficacy of cultural factors.

Another theoretical account of adult intellectual development that elaborates on the *Gf–Gc* theory is the *PPIK* theory by Ackerman (1996). Besides proposing dynamics of intelligence-as-process (P) and intelligence-as-knowledge (K) similar to the *Gf–Gc* theory, this approach explicitly incorporates a small set of personality (P) and interest (I) factors that underline the importance of motivational aspects. Specifically, those motivational aspects are essential for intelligence conceptualized as typical—as opposed to maximal—intellectual engagement (Ackerman, 1994). Furthermore, adult intellectual knowledge and skill are represented in this theory as complexes that may demonstrate little overlap for different individuals—a notion comparable to the expertise aspect of Baltes' cognitive pragmatics.

The most comprehensive data on adult age gradients of various constructs of psychometric intelligence is provided by the Seattle Longitudinal Study (SLS; Schaie, 1994, 1996; Schaie & Willis, 1993). The cohort-sequential design used in the SLS allows comparisons of results from cross-sectional and longitudinal analyses. The cross-sectional findings indicated steady monotonic decline in the mechanic abilities of inductive reasoning, perceptual speed, spatial orientation, and verbal memory, whereas the more crystallized numeric and verbal abilities peak during middle adulthood and show little or no decline up to about age 70. The longitudinal findings of the SLS demonstrated less decrement with aging and more uniform shapes for the different abilities, with peaks of the trajectories shifted to later ages than the cross-sectional data suggest. The construct of perceptual speed was an exception to this pattern as it displayed linear decline from early adulthood on. The discrepancies of the cross-sectional and longitudinal results could be partly resolved by time-lagged comparisons of same-aged individuals from different cohorts across historical time and by comparisons of independent samples from the same cohort at different time points. These analyses indicated the presence of cohort effects in cross-sectional studies—favoring later cohorts especially in inductive reasoning and verbal memory—and practice as well as selection effects affecting the longitudinal findings. Longitudinal and same-cohort comparisons could therefore be adjusted for the environmental influences estimated by the time-lagged effects of same-age groups. Such adjustments led to very similar cross-sectional and same-cohort estimates of age changes (Salthouse, 1991, pp. 107–119), which indicates environmental influences that are general to all age groups, rather than specific interactions of cohorts and environmental experiences in certain time periods.

Recent longitudinal structural equation analyses by McArdle, Ferrer-Caja, Hamagami, & Woodcock (2002) were conducted on a large sample, which covered the entire lifespan from early childhood on, and combined cross-sectional with longitudinal retest information. These analyses showed that the assumption of one general latent construct explaining the cognitive changes was overly simplistic. Instead, different growth curves, e.g. for *Gf* and *Gc*, had to be specified.

Expanding the scope of research to very old age, cross-sectional findings from the Berlin Aging Study (BASE; Baltes & Mayer, 1999) provide a picture of age gradients showing negative age trends for the abilities of perceptual speed, reasoning, memory, fluency, and knowledge within the age range of 70 to 103 years (Lindenberger & Baltes, 1997). The age-relations were more pronounced, however, for the mechanic (speed, reasoning, and memory) than for the pragmatic (fluency and knowledge) abilities. Results from the longitudinal analyses also indicated multidirectionality of cognitive development, with mechanic abilities declining fast and knowledge being remarkably stable (Singer, Verhaeghen, Ghisletta, Lindenberger, & Baltes, 2003). In conclusion, cross-sectional and longitudinal findings from research on psychometrically defined abilities have taught us that the general lifespan developmental conceptions, which view the ontogenesis of mind and behavior as dynamic, multidimensional, and multidirectional (Baltes, 1997), also, and particularly, apply to the development of cognitive functioning. Theoretical and statistical models of cognitive aging, therefore, have to be able to account for these qualities.

In summary, psychometric approaches have provided consistent evidence for multidirectional age gradients of fluid mechanic versus crystallized pragmatic cognitive abilities. The different theoretical accounts of aging effects on the information-processing mechanisms underlying the fluid mechanic abilities, however, still need to be developed further. An integration of theories about aging of the cognitive mechanics particularly calls for an integration of the psychometric and information-processing approaches (Deary, 2001) and a cross-level unification that also considers the neurobiological and functional-anatomical levels of cognitive aging (e.g., S.-C. Li, Lindenberger, & Sikström, 2001). For the cognitive pragmatics, it will be of special interest to enlarge the research scope to encompass knowledge from areas of the individuals' occupational and avocational knowledge, which obviously requires focusing on idiosyncratic fields of expertise and interest (Ackerman, 2000; Ackerman & Rolfhus, 1999). To understand the interplay and the developmental dynamics between the cognitive mechanics and the cognitive pragmatics, it is important to further consider general concepts of bio–cultural co-constructivism in lifespan ontogeny and gene–culture-coevolution (Baltes & Singer, 2001; S.-C. Li, 2003).

## 1.3 The Structure of Human Cognitive Abilities

In this section, an overview of models used in intelligence research to describe the structure of human cognitive abilities is given. Recent extensions of using structural models to describe individual differences in performance on experimental tasks measuring information-processing constructs are also reviewed. This overview serves as a historical and theoretical background for the later discussion on the structural models used in cognitive aging research. In the second part, the static view on individual differences implied by these theoretical models is complemented by dynamic perspectives on developmental antecedents and consequences of the structure and on changes of the structure itself across the lifespan. These considerations build a basis for interpreting models that include and relate chronological age to individual differences in cognitive functioning.

### 1.3.1 Hierarchical Models of Intelligence: A Static View on the Structure of Cognitive Abilities

Human cognitive abilities as constituents of the structure of intelligence have been studied with individual difference approaches for over a century now (see Carroll, 1993, for review). During this time, the development of factor analytic methods to describe multivariate individual differences has paralleled the development of theoretical accounts on the structure of intelligence. The theoretical controversies about the importance of general versus specific factors for describing the structure of human intelligence have a tradition dating back to the beginnings of factor analytic intelligence research and continue currently. However, Carroll (1993) demonstrated that the models for testing these different accounts can be very well integrated into general hierarchical models, within which the different theoretical accounts can be seen as special cases.

Based on the finding that performances on a variety of cognitive tests almost ubiquitously correlate positively with each other (i.e., the positive manifold), Spearman (1904) presented a theory of general intelligence, proposing that observed performance on a test can be explained by one component that is general to all different kinds of cognitive tests—commonly known as *g*—and a test-specific component. To test this two-factor theory, he developed the first statistical models for factor analysis. Though his methods provided tests of whether the assumption of one general factor is sufficient to explain the observed covariances among a set of tasks, it did not provide means to test alternative models with differing numbers of common factors. Such multiple-factor methods were later developed by Thurstone (1938), who was led by the theoretical proposition of primary mental abilities instead of just one general factor of intelligence. While being able to identify distinct abilities, such as perceptual speed or reasoning ability, Thurstone's assumption that these primary mental abilities can be represented by orthogonal factors was not supported by empirical evidence. Rather, models with correlated factors—for which Thurstone also developed factor rotation techniques—were necessary to explain the correlational patterns among tests measuring the various primary mental abilities.

The observation that the factors, which represent correlations among single tasks, were themselves correlated opened the possibility of generating higher-order factors. Such higher-order factors, in turn, can also be correlated and further factor analyzed. Applying such analyses to broad batteries of cognitive tasks leads to a hierarchical organization of the intelligence structure with single tests at the bottom, intermediate layers of factors with different levels of generality, and broad general abilities at the top of the structure. Cattell and Horn proposed up to nine such broad factors in different stages of developing their *Gf–Gc* model (e.g., Horn, 1982). Besides the already mentioned fluid and crystallized intelligence factors, factors such as general visual processing ability ($Gv$), short-term memory ($Gsm$), or general quantitative ability ($Gq$) had been identified.

Vernon's (1961) hierarchical group factor theory integrates the theoretical notions and empirical findings of a general intelligence factor $g$ with major and minor group factors and task-specific residual factors. It distinguishes broad verbal–numerical–educational and mechanical–spatial group factors. General and specific group factors at different levels of generality exist simultaneously and are modeled as orthogonal factors (based on methodological foundations given by Thomson, 1946, and C. Burt, 1949). The relative importance of general and specific group factors is evaluated in terms of communality estimates. Vernon emphasized that the existence and communality of general and specific factors in a given data set strongly depends on the heterogeneity of the task battery and the sample of subjects. The terms general and specific, broad or narrow, major or minor group factors are always relative to the selection of tasks and, therefore, most meaningful for comprehensive batteries of cognitive tests. In addition, the selection of subjects can have strong influence on the relative communalities of specific factors. In homogenous and high-functioning individuals, such as university students, the relative contribution of specific group factors is stronger because the variability in general cognitive functioning is reduced. In age-heterogeneous samples covering wide age ranges, the observed structures will be more strongly dominated by a general factor.

Reviewing and reanalyzing more than 400 factor-analytic studies on the structure of psychometric intelligence, Carroll (1993) derived a three-stratum structure with second-order factors that are very much reflecting the factors proposed by Cattell and Horn. Because the correlations among these factors were of relatively similar magnitude, one general factor on top of the structure could be derived. To separate the amount of total variance attributable to this general factor from factor variances that were not shared with other factors, Carroll used the Schmid–Leiman orthogonalization (Schmid & Leiman, 1957). This method redistributes the variance of the observed test variables into orthogonal general and specific components. Applying this method to all available data sets provided an integrating view on the old debates of general versus specific factors. It showed that for all kinds of intelligence test batteries with broad coverage of various tests, a higher-order general factor could usually be modeled on the top layer of the structure, but generally could not explain the structure completely because of variance attributable to specific group factors.

