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GETTING BETTER WITH AGE

Toward an Integrative Science of Life-Span Development and Aging

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The study of aging demands an integrative life-span developmental framework, involving interdisciplinary collaborations and multiple methodological approaches for understanding how and why individuals change, in both normative and idiosyncratic ways. We highlight and summarize some of the issues encountered when conducting integrative research for understanding aging-related change, including, the integration of results across different levels of analysis; the integration of theory, design, and analysis; and the synthesis of results across studies of aging. We emphasize the necessity of longitudinal designs for understanding development and aging and discuss methodological issues that should be considered for achieving reproducible research on within-person processes. It will be important that current and future studies permit opportunities for quantitative comparison across populations given the extent to which historical shifts and cultural differences influence life-span processes and aging-related outcomes.

Key Words: Cross-cultural differences—Developmental methods—Life course and developmental change—Longitudinal change—Measurement—Quantitative methods—Research Methods and Issues.

THE study of aging demands an integrative life-span developmental approach. Developmental and gerontological orientations, involving a melding of biological, psychological, and social perspectives, merge in life-span development and life course epidemiology (e.g., Alwin & Wray, 2005; Baltes, 1987; Kuh, Ben-Shlomo, Lynch, Hallqvist, & Power, 2003) to examine lifelong processes and evaluate how early development can carry forward and influence later life health and behavioral outcomes. The need for an integrated and unified research framework has been championed, particularly in terms of multidisciplinary and multilevel integration (e.g., Bachrach & Abeles, 2004; Butz & Torrey, 2006; Hofer & Alwin, 2008; Magnusson & Cairns, 1996; National Research Council, 2000, 2001a, 2001b; Shanahan & Hofer, 2005; Widaman, 2008). With respect to these integrative orientations, gerontological science shares a great deal with developmental science, as it

> emphasizes the dynamic interplay of processes across time frames, levels of analysis, and contexts. Time and timing are central to this perspective. The time frames employed are relative to the lifetime of the phenomena to be understood. Units of focus may be as short as milliseconds, seconds, and minutes, or as long as years, decades, and millennia. In this perspective, the phenomena of individual functioning are viewed at multiple levels—from the subsystems of genetics, neurobiology, and hormones to those of families, social networks, communities, and cultures." (Carolina Consortium on Human Development, 1996, p. 1)

The scientific discovery of life-span determinants and within-person processes leading to aging-related changes is a major research priority internationally. Extant evidence indicates that individual differences in adult development and aging involve broad, diffuse, multivariate, and perhaps highly idiosyncratic processes. An integrative science of aging requires multiple interdisciplinary collaborations and methodological approaches for understanding how individuals and populations change over time. The term, "integrative," is important in several ways that represent promising directions in the field of gerontology: in terms of the integration of domains of study (i.e., health, cognition, biology, and social), and the integration of information across independent studies and across alternative research designs and statistical methods. The interplay between replication and establishing the range of generalizability of results in interdisciplinary longitudinal research can present remarkable challenges. Careful discussion of results must include consideration of the age, birth cohort, health, and education of individuals in the sample, the measures used, the number and spacing of assessments, and rates of response and attrition (e.g., Van Dijk, Van Gerven, Van Boxtel, Van der Elst, & Jolles, 2008). Placed in a broader and historical (or future) context, we must consider research design, population sample, historical period, measurement, and analysis in assessing the validity of inferences and the reproducibility and generalizability of findings.

Along these lines, the role of context in development and aging has long been appreciated (e.g., Kuhlen, 1940; Schaie, 1965). Contextual effects are often operationalized in terms of birth cohort to capture broad environmental differences. Currently, the majority of knowledge about aging-related change comes from cohorts born in the early 1900s. As social and environmental contexts change, any single longitudinal study may be of limited utility for predicting influences on aging-related outcomes in future studies of later born cohorts. Given societal changes in health, nutrition, and access to educational opportunities, results from previous and current studies may differ from those of future studies, providing an

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important context for understanding changes in population and individual aging over time (Alwin, 2008; Schaie, 2008).

