Center for Lifespan Psychology

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Research Project 7: Formal Methods in Lifespan Psychology

Since its foundation by the late Paul B. Baltes in 1981, the Center for Lifespan Psychology has sought to promote conceptual and methodological innovation within developmental psychology and in interdisciplinary context. Over the years, the critical examination of relations among theory, method, and data has evolved into a distinct feature of the Center. The overarching objective of the *Formal Methods* project is to test theories, develop methods, and explore research designs that articulate human development across different timescales, levels of analysis, and functional domains. The temporal resolution of data relevant for lifespan research varies widely, from the millisecond range provided by behavioral and electrophysiological observations to the small number of occasions spread out across several years provided by longitudinal panel studies. The project is based on the premise that a comprehensive understanding of human development across the lifespan requires a person-oriented, multivariate, and longitudinal approach. Such high-density, large data sets offer great opportunities for discovery and hypothesis testing, but also pose new theoretical and methodological challenges. The project meets these challenges by a strong emphasis on *methodology,* understood as the reciprocal interplay between concepts and methods that is at the heart of scientific progress.

In line with its interest in delineating and explicating individual differences in change, the project has continued and expanded its work on Structural Equation Modeling (SEM) and hierarchical state-space methods, both of which integrate a wide range of different multivariate analysis techniques. During the reporting period, project members have shown how these approaches can assist researchers in: (a) optimally planning longitudinal studies under constrained resources; (b) refining or modifying hypotheses through comprehensive exploratory data analysis; (c) appropriately modeling unequally spaced measurements, context effects, and individual differences in longitudinal research; and (d) modeling the dimensionality of age-related changes in cognition.

New Methods for Analyzing Change

Longitudinal panel studies are a key empirical method to chart between-person differences in behavioral and neural development. The project members have been working on developing and evaluating new methods to analyze change. Most dynamic models (e.g., cross-lagged panel models) currently in use in psychological research assume that measurement occasions are equally spaced in time. This failure to account for unequal spacing of measurement occasions may seriously bias parameter estimates. Driver, Oud, and Voelkle (2017) have developed a software package for the estimation of hierarchical continuous-time system dynamics, called *ctsem* (continuous-time structural equation modeling). The package is suited for the analysis of panel data (repeated observations from more than one individual) and time-series data (repeated observations from one individual). Using stochastic differential equations coupled with a measurement model, *ctsem* accommodates any pattern of measurement occasions. *ctsem* can estimate relationships over time for multiple latent processes, measured by multiple noisy indicators with varying time intervals between observations (see Figure 20). With recent developments in hierarchical and nonlinear modeling, as well as Bayesian estimation (Driver & Voelkle, 2018a), parameters themselves can be modeled as slowly changing dynamic states. Coupled with the inclusion of event- and intervention-related effects over time (Driver & Voelkle, 2018b), this allows for the high level of model expressiveness that is necessary for developing and testing theories of development across multiple timescales.

Andreas Brandmaier and Timo von Oertzen have continued their work on Ωnyx, a freely available software environment for creating and estimating SEM. The software offers a graphical user interface to facilitate the specification of models and includes a powerful back-end for performing parameter estimation (von Oertzen et al., 2015).

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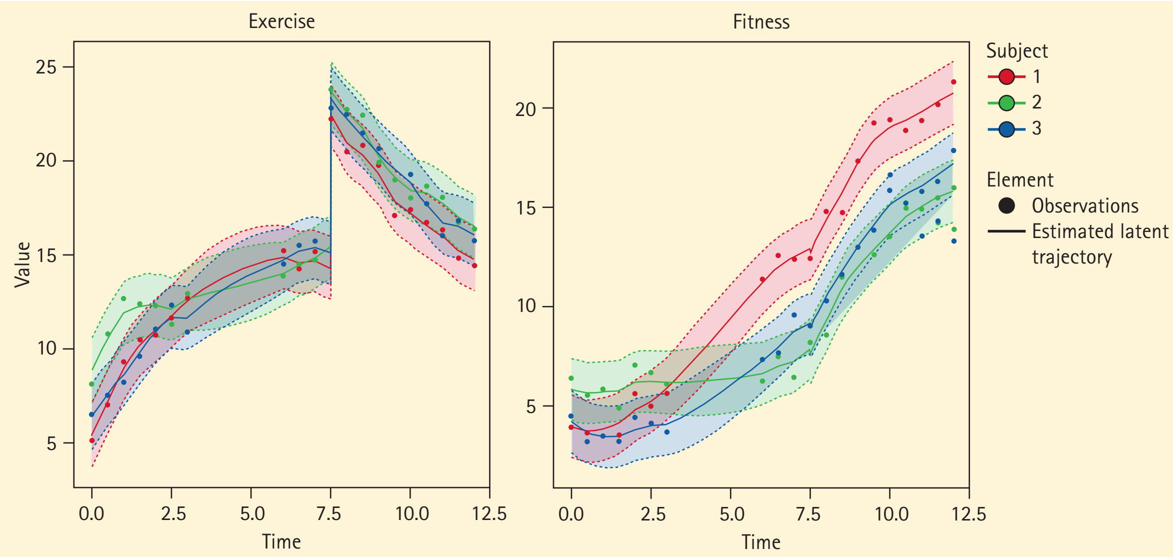

Figure 20. Estimated latent processes from a simulated hierarchical dynamic system of fitness and exercise. After a motivation intervention temporarily increasing exercise levels, fitness rises more quickly until exercise drops back to an equilibrium level determined by specific characteristics of the subject.