In contrast to the more empirically driven research of Cattell, Horn, and Carroll, facet theories have tried to use a more theory-guided approach to structure the space of human intelligence. Guilford's structure of intellect model (Guilford, 1967) cross-classifies tasks a priori into component facets of operation, content, and product aspects. A total number of 120 independent abilities that could be derived from this classification should then be identifiable using confirmatory factor rotation methods. Empirical analyses of Guilford's model, however, have shown that the factors tend to be correlated, so that it is possible to rearrange them into hierarchical models (Guilford, 1982; Haynes, 1970). Other facet theories of intelligence such as Guttman's radex model, which proposes that abilities can be organized by their content—as figural, numerical, or verbal—and by their complexity (e.g., Guttman, 1954; Guttman & Levy, 1991) or the Berlin model of intelligence structure by Jäger (1984), can be also represented by hierarchical models (Marshalek, Lohman, & Snow, 1983; Süß et al., 2002). These hierarchical models, then, imply that the variance of each ability can be subdivided into general and specific components.

Given that an integrative view of the structure of cognitive abilities as a combination of general and specific sources of variance seems indisputable, the discussions about the superiority of parsimonious or detailed descriptions of the structure itself can be easily seen as a debate about whether the glass is half-full or half-empty. Nevertheless, the question about the importance of a general as opposed to specific factors is still an issue of much controversy (see Sternberg & Grigorenko, 2002, for a recent collection of controversial positions), especially when it comes to the relation of intelligence to all kinds of external variables. Debates over the incremental predictive utility of specific variance over a general factor for the prediction of educational achievement or job performance are good examples. The most heated public debate was generated by the book of Herrnstein and Murray (1994), claiming that even all sorts of "real life" outcomes, such as poverty, unemployment, and crime, could, to an impressive degree, be predicted by a factor of general intelligence (for a critique, see Horn, 2002). The question of whether performance differences in intelligence tests between racial groups can be best described by general factor models and the related issue of whether genetic variability is most closely related to a general factor is another field where the controversies are still lively pursued (Fish, 2002; Herrnstein & Murray, 1994; Jensen, 1998).

A general issue in all these debates on the relative roles of the general factor and specific factors is how much of the controversies can be attributed to differing use of methods and models, and whether different models might bias results in one or the other direction. The central topic of this thesis is to develop structural equation models that allow an unbiased representation of the relations between external criterion variables, such as age, and general and specific factors. The development of such models, therefore, might also have impact on other areas of research, as reviewed above, where similar methods are applied to similar questions, involving different external criterion variables.

### 1.3.2 Hierarchical Models of Information-Processing Constructs

So far, the review of individual difference approaches to cognitive functioning has focused on the so-called psychometric abilities, which are mainly descriptions and classifications of test performance at the behavioral level. Individual difference approaches and the corresponding factor analytic methods, however, are not tight only to these measures. They can be extended to tasks measuring information-processing constructs of the experimental tradition. This yields one way of approaching a combination of experimental and differential perspectives as recently called for by Deary (2001), echoing Cronbach's (1957, 1975) earlier appeals. The potential benefit of the application of such methods to experimental cognitive tasks is twofold. First, correlational approaches can help explain the underlying cognitive resources of long-established psychometric constructs such as fluid abilities. Second, multivariate structural analyses provide one way of integrating findings for different experimental tasks that supposedly operationalize the same theoretical construct. These benefits are of special importance for the field of cognitive aging research, because of its parallel psychometric and information-processing traditions, and because of the often-inconsistent findings across different operationalizations of theoretical constructs. Therefore, some recent individual differences studies will be reviewed here along the lines of information-processing cognitive aging theories.

With respect to the construct of mental processing speed, Roberts and Stankov (1999) have conducted a factor analytic study with reaction time measures of a large set of elementary cognitive tasks and speed indices derived from psychometric ability tasks. They found a hierarchical factor structure with broad second-order factors measuring general psychomotor speed, general decision speed, and general psychometric test-taking speed, each consisting of three or more narrow first-order factors, and a relatively weak third-order general speed factor on top. They thus concluded that

> "...'mental processing speed ' serves as a rather imprecise term for a broad class of constructs. ... , there is clearly evidence for narrow, broad, and general factors of mental processing speed. (Roberts & Stankov, 1999; p.84)".

For the construct of working memory, Engle, Tuholski, Laughlin, and Conway (1999) have shown that it is highly correlated with, but still separable from a short-term memory factor with working memory being a much better predictor of fluid intelligence, in line with earlier findings of Kyllonen and Christal (1990). Oberauer, Süß, Schulze, Wilhelm, and Wittmann (2000) also showed that working memory can be empirically differentiated into related sub-constructs such as storage, processing, and supervision. The question of whether different memory systems underlie the performance on spatial and verbal working memory tasks has been addressed by Shah and Miyake (1996), who interpreted their results in terms of working memory being a domain-specific construct. Further research on this controversy will also be relevant to the findings of differential age-associated effects with respect to lexical and non-lexical tasks (e.g., Jenkins, Myerson, Joerding, & Hale, 2000).

For the broad theoretical constructs of executive functioning or inhibition, Miyake, Friedman, Emerson, Witzki, Howerter, and Wager (2000) identified correlated factors of inhibition, switching, and updating, with differential patterns of predictive validity for complex executive functioning tasks, such as the *Wisconsin Card Sorting Test* or the *Tower of Hanoi*. Miyake, Friedman, Rettinger, Shah, and Hegarty (2001) further examined the relations of visuospatial short-term and working memory, and executive functioning.

All these studies show the utility of correlational multivariate analyses for explaining the structure of cognition beyond established psychometric ability factors. It seems that for broad information-processing constructs, like executive functioning or mental speed, which lack a unique operational definition, it is likely to find several correlated subconstructs that usually can be represented by hierarchical models. The increasing number of such studies conducted by researchers interested in cognitive processes begins to build a basis for latent factors with an information-processing interpretation.

Despite the theoretically meaningful and sometimes strong relations of these cognitive resource constructs to psychometric abilities, it makes sense to keep these two areas conceptually separate because the gap between the two is still too large. To close this gap, it will first be necessary to further elaborate the structure of cognitive resources, because there is still an apparent overlap of the different conceptualizations, e.g., for the working memory, executive functioning, and inhibition constructs. And second, it also will be important to disentangle the complex interplay of basic cognitive resources on the one hand and the role of acquired knowledge and strategies on the other hand in performance on intelligence tasks.

## 1.4 Dynamic Perspectives on the Structure of Cognitive Abilities

Most of the theories and models presented in the last section correspond to a static view on the individual differences in cognitive abilities represented by the factor analytical models. Even though existing theories of intelligence structure might incorporate dynamic ideas of developmental processes, the models used for most of these theories only give a static description of individual differences. The notion of *true scores* as a basis for the interpretation of common factors, and the use of retest stability as a measure of the reliability of intelligence tests implies that the common factors are conceptualized as measuring stable traits of individuals. Even though it has been acknowledged that the observed structures need not be invariant for different age groups, e.g., Spearman's idea that the strength of the general factor varies as a function of ability level and age (Spearman, 1926, 1927; Deary & Pagliari, 1991), most of the studies supporting the different models have been conducted with young adults and therefore could not address such questions.

Considering a lifespan developmental perspective, several issues become important. First, it can be asked whether the observed ability structures are stable over time, or whether different representations of intelligence have to be considered for different parts of the lifespan. Early conceptions of structural differentiation in childhood and dedifferentiation in old age suggest that the latter assumption is true (e.g., Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980). Second, the questions arise of what antecedents underlie the development of individual differences and their covariation across domains of functioning, which non-cognitive or everyday cognitive variables correlate with these individual differences, and, finally, what the developmental outcomes of differential cognitive levels and profiles are. Third, a developmental perspective on individual differences also provides a different view on the logical status of common factors when interpreting the variance-covariance pattern among a set of variables. Issues such as training effects, plasticity, and covarying environmental influences need to be considered before drawing inferences from observed covariances among variables to latent causal entities that are supposed to influence observable behavior.

### 1.4.1 Developmental Differences of the Cognitive and Sensorimotor Factor Structures

#### *1.4.1.1 Dedifferentiation Hypothesis*

The idea of changes in the factor structure across the lifespan is based on early empirical findings of stronger correlations between subtests of intelligence scales in children than in teenagers and young adults. Garrett (1946) and C. Burt (1954) put forth the age-differentiation hypothesis stating that the factor space in children is more condensed than in adults—with higher covariances among tasks implying higher loadings on a, consequently, more influential general factor. Reinert (1970) gave an excellent review of the early empirical findings—including studies that examined factor structures across a much broader age range—and indicated the possibility of a dedifferentiation of the ability space with aging (Balinsky, 1941; Green & Berkowitz, 1964; Lienert & Crott, 1964). Baltes et al. (1980), who also took a lifespan orientation, proposed that the structure of cognitive abilities is rather undifferentiated in childhood, undergoes a process of differentiation, which leads to a multidimensional structure that stays largely invariant during adulthood, and starts a process of dedifferentiation in old age. These developmental changes in the structure of cognitive abilities could be driven by general environmental and/or biological factors having differential impacts on individual differences in cognitive performance at different stages of the lifespan.