Integrative theoretical approaches and interdisciplinary research require integrative data analysis. The central foci of the current article are, therefore, the methodological issues related to integrative approaches for understanding aging-related change. These analytical challenges include (a) integration of results across different levels of analysis, (b) integration of theory, design, and analysis, and (c) synthesis of results across longitudinal studies of aging. Throughout, we emphasize the necessity of longitudinal designs for understanding development and aging, with emphasis on methodological issues that must be considered for achieving replicable research on within-person processes. In the larger context, it will be important that current and future studies permit analytical opportunities for quantitative comparison across populations given the historical shifts and cultural differences that influence life-span processes and late-life outcomes. These many challenges that must be taken into account for a cumulative science of life-span development and aging may best be resolved through international collaborative research.

Although direct assessment and analysis of within-person change and variation is fundamental for understanding development and aging (e.g., Baltes & Nesselroade, 1979; Hofer & Sliwinski, 2006; Molenaar, 2008; Wohlwill, 1970), cross-sectional research focused on explaining between-person age differences has dominated theoretical developments. Implicitly or explicitly, the objective of much cross-sectional research has been to infer age-related change and associations among change processes based on analysis of between-person age differences. However, the variety and significance of confounds related to cross-sectional designs greatly limit their utility for adequately answering questions regarding individual change. Age-heterogeneous cross-sectional designs, in particular, present with many confounding features, essentially capturing the state of individuals of different ages, drawn from different life-span contexts (birth cohorts), and undergoing differential mortality selection (related to age, birth cohort, and other characteristics). Additionally, any single measurement is a complex function of initial individual differences, previous development and cumulative change, intra-individual variation, and measurement error. The analysis of associations using age-heterogeneous cross-sectional designs is confounded by between-person age trends (Hofer, Flaherty, & Hoffman, 2006; Hofer & Sliwinski, 2001; Hofer, Sliwinski, & Flaherty, 2002), leading to spurious inferences regarding interdependencies among age-related functions (e.g., common cause hypothesis and age-related mediation; see Hofer, Berg, & Era, 2003 for example of sensory acuity and cognitive decline). Although the variety of questions asked of cross-sectional data remain of high interest to the field, results based on cross-sectional observations have not usually held up when evaluated in longitudinal data (e.g., speed mediation hypothesis; Sliwinski & Buschke, 1999).

Longitudinal designs and analysis can overcome many of the intractable confounds of between-person age-comparative approaches (e.g., Schaie & Hofer, 2001). Longitudinal designs permit separation of individual differences at the initiation of the study from within-individual change and provide a basis for obtaining valid inferences regarding change conditional on study attrition and mortality. In some longitudinal designs, measurements obtained over both short and long time periods permit analysis of the dynamic interplay between processes that unfold over varying time periods (e.g., intra-individual variation, retest, and aging). The comparison of results across birth cohorts permits important opportunities for understanding differences across historical periods.

We highlight and summarize some of the issues for integrative research for understanding aging-related change. First, we discuss issues related to levels of analysis and the importance of both separating and integrating results from different levels of analysis. Second, we consider the need for a variety of research approaches and an integration of theory, research design, and statistical methods. We then discuss the need for integrating findings across studies, with an emphasis on rigorous cross-study comparison to evaluate reproducibility of results as well as differences related to birth cohort and social and cultural differences in a global context.

Integrating Across Levels of Analysis: From Population to Individual Effects

Research on developmental and aging-related processes, relying on a variety of designs and methods, provides information on population average patterns of change, individual differences in level and rate of change, and the dynamics of within-person processes (Figure 1). These levels of analysis provide complementary information about population and individual effects (e.g., Baltes & Nesselroade, 1979; Hofer & Sliwinski, 2006). From the population level of analysis to the analysis of temporal dynamics within individuals, these levels correspond to a hierarchy of aggregated effects and, often, to different temporal sampling frames that have ramifications for the interpretation and comparison of effects within and across levels of analysis.

