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Longitudinal Analysis using data from the ABCD© Study

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Abstract

The Adolescent Brain Cognitive DevelopmentSM (ABCD) Study presents a unique opportunity for researchers to investigate developmental processes in a large, diverse cohort of children and adolescents. Given the breadth and complexity of the ABCD Study, researchers analyzing its data are likely to encounter a myriad of methodological and analytic considerations and concerns. This review provides an examination of key issues and techniques related to longitudinal data analyses of the ABCD data. We discuss the value of longitudinal data over cross-sectional data, focusing on the types of inferences that are possible when one assesses individuals across multiple time points, including: 1) characterization of normative variation in developmental trajectories and the genetic and environmental factors that may lead to deviations from normative development; 2) assessment of how variation in the development of one domain may or may not impact development in another; 3) identification of developmental disturbances, snares, and cascade effects; and 4) relative timing and reciprocal relationships of within-person changes from different developmental domains. We emphasize the importance of selecting appropriate methods to address these research questions, such as accounting for correlation in repeated measurements and using models for continuous or discrete outcomes as necessary. By addressing the advantages and potential challenges of developmental analyses in the ABCD Study, this review seeks to equip researchers with foundational knowledge and tools to make informed decisions as they navigate and effectively analyze and interpret the multi-dimensional longitudinal data currently available.

Keywords: ABCD Study, longitudinal analyses, development

1. Introduction

The Adolescent Brain Cognitive Development (ABCD) Study® is the largest long-term investigation of neurodevelopment and child health in the United States. Conceived and initiated by the National Institutes of Health (NIH), this landmark prospective longitudinal study aims to transform our understanding of the genetic and environmental influences on brain development and their roles in behavioral and health outcomes in adolescents (Volkow et al. 2018). At its heart, the study is designed to chart the course of human development across multiple, interacting domains from late childhood to early adulthood and to identify factors that lead to both positive and negative outcomes. Central to achieving these goals is the ABCD Study's® commitment to an open science framework, intended to facilitate sharing of data and analytical methods, by espousing practices that increase access, integrity, and reproducibility of scientific research (e.g., public data releases). In this sense, the ABCD Study is a collaboration with the larger research community.

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The size and scope of the ABCD Study data allow the research community to perform a large variety of developmental analyses of both substantive and methodological interest, presenting a unique opportunity to significantly advance our understanding of how a multitude of biopsychosocial processes unfold across critical periods of development. In this paper we describe models and methods for longitudinal analysis of ABCD Study data that can address these fundamental scientific aims, as well as some challenges inherent in a large, longitudinal observational study of adolescents. We instantiate many of the longitudinal analyses in worked examples with accompanying R scripts available at XXXX.

1.1. The ABCD Study Data

The ABCD Study enrolled a large cohort of youth (n=11,880) born between 2006-2008 and aged 9-10 years at baseline, as well as their parents/guardians. The study sample was recruited from household populations in defined catchment areas for each of the 21 (originally 22) study sites across the United States. Information regarding funding agencies, recruitment sites, investigators, and project organization can be obtained at https://abcdstudy.org/.

The ABCD Study is currently collecting longitudinal data on a rich variety of outcomes that will enable the construction of complex statistical models potentially incorporating factors from many domains. Each new wave of data collection provides another building block for estimating developmental trajectories and implementing probing longitudinal analyses that allow researchers to characterize normative development, to identify variables that presage deviations from prototypic development, and to assess a range of outcomes associated with biopsychosocial variables of interest. These data include: 1) a neurocognitive battery [? ?]; 2) mental and physical health assessments [[?]); 3) measures of culture and environment [? ?]; 4) substance use [?]; 5) biospecimens [?]; 6) structural and functional brain imaging [? ?]; 7) geolocation-based environmental exposure data [?]; 8) wearables, and mobile technology [?]; and 9) whole genome genotyping [?]. Many of these measures are collected at in-person annual visits, with brain imaging collected at baseline and every other year going forward. A limited number of assessments are collected in semi-annual telephone interviews between in-person visits. Data are publicly released on an annual basis, currently through the NIMH Data Archive.