Reviews of studies examining stability of factor structure across different age groups, for the most part, have relied on piecing together of results from separate studies, and were prone to the limitations of exploratory factor analytical methods used in many of the studies (Cunningham, 1978). Using confirmatory factor analysis methods, Baltes et al. (1980) found that the factor structure of a broad battery of cognitive tasks was less differentiated in old people (60 to 89 years old). Comparing a sample of adults aged 25 to 69 with the sample from the first cross-sectional measurement occasion of the Berlin Aging Study, Baltes and Lindenberger (1997) found evidence for strongly increased correlations among cognitive abilities in the older sample. The general picture of findings from studies comparing factor structure in different age groups with appropriate methods of multiple-group confirmatory factor analysis is one of a relative stability of the structural configuration and sometimes even factor loading patterns, while factor covariances tend to increase with age (e.g., Cunningham 1980, 1981; Hertzog & Bleckley, 2001; Schaie, Willis, Jay, & Chipuer, 1989; but notice also some exceptions, e.g., Bickley, Keith, & Wolfle, 1995; Juan-Espinosa, García, Escorial, Rebollo, Colom, & Abad, 2002).

Expanding the scope of investigation to include elementary cognitive tasks and using an age-stratified lifespan sample, Li, Lindenberger, Hommel, Aschersleben, Prinz, and Baltes (in press) provided evidence for differentiation as well as dedifferentiation across the domains of psychometrically-defined mechanic and pragmatic cognitive abilities and basic information-processing functions. Evidence from longitudinal comparisons, however, is not conclusive on the issue of dedifferentiation (Cunningham & Birren, 1980; Schaie, Maitland, Willis, & Intrieri, 1998).

The compression of the factor space, as implied by the increased correlations among the factors, can be modeled by a second-order general factor with higher loadings of the first-order factors in older samples as one way of representing ability dedifferentiation. A *strong form* of the dedifferentiation hypothesis would have predicted that the number of factors reduces, which has not been supported by confirmatory factor analyses of available data. Regarding the age range studied in the Berlin Aging Study (i.e., age 70–103), Lindenberger and Baltes (1997) report a lack of evidence even for a weaker form of dedifferentiation, i.e. no significant differences of the first-order factor loadings on the general factor between the subsamples of old (i.e., age 70–85) and very old (i.e., age 85–103) participants.

#### *1.4.1.2 Common Cause Hypothesis*

Previously, the role of sensory functions as antecedents, correlates, or consequences of cognitive abilities in the elderly has been the focus of only a limited number of empirical investigations (e.g., Granick, Kleban, & Weiss, 1976; MacFarland, 1968; Stelmach & Hömberg, 1993). Investigating the relationships between these two domains of functioning with BASE data, Lindenberger and Baltes (1994; Baltes & Lindenberger, 1997) not only found that abilities tended to show increased correlations in old age, but also a strong connection of cognitive performance and measures of sensorimotor functioning. These findings led to the formulation of the *common cause hypothesis* (Lindenberger & Baltes, 1994), which states that both sets of measures indicate the decline in the physiological architecture of the brain.

Because this hypothesis proposed one underlying mediating variable (i.e., the general efficiency of brain functioning), it has been subjected to structural tests based on cross-sectional data that are similar to those testing the processing speed hypothesis. The problems that will be discussed in relation to the models proposed by Salthouse and Czaja (2000) for testing general mediation models, therefore, also apply to similar models used for examining the common cause hypothesis.

### 1.4.2 Lifespan Developmental Antecedents, Correlates, and Consequences of Cognitive Abilities

The lifespan perspective regards change and plasticity as important concepts for all kinds of abilities and personal characteristics. Furthermore, it defines individual differences in these change processes as central for understanding the complexities of human development. The interindividual differences that can be observed at any point in time in a given sample of individuals, however, are not more than a snapshot of the individuals' current positions on a bundle of intraindividual change trajectories. Putting this snapshot back into its developmental context requires a conceptual framework that relates the observed individual differences to variables that can explain how these differences were produced (antecedents), to other theoretically related variables in a multivariate context (correlates), and to variables that can themselves be explained as being outcomes of preceding developmental processes (consequences) (Baltes & Labouvie, 1973).

#### *1.4.2.1 Antecedents*

Developmental antecedents refer to person and environmental differences that lead to differential developmental trajectories that manifest as individual differences at a given point in time in cross-sectional data. Differential availability and allocation of resources that are related to individual and environmental selection processes and their complex interactions can produce large variation in all kinds of dependent measures. The differential allocation of available resources can be described by the model of *selective optimization with compensation* (SOC model; Baltes, 1997). Krampe and Baltes (2003), for instance, use the SOC model to integrate expertise development and classical conceptions of cognitive abilities. Specifically, their framework separates the investment of cognitive resources into culturally or personally defined goals and considers such differential investments as a key to individual differences in cognitive capabilities as defined by either psychometric ability measures or more idiosyncratic expressions of expertise.

On a higher level of abstraction, the framework of *bio–cultural co-constructivism* (Baltes & Singer, 2001; S.-C. Li, 2003) describes the complex and dynamic interactions of environmental and experiential factors with genetic and neurobiological processes. For individual development of cognitive abilities, such co-constructive influences can encompass multiple levels of interactions between biological (e.g., genetic, neurophysiological, and neuroanatomical) and cultural (e.g., educational, occupational, and avocational) factors. In contrast to a modularity view, which reduces the environmental influences to a trigger function for innate cognitive capabilities, bio-cultural co-constructivism much more strongly emphasizes the role of environmental influences on learning, skill acquisition, training, and plasticity for the development of cognitive abilities.

Combining the findings from cognitive psychology—showing that learning curves for all kinds of tasks approach limits of performance—with the psychometric notion of abilities as stable traits, Ferguson (1954, 1956) conceptualized abilities as overlearned behaviors. The observed temporal stability of such trained performance on cognitive tasks is due to asymptotic performance after considerable training on the same or similar cognitive tasks. Ferguson further proposed complex developmental interactions. Transfer from overlearned abilities to new tasks can produce positive correlations among all kinds of cognitive tasks, resulting in the positive manifold. This leads to a two-factor theory of learning, which explains the hierarchical structures found for cognitive abilities by a general positive transfer from learned abilities, together with specific components that have to be acquired additionally when encountering a new task. Using this theory as a framework, all environmental and personal characteristics that can lead to different learning opportunities or differing amounts of practice have the potential to produce differences in the individuals' positions on the learning curves and, subsequently, the individual differences observed in cognitive performance. For example, education obviously has a very important influence on the amount and type of training of cognitive abilities, which could contribute to the development of individual differences on crystallized abilities (as well as other cognitive abilities, such as reasoning; see Ceci, 1991). Furthermore, resource investments driven by personal goals can lead to the development of context-specific expertise in cognitive abilities in addition to the culturally defined goals of achievement on abilities measured by established intelligence tests (Krampe & Baltes, 2003).

An important methodological issue regarding developmental antecedents is whether their causal status can be supported by longitudinal data or by addressing isolated causal mechanisms with *experimental simulation* and *testing-the-limits* approaches (Kliegl, Smith, & Baltes, 1989; Lindenberger & Baltes, 1995). In the case when the information about developmental histories is only available as cross-sectional retrospective data, the causal nature of the theoretical antecedents is confounded with elements of person-environment interactions. Causal interpretations could therefore not be qualified by such data alone.

#### *1.4.2.2 Correlates*

Correlations between cognitive abilities—as measured by psychometric performance indicators—and other variables or constructs can be expected for different theoretical reasons. First, psychometric performance measures should correlate with measures of related constructs at different levels of analysis, such as information-processing tasks or neuropsychological substrates, if it is assumed that they measure the processes underlying the observed performance assessed by psychometric tests. Second, constructs that are related to cognitive performance, but for which the causal direction of the relation is either not clear or for which reciprocal relations over time are expected, can also be treated as correlates of cognitive abilities. Personality and motivation constructs such as *openness for experience* (Costa & McCrae, 1985) or *typical intellectual engagement* (Goff & Ackerman, 1992) can be anticipated to play mediating roles in the interplay between acquired abilities and their investment into further skill and knowledge acquisition (Ackerman, 1996), and might themselves be influenced by the experience of success in developing cognitive abilities. In cross-sectional data reflecting the current status of cognitive abilities and personality characteristics, correlations between measures of both domains can therefore be predicted.

Correlates of cognitive performance as measured with psychometric tests should further show theoretically meaningful patterns of correlations with other constructs that assess or include cognitive functioning. For example, everyday cognitive competency, as measured by complex cognitive tasks with ecologically valid content (Allaire & Marsiske, 1999; Bronfenbrenner, 1979; Demming & Pressey, 1957; Schaie, 1978; Poon, Rubin, & Wilson, 1989) should show higher relations to cognitive ability constructs than measures of basic competencies that require less investment of cognitive resources.

#### *1.4.2.3 Consequences*

Individual differences at a given point in time might predict individual differences in further points of the developmental trajectories and developmental outcomes, namely the gains and losses of resources and functionality in different domains. Maintenance of status in certain cognitive abilities and health, relative independence of other's assistance, and time to death are important possible future outcomes of current cognitive status. To approach such questions, again, repeated measurement designs are necessary, either as longitudinal studies or as *experimental simulation* or *testing-the-limits* studies (Kliegl et al., 1989; Lindenberger & Baltes, 1995).