Population Average "Developmental" Trends

Population trends can be based on between-person age differences, within-person age changes, or an aggregate of between-person and within-person effects. Although population trends are useful for many purposes (e.g., identifying the average age at which distinct types of cognitive functions begin to decline), such trends often fail to describe individuals (Estes, 1956; von Eye & Bergman, 2003). Estimating a valid single age-based trend is challenging because aggregation across conditional effects related to chronological age, birth cohort, and survival age is not plausible. For example, in age-heterogeneous designs, whether cross-sectional or

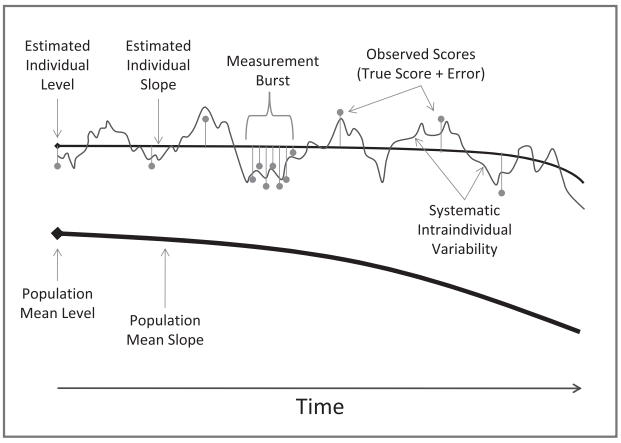

Figure 1. Theoretical decomposition of an individual's observed scores.

longitudinal, samples are drawn from surviving members of different birth cohorts, and require conditioning on initial selection, age, attrition, and survival age in order to make valid inferences to defined (i.e., mortal) populations of aging individuals (Hofer & Hoffman, 2007; Kurland, Johnson, Egleston, & Diehr, 2009).

Between-Person Age Differences

Cross-sectional variance decomposition methods have been central for gerontological, and particularly for cognitive aging, research with emphasis on mediation models of age differences and shared age-related variance. In between-person analysis of time-dependent variables, covariation can arise due to (a) individual differences in rates of change on different variables (i.e., random effects, expressed as deviations from population average change), (b) systematic and random time-specific variation occurring within an individual, and (c) magnitudes and patterns of population average change. Hofer and colleagues presented a formal treatment of the aggregation bias due to age-related mean differences in cross-sectional designs, showing the problems with relying on age-heterogeneous cross-sectional designs for estimating associations and age-based mediation models (Hofer & Sliwinski, 2001; Hofer et al., 2006; see also Kraemer, Yesavage, Taylor, & Kupfer, 2000). A comprehensive account of confounds in analysis of age-heterogeneous cross-sectional data and utility of alternative narrow age-cohort designs, often used to evaluate age-related dedifferentiation, can be found in Hofer et al. (2006; see also Hofer et al., 2003).

Between-Person Differences in Within-Person Rates of Change

In contrast to cross-sectional between-person analyses, latent growth curve models permit direct assessment of within-person rates of change and the influence of static and time-varying predictors. Multivariate extensions of these models can also address correlated levels and rates of change across variables. When conditioned on initial between-person age differences, the structure of individual differences in change provides a stronger basis for understanding the relative independence or interdependence of aging-related processes within the population. Models of correlated age slopes at the between-person level are based on smoothed (e.g., linear) individual trajectories over time, with the time-specific residuals providing complementary evidence regarding the structure or commonality of change.

Within-Person Variation and Covariation

Interdependency and dimensionality of dynamic within-person processes is increasingly the focus of research on developmental and aging-related change (Larsen, 2007; Li, Huxhold, & Schmiedek, 2004). Within-person variation and covariation, after careful detrending of within-person means and trends, can be treated analytically as "aggregated," "coupled," and "patterned." Aggregated within-person variation is based on overall within-person variation (e.g., standard deviation and variance; MacDonald, Nyberg, & Bäckman, 2006) without regard to time structure (ordering). It is an index of magnitude of variation that is useful for evaluating between-person differences in variability and change in variation over time or conditions. Coupled or "correlated within-person covariation" focuses instead on the interdependency and dimensionality of within-person processes, includes both p-technique and dynamic factor models, and refers to systematic concurrent (and possibly lagged, e.g., related to exogenous influences) associations in a temporally ordered multivariate system (e.g., Molenaar & Nesselroade, 2009). Temporal ordering involves simultaneous as well as lagged processes—one cannot reshuffle time within processes without distorting the covariation (as one can with aggregate indices). "Patterned intra-individual variation" (e.g., Nesselroade & Ghisletta, 2000) refers to cyclic variation (e.g., cortisol levels) but also includes deterministic (i.e., chaotic) functions that may appear random. Within-person covariation and patterned variation are particularly sensitive to temporal sampling features of the study design (e.g., Boker, Molenaar, & Nesselroade, 2009; Martin & Hofer, 2004).