By necessity, the study's earliest data releases consisted primarily of cross-sectional (baseline) data; however, the most recent public data release (Release 5.0) contains data collected across four annual assessments, including three brain imaging assessments (baseline, year 2 follow-up, and year 4 follow-up visits). Thus, the time is ripe for implementing a more longitudinal perspective and a focus on estimation of trajectories (i.e., within-person change over time).

1.2.

Organization and Aims

- Part I. Longitudinal Research
  - Identify fundamental concepts
- Part II. Longitudinal Data
  - Highlight key challenges
- Part III. Longitudinal Analysis
  - Learn methods & analysis to apply
- Part IV. Supplemental materials
  - Make use of linked open-source resources

2. Longitudinal Research

2.1. Basic Concepts and Considerations

There are several important concepts to consider when conducting longitudinal analyses in a developmental context. These include different ways of thinking about developmental course, whether certain periods of development are relatively sensitive or insensitive to various types of insults or stressors, whether some time periods or situations inhibit the expression of individual differences due to extreme environmental pressures, and whether the same behavior manifested at different times represent the same phenomenon or different ones. Further, in the case of developmentally focused longitudinal research, each new measurement occasion not only provides a more extended portrait of the child's life course but also brings with it greater methodological opportunities to make use of statistical models that distinguish within- and between-individual effects and that loosen constraints that need to be imposed on the furtherance of critical scientific questions. For example, collecting two or more within-person observations on the same construct but at different times enables estimation of within-person rate of change (slopes); more observations allow for more precise estimates of individual slopes, as well as characterization of non-linear development. Rate of change or other aspects of trajectory shapes may be more informative than the simple snapshots of level differences that cross-sectional data are limited to. Appreciation of these and other issues can help to guide the analysis and interpretation of data and aid translation to clinical and public health applications.

2.1.1. Vulnerable periods.

Adolescent development progresses normaly from less mature to more mature levels of functioning. However, unique epochs and experiences can alter the course of this idealized form of development. Consider research that shows cannabis use during adolescence is associated with later psychosis to a greater degree than cannabis use initiated later in development [**?** **?** **?** **?**]; or, similarly, experimental research on rodents that shows rodent brains to be especially sensitive to the neurotoxic effects of alcohol on brain structure and learning early in development (corresponding to early adolescence in humans) [**?** **?** **?**]. For example, longitudinal data from the National Consortium on Alcohol in Adolescence (NCANDA) show that binge drinking is associated more strongly with decrements in gray matter volume early in adolescence compared to later [**?**]. These examples highlight the importance of considering the role of vulnerable periods – e.g., temporal windows of rapid brain development or remodeling during which the effects of environmental stimuli (e.g. alcohol exposure) on the developing brain may be particularly pronounced– when trying to establish an accurate understanding of the association between exposures and outcomes.

2.1.2. Developmental disturbances.

Whereas vulnerable periods heighten neurobiological susceptibility to environmental influences, at other times, environmental presses will tend to suppress stability and disrupt the orderly stochastic process of normative development [e.g., **?**]. This situation reflects a developmental disturbance in that the normal course of development is "altered" by some time-limited process. In such cases, we might find that prediction of behavior in the period of the disturbance is reduced and/or, similarly, the behavior exhibited during the disturbance might have less predictive power with respect to distal outcomes compared to the behavior exhibited before and following the disrupted period. That is, once the environmental pressures are removed (or the individual is removed from the environment), patterns of individual differences (and autoregressive effects) recover to levels similar to those prior to entering the environment. For example, in [**?**], recent binge drinking appears to be most predictive of gray matter volume trajectories, as opposed to prior binge drinking or cumulative number of binge drinks, suggesting the potential for recovery of gray matter trajectories to prior levels of growth if binge drinking subsides.