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Brandmaier, A. M., Wenger, E., Bodammer, N. C., Kühn, S., Raz, N., & Lindenberger, U. (2018). Assessing reliability in neuroimaging research through intra-class effect decomposition (ICED). *eLife, 7,* Article e35718. https://doi.org/10.7554/eLife.35718

Optimizing the Design of Longitudinal Studies

Longitudinal studies often require a large investment of resources. In earlier work, we have shown how design-related choices, such as the number of individuals or number of measurement occasions, affect statistical power and how optimal choices maximize the efficiency of longitudinal designs while keeping power constant (Brandmaier et al., 2015). In the meantime, we have extended this framework to arrive at an integrated understanding of measures of precision, reliability, and effect size for individual differences in change (Brandmaier, von Oertzen et al., 2018). Thus far, cognitive neuroscience has paid relatively little attention to questions of reliability and statistical power. For instance, surprisingly little is known about the psychometric properties of measures attained from structural and functional magnetic resonance imaging (fMRI) protocols. We have introduced the intraclass effect decomposition (ICED) framework to overcome this shortcoming (Brandmaier, Wenger et al., 2018). With ICED, researchers can separate and quantify the effects of different measurement characteristics, such as day, session, or scanner, on measurement reliability. Using this framework, we showed that some standard designs, such as 5 minutes of resting-state functional connectivity assessment, come with low reliability that hardly affords any kind of statistical inference about individual differences. We hope that ICED will encourage and assist researchers in delineating sources of unreliability and guide them in developing more efficient research designs.

To increase statistical power or achieve identical power with fewer measurements, planned missingness (PM) is a convenient but often overlooked design option. In PM designs, participants are tested on a random subset of all possible measurement occasions, thereby reducing potential resource bottlenecks, such as those arising from limited availability of an MR scanner, as well as research participants' testing load. To find optimal PM designs, we developed an asymptotic approach to generate, evaluate, and select optimal longitudinal designs for measuring change with PM (Brandmaier et al., 2020).

In research on adult cognitive development, available theories of change often posit nonlinear (e.g., exponential) decline. However, growth models used for data analysis typically test linear or quadratic polynomials, with less than 5% of the analyses being based on functions that are nonlinear in the parameters (Ghisletta et al., 2020). Given this apparent bias in favor of polynomial decomposition, Ghisletta and collaborators explored what conclusions about individual differences in change are likely to be drawn if researchers apply linear or quadratic growth models to data simulated under a conceptually and empirically plausible model of exponential cognitive decline. The simulation results show that fit statistics generally do not differentiate misspecified linear or quadratic models from the true exponential model. Moreover, power to detect variance in change for the linear and quadratic growth models is low, and estimates of individual differences in level and change can be highly biased by model misspecification. The authors encourage researchers to also consider plausible nonlinear change functions when studying behavioral development across the lifespan.

Exploration and Model Testing

Building models fully informed by theory is impossible when data sets are large and theoretical predictions are not available for all variables and their interrelations. In such instances, researchers may start with a core model guided by theory and then face the problem of which additional variables should be included. In earlier work, we have shown that SEM Trees and Forests provide a straightforward solution to this variable selection problem (Brandmaier et al., 2016). SEM Trees hierarchically split empirical data into homogeneous groups sharing similar parameters of a model by recursively selecting optimal predictors from a potentially large set of candidate predictors. SEM Forests aggregate predictive information over a set of trees

Coupled Cognitive Changes in Adulthood

With advancing adult age, cognitive abilities such as memory, processing speed, and reasoning tend to decrease. At the same time, there are marked individual differences in rates of change, with some adults showing maintenance and select improvements and others showing precipitous decline. To shed light on the dimensionality of cognitive aging, we revisited a classical question posed by Patrick Rabbitt more than 25 years ago: "Does it all go together when it goes?" Specifically, we conducted a meta-analysis to examine the degree to which changes in different cognitive abilities in adulthood and old age are correlated (Tucker-Drob et al., 2019). Across 22 unique data sets with over 30,000 individuals, a common factor of change accounted for 60% of the reliable variance in cognitive change (see Figure 21). The couplings among rates of changes increased with advancing adult age, presumably reflecting "dynamic dedifferentiation" or the increasing importance of an ensemble of common causes on cognitive change. Notably, abilities showing little average decline, such as verbal knowledge, contributed to common change to about the same extent as abilities showing pronounced average decline, such as perceptual speed. Hence, individuals who improve more on verbal knowledge relative to others are likely to decline less in perceptual speed. This generalized pattern of change adds to an important qualification to two-component theories of intellectual development in adulthood, such as the Cattell/Horn theory of fluid versus crystallized intelligence.

Box 1.