Separating Levels of Analysis

These levels of analysis represent a broad system of increasingly disaggregated effects that are complementary to one another in that each conveys different information about individual and population change. Results are confounded when incomplete separation of effects across levels occurs. For example, although age-related mean trends are important for understanding population differences across cohorts and countries, incomplete estimation of age-related population trends can lead to spurious associations in the analysis of individual differences in level, change, and variation. In

studies focusing on within-person variation, between-person sources of variance, such as intra-individual means and trends must be separated so as to not bias model estimates (e.g., Hoffman & Stawski, 2009; Horn, 1972; Mroczek, Spiro, & Almeida, 2003; Sliwinski & Buschke, 1999). This requires explicitly estimating multiple levels within a simultaneous analysis (e.g., in a multilevel or structural equation modeling framework; e.g., Diggle, Liang, & Zeger, 1994).

Despite the relative prevalence of cross-sectional work in the ostensibly developmental field of gerontology, it is generally agreed that age difference information is merely a proxy for age change information, which is only available in longitudinal data. However, longitudinal data, and particularly longitudinal data based on an initially age-heterogeneous sample, contain both between-person and within-person information. Many models currently presented in the literature, among them sophisticated multilevel or structural equation models, do not explicitly differentiate these aspects of longitudinal data. It is surprisingly easy, in this way, to unintentionally rely too heavily on cross-sectional aspects of the data. Ware (1985) explained clearly that initial age should be included as a covariate in time-based random effects models in order to separate the effects of between-person initial differences in age from within-person changes with age over time. This admonition, however, was forgotten once computer software was developed to handle the extremely sparse matrices required to estimate models with an age basis. The advice, however, is no less relevant in this context, and Mendes de Leon (2007) reminded researchers of the need to account for initial age differences, particularly in the field of gerontology where a "healthy participant" (i.e., between-person selection) effect can be very strong. Neglecting to model initial age and other selection-related individual differences in intercept (i.e., level) and slope (i.e., rate of change) essentially constrains them to be equal. This misrepresents cross-sectional information as longitudinal (Sliwinski, Hoffman, & Hofer, 2010), undermining the utility of the longitudinal information.

Integrating Multiple Levels of Analysis

As the analysis of individual change and variation requires the disaggregation of between-person and within-person effects, the challenge is to consider all aspects of population and individual change rather than focusing on each level of analysis in isolation. We can accomplish this in several ways. At the level of description and reporting, all effects should be included in the overall findings regarding a particular research question. For example, when an analysis provides information on mean trends, within-person slopes, and within-person covariation, these should all be reported and their combined roles in the broader context should be considered. Results from any particular level of analysis must be considered in the context of other levels, providing a coherent picture of population and individual variation and change.

Analytically, models addressing within-person slopes and variation represent a large step toward capturing relevant individual-level aspects of change. A multilevel or random effects model is one type of model that permits the simultaneous estimation of both population-level and individual-level effects (see McArdle, 2008 for discussion of longitudinal models). Although within-person change must provide the basis for developmental theory and research (e.g., Molenaar, 2008; Wohlwill, 1970), the analysis of between-person differences in within-person change processes is equally essential for understanding developmental and aging-related processes due to numerous individual-specific conditions (i.e., genes), intrinsic differences in developmental and aging-related change, and limited exposure of any single individual to the breadth of contextual factors across the life span. We need comprehensive, developmental theories that combine both between-person and within-person effects because (a) between-person differences are important modifiers of within-person change and (b) within-person processes lead to a reorganization of between-person differences. In the analysis of longitudinal data, it is important for estimates to be conditional on between-person aspects of the data (e.g., chronological age and survival age) in order to directly evaluate the within-person developmental information in longitudinal data that is separate from population selection effects (e.g., Hofer & Sliwinski, 2006; Mendes de Leon, 2007; Sliwinski, Hoffman, & Hofer, 2010; Thorvaldsson, Hofer, & Johansson, 2006). Analytical approaches, such as multilevel models, permit explicit models of cross-level interaction, such as between-person differences in within-person magnitude of variance (e.g., Hoffman, 2007).