In cross-sectional data, outcomes can only be treated as correlates. While a causal prioritization of such concurrently measured variables can be pursued by testing the fit of statistical causal models with path analysis and SEM, a prediction of relevant outcome variables by cognitive measures in terms of explaining variance—without making explicit causal claims—is already of scientific value in itself. For example, showing that positive affect is related to cognitive functioning is an important step towards understanding the interrelatedness of psychological variables in old age, even if the causal relations are not clear and cannot be unambiguously determined with correlational data. A possibility that always has to be considered in correlational analyses, however, is that observed relations between two variables might be spurious, that is, caused by the common influence of variables not measured in the analyses.

A classical method for relating factors of an established structure to external variables is *extension analysis* (Dwyer, 1937; Horn, 1973). With this method, the loadings of an external variable on the factors of an established structure can be calculated without changing the structure itself—as would be the case if the external variables were factor analyzed together with the structural set of variables. This allows the examination of the relations of the factors to the external criterion without changing the interpretation of the factors themselves. The newer method of SEM relates confirmatory factors to external variables by explicitly defining statistical causal relations. The property of leaving the measurement model part of a SEM model unchanged when introducing different criterion variables can be achieved by fixing the factor loadings when estimating the external relations.

### 1.4.3 The Logical Status of Common Factors

Taking a developmental perspective on individual differences leads to the questioning of the often-endorsed interpretation of common factors as unobservable latent causal entities. Being, in the first place, mathematical representations of the correlations among a set of variables, can they really be interpreted as underlying unitary resources or processes that manifest in observable performance?

An alternative view on the correlated individual differences that are the basis for common factors is based on the already introduced notion of training and transfer effects (Ferguson, 1954, 1956). More generally, Baltes, Nesselroade, and Cornelius (1978) introduced the idea that differential patterns of level and covariation of environmental input across different abilities can lead to differentiation as well as integration of the ability factor space. They argued that to the degree that environmental treatments can increase performance on cognitive tasks, common learning histories for different tasks could lead to correlations, which in turn could be represented by common factors. By means of simulation analyses, they showed that average correlations among a set of tasks increased or decreased within and between clusters of variables—implying changes in the factor structure—depending on the level and covariation patterns of environmental differences. Environmental differences that were general across behaviors uniformly increased the correlations within and between clusters of variables, which then resulted in a correlation pattern that could be explained by one general factor. Behavior-specific environmental differences increased the correlations within clusters of variables that measured the specific behaviors but decreased the correlations between the variables of different clusters. Such a correlational pattern has a factor structure with correlated but distinct factors.

It follows from these results that the presence of a common factor does not demand the existence of a common "latent" resource; rather it can as well be explained by patterns of correlated environmental differences. This is of special importance for the interpretation of the general factor of cognitive ability. The fact that first-order factors are correlated can be explained by assuming that the performance-increasing components of a learning history—such as motivational aspects or environmental support—are correlated across ability domains. In this sense, education with its complex patterns of general influences as well as opportunities to specialize will have an important influence on the development of the structure of cognitive abilities.

The question of whether common factors describe the structure of cognitive *processes* in individuals is related to the testing of the so-called *ergodicity hypothesis* (Molenaar, 1994). This hypothesis states that the factor structure found for a given sample of individuals does apply to each of the individuals in the sample if they were tested repeatedly on many occasions, and correlations were calculated on the basis of intraindividual variability instead of interindividual differences. While this hypothesis has not been directly tested in the established intelligence structure models, recent simulations by Molenaar, Huizenga, and Nesselroade (2003) have shown that factor structures for inter- and intraindividual variability need not match if there is heterogeneity in the intraindividual structures. Therefore, the interpretation of individual difference factors as indicating the amount of a certain resource available to individuals—and of age relations of these factors as indicating processes of individual development—is not straightforward, to say the least. To describe the cognitive structure of individuals and potentially separate specific processes at this within-individual level, different methods, such as time-series studies and dynamic factor analysis would be necessary (Nesselroade & Schmidt McCollam, 2000). This issue should be kept in mind for the whole empirical part of this thesis, which contains descriptive models of interindividual differences that would have to be tested with P-technique data and models before conclusions about processes on the level of individuals could be drawn.

## 1.5 Methodological and Design Issues of Cognitive Aging Research

One important reason for the great difficulties in integrating findings from different traditions of cognitive aging research seems to be that the studies have used different kinds of research designs. Cross-sectional correlational or quasi-experimental and longitudinal studies have different perspectives on the same subject matter and need not necessarily converge on the same interpretations, due to their different strengths and weaknesses. Therefore, an integration of different findings and theories will also depend upon methodological development that advances methods and statistical models to combine the strengths and overcome the weaknesses of the different study designs and analysis procedures used so far. Therefore, this section provides a short introduction to the methods used in cognitive aging research and the problems associated with them. Because the empirical part of this thesis only addresses cross-sectional data, this section focuses more on the advantages and problems of cross-sectional data and multivariate correlational analyses as compared to other designs and methods.

### 1.5.1 Cross-Sectional Designs

Studies based on cross-sectional data examine aging effects on a between-individual basis. As compared to longitudinal designs, this is a very efficient way of gathering data in terms of required time and resources. However, it is based on the assumption that observed differences between individuals of different age approximate individual age changes. This requires that the individuals being compared are equivalent in all aspects other than chronological age. Besides the possible confound with cohort differences (Baltes, 1968; Buss, 1973; Riley, 1973; Schaie, 1965), the potential impact of all kinds of selection effects seems to be the major challenge for cross-sectional age comparative studies (Baltes, Reese, & Nesselroade, 1977). This includes mortality and morbidity effects, as well as nonequivalent sampling frames and differential sampling techniques at different age levels (Hertzog, 1996). In addition, mean age differences observed in cross-sectional data can be produced by different subpopulations of individuals with substantial interindividual differences around an average intraindividual change (Baltes, Reese, & Nesselroade, 1977; Hofer & Sliwinski, 2001), a phenomenon that can only be captured by longitudinal designs and models using parameters that represent random effects. In fact, an observed mean trend in cross-sectional age-heterogeneous data may not represent the change trajectory of any single individual in the sample.

Two different kinds of designs and corresponding data analysis methods are most commonly used in cross-sectional cognitive aging research: comparisons of extreme age groups using methods of factorial (ANOVA) analysis and multivariate correlational designs. These are compared here to highlight the advantages and problems associated with both designs.

#### *1.5.1.1 Extreme Age-Group Studies*

The prototypical design used in cognitive aging research is a cross-sectional comparison of extreme age-groups, often combined with within-subject experimental manipulations of tasks. Extreme age-groups are often used for the pragmatic reason of sampling convenience and for the statistical power of such comparisons to detect interaction effects (McClelland & Judd, 1993). The efficiency of this design to detect age differences and moderating variables, however, is bought for the price of downscaling age to a dichotomous variable. This implies that population effect sizes—as important measures of the practical relevance of statistically significant effects—are difficult to estimate, and that potentially nonlinear lifespan trajectories are reduced to linear mean differences.

Besides the issue of loosing important information that would be contained in a continuous age variable, there is another major shortcoming of examining cognitive aging by collecting data on different paradigms in separate experiments with different samples. The finding of *age by condition*-interactions allows the determination of a minimum number of processes that have to be assumed to underlie task performance, if appropriate methodological approaches are employed. *State trace analyses* (Bamber, 1979; Verhaeghen, 2000), *time–accuracy functions* (Kliegl et al., 1994), and the principle of *reversed association* (Dunn & Kirsner, 1988) have been proposed for this purpose. Identifying such interactions, however, does not solve the problem of whether different tasks used in different experiments to operationalize a particular theoretical construct are really measuring the same factor. The heterogeneity of findings in the experimental cognitive aging literature, however, calls for integration. Meta-analyses that combine effect sizes of single studies to achieve a best estimate of the population effect size cannot overcome the problem that different operationalizations of theoretical constructs need not measure the same processes. The dimensionality of cognitive aging might be over- or underestimated, by either interpreting different operationalizations of the same process as independent processes, or by taking operationalizations of different process as indications of the same underlying mechanism. An example for the latter can be taken from research on cognitive aging and general decline in inhibitory efficiency. Calculating correlations for a whole set of tasks that are commonly interpreted as measuring inhibition, such as *negative priming*, *directed forgetting*, and *stop-signal* tasks, based on the same sample of subjects, Kramer, Humphrey, Larish, Logan, and Strayer (1994) found little evidence for a common construct of inhibition. It is therefore not clear, and will not become so by using isolated studies each involving a single paradigm, whether the age-associated effects found for these tasks can be explained by a general mechanism.

Because the age variable in experimental designs is only an individual characteristic variable and not a factor of experimental manipulation, the conceptual difference between studies in the experimental tradition and correlational studies is not as large as it might seem. Tasks in a correlational study can be constructed in the same way as in experiments to allow for dissociations of differential aging effects (i.e., analyses of age by task-interactions) by separating independent age-related factors. Furthermore, multivariate correlational designs have the advantage of permitting individual differences in performance on different tasks to be related to each other, thus allowing the examination of their multivariate structure. This strength, however, has to be bought at the price of larger samples and larger numbers of tasks.

#### *1.5.1.2 Correlational Studies*

In correlational studies, age is usually treated as a continuous variable. Samples that are more representative than in extreme age group designs can be created by age-stratified sampling schemes. Another major advantage is that multivariate batteries of dependent measures can be used. This allows individual differences to be related across measures and, therefore, investigations about the multivariate structure of these individual differences by exploratory and confirmatory methods, such as factor analysis and SEM. This opens the possibility of directly addressing cognitive aging phenomena with a multidimensional and multidirectional perspective. These benefits, again, can be combined with experimental manipulations of task demands and comparisons with different age groups (e.g., Rogers, Fisk, & Hertzog, 1994). Some limitations and critiques of cross-sectional analyses of multivariate age differences, however, have to be addressed here.