Key Reference

Tucker-Drob, E. M., **Brandmaier, A. M.,** & **Lindenberger, U**. (2019). Coupled cognitive changes in adulthood: A meta-analysis. *Psychological Bulletin, 145*(3), 273–301. https://doi.org/10.1037/bul0000179

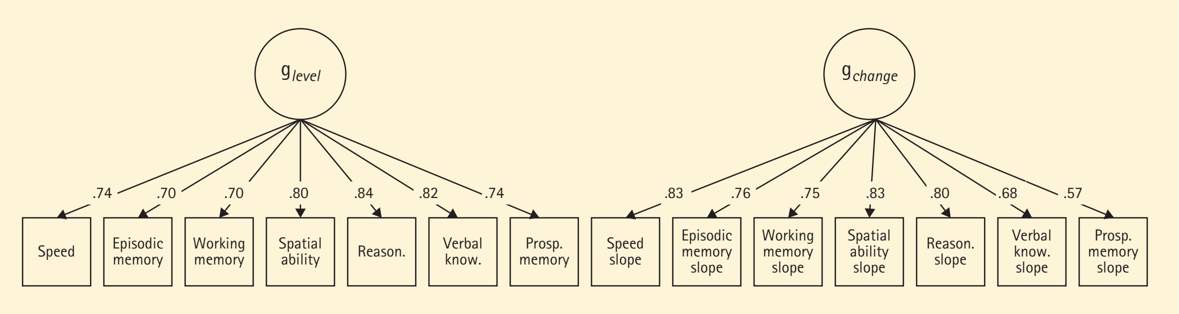

Figure 21. Path diagram representing meta-analytic estimates for standardized factor loadings of individual cognitive abilities on a general factor of levels (left) and standardized factors loadings of longitudinal slopes for individual cognitive abilities on a general factor of changes (right). Variances were omitted from the diagram. Reason. = Reasoning; Verbal know. = Verbal knowledge; Prosp. memory = Prospective memory (adapted from Tucker-Drob et al., 2019).

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and yield a measure of variable importance that is more robust than corresponding measures from single trees. Variable importance guides researchers on what variables may be missing from their models and the underlying theories. In a recent application of SEM Forests, we investigated longitudinal trajectories of well-being toward the end of life using data from the German Socio-Economic Panel study. We found that individual differences in the decline of well-being are associated with factors related to physical health, social participation, and perceived control (Brandmaier et al., 2017).

Longitudinal data sets with dense observations generally offer great opportunities for discovery and hypothesis testing. Therefore, we have merged the *ctsem* approach described above with SEM Trees into CTSEM Trees (Brandmaier et al., 2018). When the goal is variable selection to build predictive models with linear effects only, we introduced a further method, regularized SEM, that brings the idea of regularization to SEM and allows one to build simple models from high-dimensional data while optimizing predictive accuracy (Jacobucci et al., 2019).

Ongoing work in this area extends the model of interest from SEM to any statistical model and seeks to quantify the mismatch between the specified model and the "best possible" model using information theoretic approaches. Inferences drawn from models are generally contingent on the models being "correct," at least in certain ways. However, checking this premise often occurs ad-hoc based on a variety of misspecification indices. Levels of mismatch between model and data that derived from information theory might guide model refinement more efficiently than currently available approaches.

Between-Person Differences and Within-Person Changes in Cognition

Over a century of research on between-person differences in cognitive performance has resulted in the consensus that human cognitive abilities are hierarchically organized, with a general factor, termed general intelligence or "g," uppermost. Surprisingly, it is unknown whether this body of evidence, which reflects between-person differences, is informative about how cognition is structured within individuals. It is likely that many factors contributing to differences between individuals vary less, or differently, within individuals. For instance, allelic variations of the genome contribute to differences between but not within individuals. To overcome this lacuna, Schmiedek et al. (in press) analyzed data from 101 young adults performing nine cognitive tasks on 100 days distributed over six months (see Box 2). The structures of individuals' cognitive abilities were found to deviate greatly from the modal between-person structure, and to vary among each other. The g factor was much less prominent within than between persons. Working memory contributed the largest share of common variance to both between- and within-person structures. The results show that between-person structures of cognitive abilities cannot serve as a surrogate for within-person structures. To reveal the development and organization of human intelligence, individuals need to be studied over time.

Overview of the COGITO Study **www.mpib-berlin.mpg.de/cogito**

In the COGITO study, 101 younger adults (20–31 years of age) and 103 older adults (65–80 years of age) participated in 100 daily sessions in which they worked on cognitive tasks measuring perceptual speed, episodic memory, and working memory, as well as various self-report measures (see Schmiedek et al., 2010, 2020).
All participants completed pretests and posttests with baseline measures of cognitive abilities and transfer tasks for the practiced abilities. Brain-related measures were taken from subsamples of the group, including structural magnetic resonance imaging (MRI), functional MRI, and electroencephalographic (EEG) recordings.
A central goal of the COGITO study was the comparison of between-person and within-person structures of cognitive abilities. Further, the COGITO study qualifies as a cognitive training study of unusually high dosage and long duration because of its 100 sessions of challenging cognitive tasks.

Box 2.