Integration of Theory, Design, and Methods

Any study design involves selecting ways to sample, evaluate, and manipulate systems (i.e., individuals) as they develop and age in different contexts. Individuals may be sampled from different populations (i.e., birth cohorts, cultures, and nations), at different life periods, using different frequencies of assessments, and with different types and sets of measures. Longitudinal designs can be categorized in several ways (e.g., Lerner, Schwartz, & Phelps, 2009) but are defined primarily in terms of differences in initial sample (e.g., age homogeneous vs age heterogeneous and representativeness), number of occasions (e.g., semiannual and intensive), spacing between assessments (e.g., widely spaced panel designs and intensive measurement designs), and whether new samples of individuals are obtained at subsequent measurement occasions (e.g., sequential designs). These features can be brought together in novel ways to create study designs that are more appropriate to the measurement and modeling of different outcomes and life periods,

and for capturing intra-individual variation, change, and events producing such changes. Of key importance for understanding aging is the sensitivity of research designs for identifying predictors and processes. Ideal designs can address the dynamics of very short-term and daily processes, capture critical events that presage decline and diagnosis, and separate rapid and gradual decline processes. We highlight some of the inferential and design issues that complicate the analysis of longitudinal studies of aging and the development of theories and models of aging based on analysis of within-person information.

Sensitivity to Different Sampling Intervals of Time

Most longitudinal studies of aging are based on research designs with widely spaced assessments to capture disease incidence and gradual changes in later life. Although the broad coverage of existing longitudinal studies has provided us with general patterns of change related to age, the increasing number of "measurement burst," "daily diary," and event-linked designs (e.g., Moskowitz, Russell, Sadikaj, & Sutton, 2009) can improve the reliability of change measurement and will enhance understanding of short-term time-dependent multivariate processes and the influences of critical factors (e.g., daily stress and health event), learning effects, and intra-individual variability in the aging process. This can be thought of as a refining process—distilling relevant intra-individual variability and covariability, using these dynamic phenotypes to obtain a clearer picture of aging-related processes over longer time periods, and including a sharpened chronology for use in identifying potentially causal linkages. However, analysis across different time samplings will likely yield different results and require different interpretations of intra-individual variability and short-term change, as they will tap into different sources of change and fluctuation and result from different exogeneous influences (i.e., will be nonergodic across time scales; Martin & Hofer, 2004; Newell, Liu, & Meyer-Kress, 2001; Sliwinski, Almeida, Smyth, & Stawski, 2009).

Related to the issue of time sampling is the assumption that causal associations must be demonstrated as lagged effects. However, the use of cross-lagged regression models and more complex models of change, such as the bivariate dual change score model (McArdle, 2008), do not provide sufficient evidence for identifying causal effects. In gerontological research, cross-lagged associations are often evaluated across widely spaced assessments (e.g., several years apart) with causal precedence given to the variable exhibiting the strongest leading association. Evidence for causality, however, cannot be obtained by inspection of a particular pattern of associations or the relative magnitude of one cross-lagged regression over another (Rogosa, 1980; Shadish, Cook, & Campbell, 2002). Some of the challenges for inferring cause from observational longitudinal designs include the potential mismatch of the temporal sampling and the causal model (e.g., Boker et al., 2009; Gollob & Reichardt, 1987); differences in reliability of measurement instruments and emphasis on relative shifts in between-person differences over time (Rogosa, 1980); unmodeled simultaneous associations between cause and effect in the evaluation of lagged effects; exclusion of other causal variables (regression misspecification; Morgan & Winship, 2007); and bias due to confounds among levels of analysis, such as unmodeled nonlinear trends (i.e. age–slope interaction; e.g., Bauer & Cai, 2009; Hofer et al., 2006). Although the identification of cause and effect relationships is challenging, there are important recent and promising developments in this regard (e.g., Morgan & Winship, 2007; Pearl, 2009; West & Thoemmes, 2010).