Hofer and Sliwinski (2001) recently criticized the use of age-heterogeneous cross-sectional data for testing theories about the interdependence of age-associated changes. They argued that correlations among age-related variables confound average population changes (fixed effects) with correlated individual differences in initial level and individual differences in rates of change (random effects). The fixed effects of age for different variables might entirely be due to independent mechanisms, but still induce correlations among these variables in age-heterogeneous data. This argument has already been made by Merz and Kalveram in 1965 (Kalveram, 1965; Merz and Kalveram, 1965) and will be discussed further in the later section on the role of the age variable.

Therefore, correlation-based analyses and models cannot be used to support theoretical accounts that propose general mechanisms. Not rejecting these critiques, in this thesis it will be argued that while theories that propose a general factor as an explanation for the observed age correlations cannot be validated with cross-sectional data, it is still possible to challenge such general factor accounts by showing correlational evidence of multidimensional and multidirectional models being superior to unidimensional representations.

In testing general theories of cognitive aging, an important class of models that have been applied to cross-sectional data are mediation models. Empirical support for Salthouse's (1996) processing speed theory, which states that age-associated changes in performance on all kinds of cognitive tasks are caused by a decline in information processing speed, is largely provided by mediation analyses that are based on hierarchical regression or path analysis. In essence, these mediation analyses test whether there are significant age correlations with the dependent variables after accounting for the mediator variable. Lindenberger and Pötter (1998) have formally shown that these approaches are problematic, because the results depend on the age-independent partial correlations between the dependent and the mediator variables. Therefore, interpretations of such results are only qualified if assumptions about these age-independent relations are theory-based and not just implicitly fixed to zero as is often done when applying these models.

A recent development in cognitive aging research is the use of SEM approaches in cross-sectional designs to test whether general mediating constructs sufficiently account for observed age correlations (Salthouse & Czaja, 2000; Salthouse, 2001). These models, and the problems associated with them, will be presented in a later section to build the foundation for introducing a different type of model as the key towards disentangling general and specific age-associated effects in cross-sectional correlational data.

### 1.5.2 Longitudinal Designs

Longitudinal studies, as compared to cross-sectional designs, have several important advantages for aging research. They allow the direct investigation of important issues, such as intraindividual change, interindividual differences in intraindividual change, and relationship among—as well as determinants of—intraindividual changes of several variables (Baltes & Nesselroade, 1979). The advantages and problems of longitudinal designs will be discussed here only with respects to questions that are of concern for the evaluation of the cross-sectional models presented in this thesis (for a broader review of longitudinal designs, see Nesselroade & Baltes, 1979).

The major point to be made here is that different types of longitudinal designs provide different opportunities to examine the structure of interrelations among change in several variables. The classical longitudinal studies in aging research (see Schaie & Hofer, 2001, for review) were conducted on relatively large samples with several hundred individuals, measured at least twice, and usually for only a few additional occasions, with inter-occasion intervals of one to seven years (for exceptions, see Schaie & Hofer, 2001). These studies allow investigations of the correlational structure of individual differences at each measurement occasions (and therefore the issue of invariance of factor structures over time) and of interindividual differences in intraindividual change. While the questions of which variables predict individual differences in rates of change are of considerable importance for aging research, the correlations among intraindividual differences in change between different variables describe only variations around the average effects of aging. The processes underlying individual differences in change (random effects), however, need not be identical to those responsible for the average change observed for the whole population (fixed effects). Therefore, it is an open question for future research to investigate how the structures of interindividual differences in intra-individual change compare to the structure observed for cross-sectional interindividual differences. A necessary precondition for the examination of structures in change, however, is that there is significant variability of individual slopes around the average slope. Random effects of slopes should not be included in structural analyses if there are no reliable interindividual differences in change to begin with.

There is, however, a different kind of analyses possible with longitudinal data. That is, to examine intraindividual differences within individuals for several variables, and to correlate these intraindividual differences *across measurement occasions*. According to Cattell's (1946, 1952) idea of slicing the data box to get *time by variable*-matrices for individuals, there is the possibility of conducting P-technique factor analyses and applying multivariate time-series methods to investigate the correlational structure of different cognitive variables. Such analyses bear the potential of getting closer to underlying processes than by relating variables to each other only on a between-subjects basis. However, these individual-oriented analyses are also associated with problems. First, it is necessary to collect data on a multivariate measurement battery from a large number of measurement occasions. The practical obstacles related to such design requirements have prevented a breakthrough of such studies until the present (see Jones & Nesselroade, 1990, for a review of existing studies, though). Second, to arrive at conclusions that are generalizable across a defined population of individuals, it is necessary to pool subjects, that is, to show equivalence in their longitudinal covariance structures (Nesselroade, 2001; Nesselroade & Molenaar, 1999). If such research would define subpopulations for which different patterns of multivariate relations among cognitive variables hold true, then cross-sectional structural analyses that are based on interindividual differences could incorporate this knowledge into the selection of samples. A third critical point to be made about P-technique analyses is more fundamental and concerns the treatment of the age variable in the underlying statistical model. Wohlwill (1973) criticized that in P-technique analyses, information about developmental regularities as a function of time or age are ignored because age is treated as a random variable. Essentially, the order of data points is of no importance for the analysis, as is true for the order of subjects in a data file submitted to R-type factor analyses. The description and explanation of developmental functions can therefore not be achieved by P-technique factor analyses. A final problem associated with P technique factor analysis—the issue of autocorrelations among successive observations (Holtzman, 1962)—can be dealt with by using models of dynamic factor analysis, which apply structural equation modeling techniques to time-series data (McArdle, 1982; Molenaar, 1985; Nesselroade, McArdle, Aggen, & Meyers, 2001; Wood & Brown, 1994).

Taking these considerations about the strengths and weaknesses of the different research designs into account, the usefulness of structural analyses based on cross-sectional data for testing general factor theories is limited—as it is not possible to take good model fit of common factor models as indicative of respective common mechanisms. It is only possible to claim that, (i) if a theory proposing common factors were true for all individuals, (ii) if there were only negligible interindividual differences in change, and (iii) if other possible confounds and selection effects could be ruled out, then a corresponding common factor model should be able to explain the observed cross-sectional correlation patterns among cognitive variables and chronological age. Even if this is found to be the case, however, possible alternative explanations with more than one mediating construct still cannot be excluded. Therefore, findings from cross-sectional correlational analyses may show the limits of general factor theories, but cannot unambiguously support these theories. This does not diminish, however, the unique value of cross-sectional data for describing individual differences, their relations to a continuous age variable, and of the patterns of correlations of the age-related individual differences within a multivariate context. With these general considerations as a background, the next section introduces and discusses recently proposed structural models for multivariate age-heterogeneous data.

## 1.6 Recent Debates About Multivariate Models of Cognitive Aging

The question of whether cognitive aging can be explained by a general mechanism, or whether several parallel mechanisms have to be conceived to describe the multivariate picture of cognitive decline, is an issue of ongoing debate. Various methodological approaches have been used to address this issue, including experimental dissociations (e.g., Kliegl et al., 1994), Brinley plots (Brinley, 1965; Cerella, 1985), correlational mediation models and variance partitioning procedures (e.g., Salthouse, 1994), computational models (e.g., Myerson, Hale, Wagstaff, Poon, & Smith, 1990) and simulation studies (e.g., Fisher & Glaser, 1996).

Recently, the theoretical issue of how many assumed causes underlie observed age-related decrements has been coupled with a discussion about the appropriate use of structural equation models to approach this question with cross-sectional data. The use of SEM allows the combination of multivariate structural models of cognitive abilities with the possibility of examining their developmental dynamics by including age as a variable into the model. At the same time, models of individual differences in cognitive abilities put structural constraints on the process explanations that different cognitive aging theories are aiming at (Salthouse & Czaja, 2000). The next section reviews different proposed modeling approaches. Because one focus of this thesis is on introducing such an alternative model representation, the following methodological excursion summarizes simulations by Schmiedek and Li (in press) demonstrating that the existing approaches tend to produce biased results and point out the necessity of a different kind of structural models.

### 1.6.1 Salthouse and Czaja (2000) Models

Salthouse and Czaja (2000; p. 45; see also Salthouse, 2001) proposed a set of four structural equation models for the differentiation of general and specific age-associated effects. The rationale underlying the selection of their models was that a comparison of the fit among the different models should identify whether age-associated effects operate independently on each single task (Model 1), are mediated either by specific factors for groups of tasks (Model 3), or by one general factor (Models 2 and 4). This general factor, again, can be modeled either in terms of a first-order single-factor model (Model 2) or as a second-order single factor in a hierarchical structure (Model 4). Figure 1 shows the structures of these models (Panels A–D represent Model 1–4, respectively).