Effects of Repeated Testing

Particularly in the context of cognitive or functional abilities, measuring an individual produces a change in brain and behavior, modifying the system under study in ways that result in improved or altered performance on subsequent assessments. As a consequence, over time, the test may measure a different construct than that originally intended. Although the first assessment is often seen as having the greatest impact in terms of learning or retest of cognitive functions, improvements actually occur during the test period and can be an explicit aspect of assessment (e.g., Buschke Selective Reminding; reaction time trials). Although retest effects are regarded by some as the critical limitation of longitudinal designs (e.g., Salthouse, 2009), such effects are a natural outcome of the processes under study (e.g., memory and learning). Because performance under "novel" conditions can never be observed repeatedly (with the alternative cross-sectional design, where different people are measured only once, providing little to no basis for understanding aging-related change), relative individual differences within each study must provide the basis for inferring relative change conditional on design effects (i.e., number of test items, test exposure; Hofer & Sliwinski, 2006; Thorvaldsson, Hofer, Berg, & Johansson, 2006; Thorvaldsson, Hofer, Hassing, & Johansson, 2008; Sliwinski, Hoffman, & Hofer, in press). Along these lines, intensive repeated measurement designs share many similarities to recent interventions related to cognitive functioning (e.g., Smith et al., 2009).

Alternative Statistical Models of Time and Causal Heterogeneity

Although the most common metric to model change is time since birth (chronological age; often as time-in-study conditional on age; Sliwinski, Hoffman, & Hofer, 2010), change in outcomes can be evaluated using alternative ways of indexing time, such as distance to death, or time elapsed until or since a health or life event (e.g., retirement, death of spouse, cardiac event; e.g., Alwin, Hofer, & McCammon, 2006; Sliwinski, Hofer, Hall, Buschke, & Lipton, 2003;

Sliwinski & Mogle, 2008). Modeling time relative to a particular event permits the direct interpretation of the average trajectory and individual differences in change relative to a common underlying within-person process. The challenge is that a population is likely to comprise individuals that are highly heterogeneous in terms of causal influences, which must often be defined retrospective to an event or condition. A major challenge in understanding aging-related change is the concomitant and increasing effects of health-related change. Late-life changes are often more appropriately modeled in terms of years of life remaining, with numerous studies providing evidence for accelerated decline in a broad range of functions toward the end of life (Bäckman & MacDonald, 2006). A combination of models based on age, terminal decline, and particular health conditions can help determine the relative contributions of normative age-graded change from nonnormative changes (e.g., Sliwinski, Hofer, & Hall, 2003; Sliwinski, Hofer, Hall, et al., 2003; Thorvaldsson et al., 2006).

Conditional Population Inference

Closely associated with aging and health-related change are population mortality and other selection effects leading to incomplete data. In longitudinal studies, at each new wave of testing, the sample becomes less representative of the population from which it originated and generalizations from the sample of continuing participants to the initial population become more difficult to justify (Nesselroade, 1988). Whereas some forms of nonparticipation can logically permit inference to a single population, in the case of mortality such an inference is impossible because individuals have left the population. In this case, inferences must be defined as conditional on the probability of surviving or remaining in the study (Hofer & Hoffman, 2007; Kurland et al., 2009).

Sensitive detection of within-person change

Intensive measurements of individual behavior and physiology over long periods of time are required for the sensitive detection of change from an individual's own normative performance. Sufficient information on the individual is required to enable the computation of a change point as a deviation from an established within-person baseline trajectory. In addition, modeling change due to pathological processes requires explicit modeling of the learning processes inherent in repeated measures designs. One approach that addresses both these needs is the measurement burst design (i.e., sets of closely spaced measurements repeated at longer intervals; Nesselroade, 1991; Sliwinski, 2008), which permits statistical decomposition of learning and decay functions (across days) that overlay normative aging, with the detection of change in an individual's asymptotic performance over longer periods of time (months or years). Recent research has focused on optimizing the design and analysis features of cognitive assessments that will permit reliable and sensitive assessment of cognitive functioning and of key causal factors underlying short-term and long-term change in functioning (Pavel et al., 2008; Sliwinski, Hoffman, & Hofer, in press). This methodology can be used to identify critical changes in an older adult's performance, leading to improved and earlier diagnosis of cognitive difficulty. In addition to the understanding of risk factors, early diagnosis provides one of our best opportunities for effective treatment.

Integrating Results Across Studies: Reproducibility, Generalizability, and Cumulative Knowledge

The reproduction and extension of research findings across independent longitudinal studies, focused on observed within-person change, is essential for a cumulative and innovative gerontological science. International and intercohort comparisons provide an important context for population and individual differences at all levels of analysis. Comparisons across international studies provide an opportunity to understand how societal and cultural differences influence developmental and aging-related outcomes. This type of research is characterized by comparison of health and aging-related outcomes in studies of distinct population samples (e.g., socioeconomic factors on health outcomes; Avendano, Glymour, Banks, & Mackenbach, 2009).

The direct comparison of results across longitudinal studies presents a number of challenges and is currently limited by the relative paucity of published information on particular research questions, the study-to-study differences in research design, sample composition, measurements, statistical analysis, and the practical limits on full reporting of results. In a cross-national context, a key issue is the comparability of outcomes and covariates based on different measurement instruments that may also differ in language, difficulty, number of items, and range of measurement. The difficulty in making direct comparisons of effects of or on these measures is that there is no natural metric on which to compare them. This is further compounded by differences in sample composition (including differences in birth cohort, culture, and social system), representativeness, and study quality. However, the variety of samples, measurements, contexts, and research designs, particularly in the area of longitudinal aging research, is also an advantage for considering the reproducibility and generalizability of research findings. There have been recent developments in the area of meta-analysis and data pooling of longitudinal studies (e.g., Cooper & Patall, 2009; Curran & Hussong, 2009; McArdle, Grimm, Hamagami, Bowles, & Meredith, 2009). Until recently, these methods have mainly been applied in cross-sectional and experimental data. Longitudinal research introduces additional dimensions and complexity, in

addition to representing primarily observational, rather than experimental, data. Recent developments in multilevel models show promise as a means to integrate complex results across independent longitudinal studies. Methods emerging under the title "evidence synthesis" focuses on combining multiple data sources in a single model and including indicators that can account for differences across different sources of evidence (i.e., account for bias; e.g., Ades & Sutton, 2006; Turner, Spiegelhalter, Smith & Thompson, 2009). As with any longitudinal study, developments and applications of integrative data analysis will need to take into account the myriad selection factors related to sample composition, representativeness, mortality selection, and design elements in order to adjust findings and provide a sound basis for data pooling and synthesis. Although many longitudinal studies may not provide a sufficient basis to generalize to the population (i.e., results apply only to sample), important and relevant research questions can be evaluated if there is sufficient exposure to "causal" influences, providing a basis for comparison of patterns and magnitudes of effects.

Collaborative Networks

Following on the increase in the number of longitudinal studies, there are a heartening number of active collaborative ventures for accelerating knowledge from existing longitudinal studies (e.g., for review, see Anstey et al., 2009; Kuh, 2007; Noale et al., 2005; Piccinin & Hofer, 2008; Woodward et al., 2006). Collaborative initiatives for reproducing results among longitudinal studies date at least to the 1970s (Riegel & Angleitner, 1975; Rose, 1976), but many have struggled to identify the best ways to combine efforts and were often bogged down by a focus on data pooling, "measure" harmonization, and obtaining a single, combined data set for analysis. Although similar measures facilitate comparison of parameter estimates, decisions regarding reproducibility and generalizability of factors contributing to maintenance or decline of cognitive or physical function can be made based on the pattern and magnitude of associations among constructs. Rather than attempting to obtain a single analysis and answer from a unified data set, of greater value from a generalized causal inference perspective may be multiple (or theoretically related) answers across studies with different designs, samples, and measures. In attempting to compare results across studies, however, it is critical that parameter estimates be conditioned on the same constructs. Model harmonization involves the coordination of statistical analysis involving selection and standardization of variables, model selection, and reporting of results, with potential for meta-analysis of longitudinal results (Hofer & Piccinin, 2009). By shifting the focus from "measure" harmonization to "model" harmonization, conclusions conditioned on conceptually similar constructs can more readily be compared.