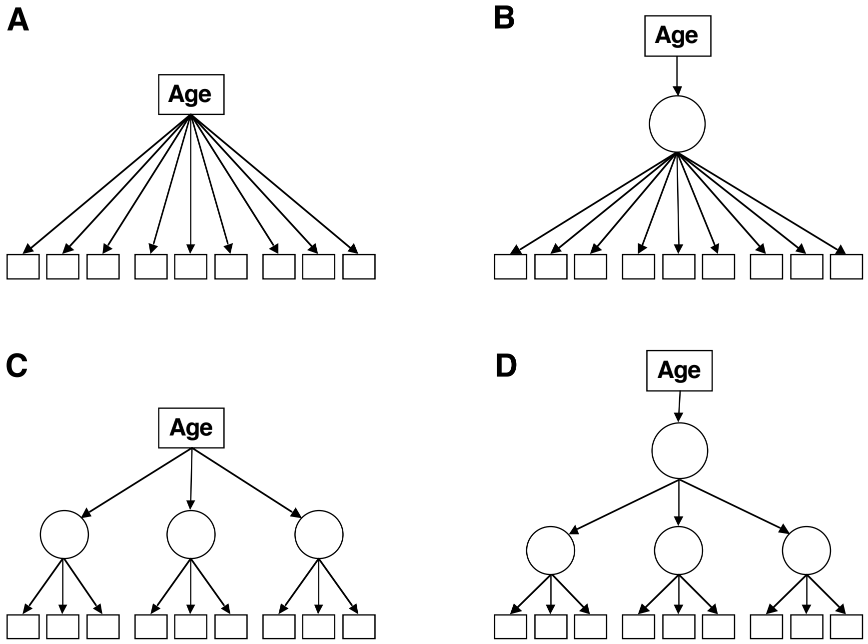

*Figure 1.* SEM models proposed by Salthouse and Czaja (2000) for testing whether age-associated effects can be conceived as general or specific. A: Task-specific age-associated effects. B: Age-associated effects mediated by a general factor. C: Age-associated effects mediated by specific factors. D: Age-associated effects mediated by a general factor in a hierarchical model. Boxes indicate observed variables, circles represent latent factors, and arrows denote factor loadings or regression weights.

Considering the hierarchical structure usually found for cognitive abilities (Carroll, 1993), it seems obvious that only Model 4 (Panel D) can provide sufficient fit, which is what Salthouse and Czaja (2000) found. Models 1 and 2 are highly unrealistic for broad sets of cognitive tasks because they imply that the correlations of these tasks can be explained either only by common age-associated effects (Model 1) or by just one general factor (Model 2). Model 3 assumes that the correlations of first-order factors are only due to common age-associated effects on these factors, disregarding age-independent relations among the factors. Hertzog, Hultsch, Dixon, and Small (2000) highlighted the importance of considering such age-independent correlations among constructs and to use hierarchical models as the basis for testing theoretical accounts such as the common cause hypothesis. Therefore, a test for specific effects has to be incorporated into Model 4. This line of arguments against Models 1 to 3 has already been made by Allen, Hall, Druley, Smith, Sanders, and Murphy (2001) in their re-analyses of several of Salthouse's data sets. These authors tried to identify specific age-associated effects by incorporating direct paths between age and the first-order factors in Model 4 in a stepwise procedure. In their re-analyses, Allen et al. found several examples of significant specific effects in addition to the general effect. Their stepwise procedure of first estimating and fixing the general effect before including specific paths, however, still can lead to results that are biased towards general factor explanations, as is demonstrated in simulations presented in Appendix A.

### 1.6.2 Statement of Problem

To give general and specific effects an equal chance of being detected, an obvious solution would be to use a model where a general effect of aging is specified together with all possible specific effects. However, such a simultaneous estimation of general and specific effects is not possible with the kind of hierarchical model used by Allen et al. (2001) due to linear dependencies among the parameter estimates. No unique solution is admissible for such a model because an infinite number of different combinations of general and specific effects can account for the observed age correlations equally well. The mathematics of this problem is equivalent to trying to solve a system of $n$ unknowns with $n$-1 equations. If any one of the unknowns were fixed to an arbitrary value, however, the system would become solvable. This property is the basis for the different previous approaches proposed to estimate the general and specific effects.

### 1.6.3 Methodological Excursion: A Critique of Stepwise Procedures

Salthouse (1998)—and also Allen et al. (2001)—used a procedure that tries to circumvent the problem of linearly dependent parameters by fixing the general effect parameter[1]. They first estimated a model with only an effect of age on the general factor and then fixed the model parameters to the estimates from this model before introducing and estimating specific effects in subsequent models. Such a procedure, however, could only lead to valid results if the first model would provide a valid estimate of the general effect. If in reality there are specific effects in addition to a general effect, the estimate for the general effect parameter will be biased and so will be the results of all subsequent models with the general effect fixed to the estimate of the first model.

Another way of trying to circumvent the dependencies among the parameters is to fix one presumably non-significant specific effect to zero. Christensen, Mackinnon, Korten, and Jorm (2001) recently have used this approach—based on a similar procedure that has been proposed by Grayson, Mackinnon, Jorm, Creasey, and Broe (2000) in the context of analyzing *differential item functioning*. The problem with this approach, however, is that one has to have knowledge about at least one specific effect being not significantly different from zero. If such prior knowledge is missing, either an arbitrary decision based on face validity has to be made (as done by Grayson et al., 2000), or an empirical procedure of finding such an effect is needed. Christensen et al. (2001) tried to identify a non-significant specific effect by testing separate models for each specific effect. In each of these models, only a general and one of the specific effects were specified. The finding of a non-significant specific effect was then taken as an indication that this effect could be fixed to zero in the final model, which contained a general and all other possible specific effects. In addition to being tied to the question of statistical power when searching for non-significant effects, such an approach faces the same problem of potentially biasing the estimates of all effects as Salthouse's method. Specifying models with only one specific effect will lead to biased estimates if other specific effects exist. Appendix A provides two simulations from Schmiedek and Li (in press), to illustrate in detail how the two stepwise procedures might lead to biased estimates.

In short, if there are true specific effects, then models specifying only a general effect—or only a general effect plus one of the several specific effects—are incorrect

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[1] Salthouse and Becker (1998) used the same kind of stepwise procedure to test whether the effects of Alzheimer's disease could be conceived as general across a broad set of cognitive tasks. Verhaeghen and Salthouse (1997) have applied this procedure to a metaanalytic correlation matrix.

models, and will lead to biased parameter estimates. Using these biased parameter estimates as a basis for subsequent tests of additional specific effects can only result in estimates of these parameters also being biased. While even with such a biasing procedure specific effects might still be detectable, they will generally be underestimated if the general effect is estimated and fixed first. These mechanisms cast doubt on the magnitudes of specific age-associated effects Allen et al. (2001) found in their re-analyses of Salthouse's data. Even though, in general, an approach as proposed by Allen et al. might be able to detect some specific relations in addition to the general effect, it could also miss such specific effects or underestimate the magnitude of the ones identified.

Having demonstrated the problems associated with existing approaches, which all—in one way or the other—hinge on stepwise procedures, the question of how to solve the problem of disentangling general and specific effects in a way that does not bias results in either direction remains. Drawing on models used in individual differences research on human cognitive abilities, an alternative representation of the hierarchical structure of intelligence is presented here. This alternative representation allows the simultaneous estimation of general and specific effects, thereby circumventing the need for fixing individual parameters to potentially biased values. Before applying the alternative model to simulated and empirical data, a brief overview of its conceptual and methodological background is given.

## 1.7 The Nested Factor Model: An Alternative Representation

Representing the structural constraints imposed by the relations among a set of cognitive tasks generally can be achieved by the kind of hierarchical model as Salthouse and Czaja’s Model 4 (Carroll, 1993). However, this model has the important property of restricting the relative composition of general and specific variance to an equal ratio across the observed variables constituting a respective first-order factor. This property is explained in some detail below to illustrate the need for a different type of model.

The model used by Salthouse and Czaja is the confirmatory factor analytic equivalent of the so-called Schmid–Leiman orthogonalization (Schmid & Leiman, 1957) of exploratory factor solutions with several strata of factors. Gustafsson and Balke (1993; see also Jensen & Weng, 1994; Rindskopf & Rose, 1988) have proposed this model as one way of representing hierarchical structures with confirmatory factor analysis and called it the *hierarchical model*, a term that will be adopted for the remainder of this thesis. This model splits variance into orthogonal contributions of the general and specific factors at the level of the first-order factors. The second-order general factor represents variance that is common to the first-order factors, while the residual variances (or *disturbance terms*) of the first-order factors after accounting for the general factor are the specific factors. By definition, the second-order general and the residual specific factors are all orthogonal to each other. The observed variables load only indirectly—through the first-order factors—on these general and specific factors. To interpret the general and specific factors in terms of their relations to the observed variables, it is therefore necessary to calculate the indirect loadings of the variables by multiplying their loadings on the first-order factors either by the loading of the respective first-order factor on the general factor, or by the loading of the first-order factor on its specific residual factor, respectively. This results in indirect loadings on the general and specific factors that are proportional to each other within each set of the variables that are assigned to the respective first-order factor. In other words, the higher the relation of an indicator variable to the general factor, the higher its relation to the corresponding specific factor will be. The ratio of variance that is due to the general and specific factors, respectively, is equal for all indicator variables of a given first-order factor. Figure 2 shows this constraint of the hierarchical model. In this example, the ratio of general to specific variance is 2:1 across all indicator variables for one first-order factor, and 1:2 for the other.

An alternative model for representing hierarchical factor structures also stems from exploratory factor analytic approaches for describing the structure of intelligence, and even dates back to 20 years earlier than the Schmid–Leiman method. In 1937, Holzinger and Swineford already presented the so-called bi-factor method, where each variable has both, a direct loading on the general and a direct loading one specific factor. All factors in this type of model are orthogonal to each other, but without the proportionality constraints implied by the Schmid–Leiman procedure. This model and similar procedures of first extracting a general factor and then examining group factors in the residual correlation matrix, have been used extensively by the British research tradition on hierarchical models of intelligence structure (e.g., C. Burt, 1949; Thomson, 1946; Vernon, 1961). This line of research contrasts the US tradition of modeling oblique and higher-order factor models (Cattell, 1971; Horn, 1967; Thurstone, 1938).

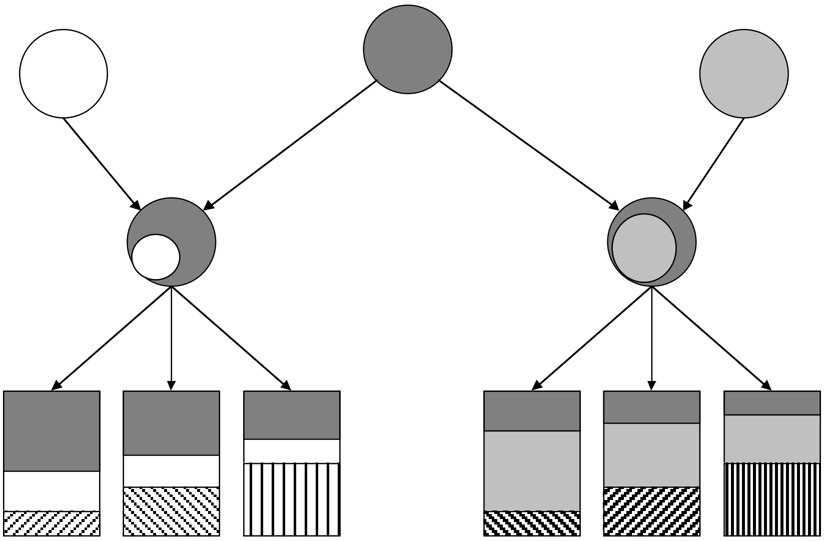

*Figure 2.* The composition of variance in the indicator variables of a hierarchical factor model. The variance of each variable can be split into a component due to the general factor (dark gray), a component due the respective specific residual factor (white and light gray, respectively), and a variable-specific-plus-error component (hatched). The specific residual factor contributions are proportional to the general factor contributions for the indicator variables of each first-order factor. The ratio of general to specific variance is 2:1 for the left and 1:2 for the right first-order factor.

The development of statistical methods for *restricted factor analysis* (Jöreskog, 1969) provided the foundation for replacing exploratory factor models with confirmatory factor models. It is important to note, however, that the use of the terms *exploratory* and *confirmatory* may be misleading in this context because both classes of methods can be used for exploratory as well as for hypothesis-testing (confirmatory) purposes. Therefore, the critical issue is the convergence of theoretical orientation and the application of analysis procedures as either exploratory or confirmatory tools rather than the choice of a statistical method per se (Nesselroade & Baltes, 1984).

A confirmatory factor analytic counterpart of the bi-factor method as an alternative to hierarchical models has been presented by Gustafsson (1989), who termed it *nested factor model* (NF model; see also Gustafsson & Balke, 1993; Jensen & Weng, 1994; Rindskopf & Rose, 1988). The structure of a NF model is shown in

Figure 3. Here, the separation of variance into one portion that is common to all tasks and orthogonal components of variance that are common to only subsets—or group factors—of the tasks is achieved at the level of the observed variables. As compared to similar models based on exploratory factor analysis, the NF model has the advantage of restricting the factor-loading pattern of the specific factors in a way that only those variables that are assigned to a theoretical construct—such as reasoning or memory—load on the respective specific factors while the remaining variables are constrained to have a loading of zero. These restrictive assumptions can be tested using model fit indices. Furthermore, the confirmatory NF model allows for a simultaneous estimation of the general and specific factors, rather than first extracting a general factor and then analyzing the residual matrix, which would tend to result in a stronger general factor than results found with a simultaneous estimation.

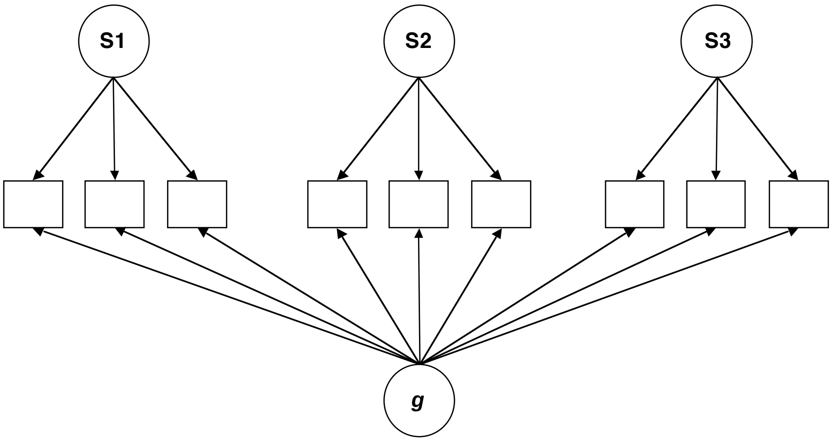

*Figure 3.* Example of a NF model with one general factor (*g*) and three specific group factors (S1 to S3).

The NF model has been applied to the cognitive domain in several studies on the structure of intelligence and on the relative importance of broad versus narrow factors of intelligence for the prediction of criterion variables such as school achievement, inspection time performance, and psychomotor skill acquisition (Chaiken, Kyllonen, & Tirre, 2000; Crawford, Deary, Allan, & Gustafsson, 1998; Gustafsson, 1989, 1999; Gustafsson & Balke, 1993; Gustafsson & Undheim, 1992; Härnqvist, Gustafsson, Muthén, & Nelson, 1994; Hertzog & Bleckley, 2001). Models that are mathematically identical to the NF model have also been used in many applications outside research on intelligence structure. For example, multitraitmultimethod analyses (Marsh, 1989; Widaman, 1985) and latent variable models for the distinction of traits and states (Steyer, Ferring, & Schmitt, 1992) often use equivalent or very similar models.

Mathematically, the NF model and the hierarchical model differ in that the ratio between the general and specific variance with respect to each of the indicator variables is free to vary in the NF model. In contrast, this ratio is constrained to be constant across all indicators of a given first-order factor in the hierarchical model (see Yung, Thissen, & McLeod, 1999, for a mathematical treatment of this issue). With the presence or absence of this proportionality constraint being the only mathematical difference between the two kinds of models, it is often difficult to empirically differentiate them in terms of model fit. Mulaik and Quartetti (1997) have examined the power to reject a hierarchical model if the true model is a NF model. According to their analyses, even with sample sizes that would be considered large in cognitive aging research, the power to distinguish these two models is generally still quite low. This means that in general both models provide equally well-fitting representations of intelligence structures, if the only concern is to capture the covariance pattern among cognitive tests. In terms of interpretation, the nested general and specific factors can be seen as being "closer to the variables" by allowing each variable to have separate loadings of independent magnitude on the general and a specific factor. In both models, the general factor contains variance that is common to all tasks and the specific factors represent variance that is common only to sub-sets of tasks, but independent of all other variables. In the NF model, however, the proportions of general and specific variance contained in each variable are allowed to vary. The simulation in Appendix B demonstrates that this conceptual difference is the key to disentangling general from specific age-associated effects. The simulations, in addition, also explore how variations of the relative contribution of general and specific factor variance in the indicator variables affect parameter interdependence and parameter sensitivity (Li, Lewandowsky, & DeBrunner, 1996) when relating the nested factors to other variables, such as age. In short, more optimal parameter dynamics—i.e., in this case high parameter sensitivity and low interdependence—was observed in cases where the ratio of general to specific variance was heterogeneous across tasks. It seems that the more heterogeneous this ratio of general to specific variance is across indicator variables, the higher the precision of the age relation estimates—reflected in smaller standard errors.

### 1.7.1 The Role of the Age Variable

The NF model introduced in the last section represents the correlational structure of a multivariate battery of cognitive tasks in a way that captures both the variance general to all tasks and the specific variance of group factors. To approach the question of how age-associated effects on mean levels of functioning can be explained, it is necessary to relate the age variable to the individual differences represented by the factors in the model. There are, however, different ways of conceptualizing the role of the age variable in relation to the factors of the NF model.

It has to be recognized that chronological age as a measure of physical time can only serve as an imperfect proxy variable for age-related processes. Variables measured in a cross-sectional age-heterogeneous study can be plotted as a function of chronological age and to some degree a linear or non-linear regression function will describe the functional form of this relation. The goal of developmental research is then to explain these functions by process measures, thereby incorporating age into the dependent variables of the research design (Wohlwill, 1970). However, as long as theory development and technical limitations do not allow a direct measurement of the underlying processes, the statistical relationship between chronological age and the cognitive variables of interest can be employed to use age as a useful proxy variable for the underlying developmental processes. Because the age variable can be used as a proxy in the description of a multitude of such functions, it potentially represents a number of simultaneously acting developmental processes—chronological age can approximate a causal heterogeneity. This role of age as a recipient of multiple causes in the models presented here is captured by simultaneous relations of the age variable to the different general and specific factors. However, a decision has to be made to either introduce age as an independent variable, covariate, or dependent variable into the structural models. While the most common use of the age variable in models of cognitive aging is as an independent cause—describing behavior as a function of age—it is argued here that conceptualizing age as a covariate or dependent variable has important advantages.