In an effort to bring together these integrative goals, we have initiated an international network for the Integrative Analysis of Longitudinal Studies of Aging (IALSA; Hofer & Piccinin, 2009; Piccinin & Hofer, 2008). The IALSA network is essentially a collaborative system for the evaluation of both parallel and alternative models across independent studies as well as models incorporating individual and study-level characteristics to account for disparities across studies differing in birth cohort and nationality. Among the stated goals of this effort are to characterize population-level cross-sectional and longitudinal trends as well as to differentiate these from individual patterns of development in midlife to late life; to consider the possible impact of broad historical and cultural influences on the observations; to evaluate the importance of attending to physical and mental health characteristics in the study of aging; and to bring best practices to bear on models to deal with age-heterogeneous samples, initial selection effects, retest effects, and missing data due to attrition and death. In the interest of reproducibility and research synthesis, it will also be necessary to consider the impact of study differences in design, measurement, and sampling.

IALSA is an open and growing network currently comprising more than 30 principal study investigators who have agreed to the idea of working collaboratively, through either independent parallel analysis and joint publication, or data sharing or pooling, or other creative methods facilitating comparisons across research output from longitudinal studies. This is done in order to build a firm foundation that will lead to empirical and theoretical advances emphasizing developmental and within-person change. The longitudinal studies on aging directed by these principal investigators currently span eight countries on three continents and have a combined sample size of approximately 70,000 individuals. These studies represent a mix of population representative and volunteer samples assessed in a variety of settings (home or lab) and methods (e.g., in-person or telephone). Within the network, data have been collected on individuals ranging from birth to more than 100 years of age (mainly more than 50), with birth cohorts ranging from 1880 to 1980 (mainly 1900–1920), and periods from 1946 to the present. Between-occasion intervals range from 6 months to 17 years (the majority 1–5 years), with between 2 and 32 (mainly 3–5) measurement occasions spanning 4–48 years of within-person assessment.

Although some previous collaborative efforts have taken such variability as an opportunity to create a pooled data set with increased "variability along the time and age distributions" (Riegel & Angleitner, 1975, p. 61; with similar thoughts voiced by Rose, 1976), data pooling requires very strong assumptions regarding sampling variability that may result in spurious findings as a consequence of mean differences across samples or results that are sensitive to the choice of data harmonization protocol. The IALSA approach is to construct and compare parallel analyses across

the different data sets (Hofer & Piccinin, 2009). This will assist in evaluating the generalizability of the results, generating hypotheses that account for inconsistent findings, developing methods to address measurement differences, and achieving research synthesis involving the comparison and combination of results from independent studies.

Summary

The study of aging demands an integrative life-span developmental approach, involving interdisciplinary collaborations and multiple methodological approaches for understanding how and why individuals change, in both universal and idiosyncratic ways, over time. The scientific discovery of life-span determinants and within-person processes leading to aging-related changes in health, physical function, cognition, and well-being is a major research priority. The potential knowledge gains from increased integration of research on aging are great. Numerous calls have been made for increased collaborative efforts as a means to focus developmental research on within-person processes. Recent recommendations for research (e.g., National Research Council reports) have highlighted the importance of such interdisciplinary, international, and collaborative research making use of longitudinal studies on aging. We have elaborated on some fundamental issues for a comprehensive and cumulative approach to understanding aging, involving the integration of within-person theory, design, and analysis. Although challenging in many ways, a focus on the reproducibility and integration of interdisciplinary life-span research must be a central objective for a cumulative science of aging.

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