#### 1.7.1.1 *Chronological Age as a Predictor Variable*

The NF model defines a structure with orthogonal general and specific factors. If the age variable is introduced into this model by specifying directed "causal" paths from age to the factors (*age-as-a-predictor* model), this implies, by the path tracing rules implemented in SEM, that these factors become correlated. Their correlations are defined by the product of the statistical causal age paths for each pair of factors. Conceptually, this reflects the fact that if a set of variables are indicators for—related or independently operating—age-related processes, they will be correlated in age-heterogeneous data, as recently pointed out by Hofer and Sliwinski (2001). In a model that is based on age-heterogeneous data, but does neither include nor explicitly specify the role of the age variable, the general factor is accounting for variance that is common to all tasks—potentially also including shared age-related variance of otherwise independent processes. The fact that a general factor in age-heterogeneous data absorbs the age-related variance of a set of variables that are all correlated with age has been termed *"Simultane Überlagerung"* [simultaneous interference] by Merz and Kalveram (Merz & Kalveram, 1965; see Kalveram, 1965, for a mathematical treatment, and Reinert, Baltes, & Schmidt, 1966, for discussion of these issues in relation to the differentiation hypothesis of intelligence development).

If the age variable is included as an independent variable with statistical causal paths on all factors of the structure, it takes the role of a second general factor on top of the whole structure. An interesting property of such a model is that its factor-loading pattern is equivalent to the pattern that one obtains if the factor model is fitted to an age-partialled covariance matrix (see Appendix C for a mathematical derivation). This property holds if the model has perfect fit. If the model does not have perfect but good fit, its measurement model will still be very similar to the one based on an age-independent covariance matrix. This implies that in the age-as-a-predictor model, age-independent relations among the observed variables predominantly define the factors. What does this mean for the interpretation of the age-associated effects on the latent factors?

Hofer and Sliwinski (2001) have shown that the observed correlations among age-related variables in age-heterogeneous data are a function of individual differences in initial level, average change (fixed effect of age), and individual differences in rates of change (random effects of age). If age is partialled out from the age-heterogeneous data, the part of the observed correlations that is due to the fixed effects of age is removed. The remaining correlations, then, are a function only of random effects reflected in individual differences in initial level and in inter-individual differences in the rates of change. The models used throughout this thesis, however, make the simplifying assumption that these random effects of age are negligible. While the relative importance of the individual differences in rates of change is an issue that needs to be addressed by further research, existing empirical evidence supports a view that they are relatively small as compared to individual differences in level (cf. Salthouse & Nesselroade, 2002). Specifically, this view is supported by the fact that retest correlations of intelligence tests with very long intervals between testing occasions are remarkably high (T. Y. Arbuckle, Maag, Pushkar, & Chaikelson, 1998; Deary, Whalley, Lemmon, Crawford, & Starr, 2000; Owens, 1966; Schaie, 1985). If the random effects were large, however, the models used in this thesis could not be fitted to the whole sample. Instead, multiple group or mixture models would have to be used in order to take into account the differential rates of change for subgroups of subjects. Under the assumption that the random effects of change are negligible, the age-partialled structure is defined only by individual differences in initial level and is, therefore, equivalent to the structure that could have been observed if all subjects would have been observed at the same age.

It can be argued, however, that age-associated processes are an important source of the interindividual differences that define a factor structure. From such a perspective, the factors identified on the basis of the age-independent covariances might not be an adequate representation of individual differences. Rather, there needs to be other ways of representing age in relation to the factor structure that do not exclude age-associated individual differences from the definition of common factors.

#### *1.7.1.2 Chronological Age as a Covariate or as a Dependent Variable*

Instead of defining chronological age as a cause or predictor of individual differences, which superimposes an age-induced correlational structure on an age-independent structure, one could argue for a representation where age differences are seen as internal to the factor structure. The role of the age variable would then change from being an predictor of individual differences to a correlate of the factor structure. This can be achieved by still using the NF model to separate orthogonal general and specific factors in age-heterogeneous data. Instead of drawing statistical causal paths from the age variable to the factors, the factors can each be allowed to correlate separately with age. Such a representation of the age relations is also more consistent with the orthogonal representation of factors in the nested factor model at a conceptual level. If this projection of chronological age into the factor space defined by the NF model results in independent significant and substantial age correlations of the orthogonal factors, this reflects the role of chronological age as a potential proxy for a multitude of heterogeneous causal processes.

The age correlations of the orthogonal nested factors are mathematically equivalent to the standardized regression weights in a model with age being a *dependent* variable that is predicted by the orthogonal general and specific factors. This is the case because in multiple regression analysis, regression weights are equal to correlations if the predictors are uncorrelated—as is the case with the orthogonal factors in the NF model. Such a representation with age being predicted by the nested factors provides a summary measure of how much age-associated information is contained in the multivariate space of individual differences in cognitive functioning. This is especially useful when comparing different models. Using different regression models, e.g., with only the general factor as predictor variable versus general plus specific factors as predictors, one can investigate how strongly a given multidimensional representation of individual differences in cognitive status, as compared to a unidimensional—general factor only—representation, is related to individual differences in chronological age.

Taken together, there are different possibilities for relating a factor structure with general and specific factors to the variable of chronological age. These different representations usually cannot be differentiated in terms of goodness-of-fit alone. Rather, one has to make a choice based on the theoretical role that is assigned to the age variable, either being a constituent part of the individual differences that define the factor structure, or as a source of variability extraneous to the factor structure. In the first case, age could be defined as a correlate or even a dependent variable of the general and specific factors. In the second case, age is conceptualized as a predictor of individual differences in the factors.

The above considerations about relating the NF structure to the age variable do apply to other external criterion variables that can also be examined in relation to the nested factors. It is therefore important to have a theoretical conceptualization of external variables as either causes, correlates, or consequences of the individual differences represented by the NF model as a basis for deciding about whether to include these variables as independent variables, correlates, or dependent variables. Each variable that is used as a cause of individual differences in cognitive abilities will be partialled out of the model structure, just as shown formally in Appendix C for the age variable. Depending on what causes are included in the model, the factor structure will differ accordingly and it will only represent individual differences partialled for the influences of the independent variables. This considerably complicates the interpretation of the general and specific factors and the comparisons of the role these factors play in analyses with different external criterion variables. Therefore, it is argued here to use the NF model with age and other external variables as correlates or dependent variables of the general and specific factors. Applied as such, the NF structure gives a full representation of individual differences in cognitive functioning that allows including age and all sorts of criterion variables either simultaneously or in separate models, without changing the conceptual interpretation of the individual differences captured by the general and specific factors.

Relating the NF structure to external criterion variables also poses the question of whether age should be controlled for when examining such correlations. It is not possible to give a general rule of whether, or under what circumstances, age should be partialled out of the factor structure and the criterion variables when external relations of the cognitive structure are of interest. The rationale used in the empirical part of this thesis therefore was to, first, estimate models with age variance contained in the factor structure, and then compare to the results from models with age-associated effects been partialled out. If the results of both approaches differ substantially, the reason *could* be that the cognitive and the external variables are correlated only because they are independently related to age without any functional relationship between the two. While this is not necessarily the case, it has to be considered as a possibility in interpreting results.

## 1.8 Summary of Theoretical Part

Several theories have been proposed to account for the age-associated performance differences observed in a manifold of different cognitive tasks. These theories use different theoretical constructs—such as fluid intelligence, processing speed, or working memory—to account for the age-related performance declines. Individual differences studies allow conducting structural analyses of the interrelations among these different constructs, no matter whether they root in the experimental or the psychometric tradition of cognitive research. These structural analyses, however, have to be enriched by considering developmental aspects as age-associated changes of the factor structure, and antecedents, correlates, and consequences of the individual differences. Furthermore, the age variable has to be related to the model components in order to test the relative importance of different factors for explaining the observed age differences in cognitive performance. The age relations of the factors in the cognitive structure have been the issue of recently proposed models, which are prone to statistical problems and biased results, however.

Based on models used in individual differences research, a different kind of structural representation is proposed here. The so-called *nested factor model* allows for an unbiased simultaneous testing of general and specific age-associated effects and of other external criterion variables. One might speculate that such a model could bias results towards specific effects, because it specifies parameters for specific effects that might not exist. This is, however, not the case. If a specific effect specified in the NF model is not present, then the expected value of the estimate of its age effect will be zero. General and specific effects, therefore, have an equal chance of being detected in the NF model.

Regarding the role of the age variable, the choice of age being either the predictor variable or a covariate influences the interpretation of the measurement structure. Using age as a covariate does not change the observed structure of age-heterogeneous data—as it is just a projection of chronological age into the multivariate space defined by the model. Using age as a dependent variable provides useful relative summary information about how well age can be projected into this space. Defining age as a predictor variable, however, has an influence on the factor structure, because the causal paths from age imply correlations among the factors, which would, otherwise, be orthogonal.

Having introduced these different ways of modeling age-associated effects, in the empirical part of this thesis these different models are applied to the BASE data to address the questions of how to adequately represent the multivariate structure of cognitive abilities in old and very old age. The models will be evaluated in terms of their goodness-of-fit, communalities (i.e., explained variance of the indicator variables), the representation of age-associated variance, and relations to external criterion variables.

In the last section of the empirical part, Monte Carlo simulation analyses are used to address some technical properties of the NF model's ability to disentangle general and specific effects of aging. The controlled conditions of these simulations allow developing recommendations of how to set up future research with multivariate correlational methods.