2.1.3. Developmental snares and cascade effects.

Normative development can also be upended by experiences (e.g., drug use) that, through various mechanisms, disrupt the normal flow of development wherein each stage establishes a platform for the next. For instance, substance use could lead to association with other substance-using or rule-breaking peers, precluding opportunities for learning various adaptive skills and prosocial behaviors, in effect creating a "snare" that delays psychosocial development, such as maturing out of adolescent antisocial behavior [**?**]. Relatedly, the consequences of these types of events can cascade (e.g., school dropout, involvement in the criminal justice system) so that the effects of the snare are amplified [e.g., **?** **?**]. Although conceptually distinct from vulnerable periods, both types of developmental considerations highlight the importance of viewing behavior in the context of development and the importance of attempting to determine how various developmental pathways unfold. Longitudinal data are crucial in this context to assess individual levels of development prior to and following onset of experiences or other environmental factors; e.g., the ABCD Study collected data starting at ages 9-10 and hence before the onset of drug use for the vast majority of participants.

3. Longitudinal Data

3.1. Interpretation / Issues / Pitfalls & Assumption

The hallmark characteristic of longitudinal data analysis is the administration of repeated measurements of the same constructs on assessment targets (e.g., individuals, families) across time. The primary rationale for collecting longitudinal data is to assess within-person change over time, allowing researchers to estimate individual developmental trajectories and the genetic and/or environmental factors that may impact these. Generally speaking, administering repeated measurements more frequently or over longer time spans enables researchers to ask more nuanced questions and to make stronger inferences.

3.1.1. Two Time Points versus Three or More.

Although the clear leap from cross-sectional to the realm of longitudinal data involves going from one assessment to two or more assessments, there are also notable distinctions in designs based on two-assessment points versus three or more measurement occasions. Just as cross-sectional data can be informative in some situations, two waves of data can be beneficial in contexts such as when experimental manipulation is involved (e.g., pre/post tests), or if the central goal is prediction (e.g., trying to predict scores on Variable A at time T as a function of prior scores on Variable A and Variable B at time T-1). At the same time, data based on two assessments are inherently limited on multiple fronts. As [**?**] noted over forty years ago, "Two waves of data are better than one, but maybe not much better" (p XX).

These sentiments are reflected in more contemporary recommendations regarding best-practice guidelines for prospective data, which increasingly emphasize the benefits of additional measurement occasions for trajectory estimation, model identification and accurate parameter estimation. It is also consistent with research recommending that developmental studies include three or more assessment points, given it is impossible for data based on two-time points to determine the shape of development, since linear change is the only estimable form given two assessments [see **?**]. Research designs that include three (but preferably more) time points allow for non-linear trajectory estimation and increasingly nuanced analyses that more adequately tease apart sources of variation and covariation among the repeated assessments [[**?**])– a key aspect of developmental research.

To illustrate, developmental theories are useful for understanding patterns of within-individual change over time (discussed in further detail, below); however, two data points provide meager information on change at the person level. This point is further underscored in a recent review of statistical models commonly touted as distinguishing within-individual vs between-individual sources of variance in which the study authors concluded "… researchers are limited when attempting to differentiate these sources of variation in psychological phenomenon when using two waves of data" and perhaps more concerning, "…the models discussed here do not offer a feasible way to overcome these inherent limitations" [**?**].

It is important to note, however, that despite the current focus on two-wave designs versus three or more assessment waves, garnering three assessment points is not a panacea for longitudinal modeling. Indeed, several contemporary longitudinal models designed to isolate within-individual variability [e.g., the Latent Curve Model with Structured Residuals; [**?**]] require at least four assessments to parameterize fully and, more generally, increasingly accurate parameter estimates are obtained as more assessment occasions are used [**?**].

3.1.2. Types of stability and change

If one were to try to sum up what developmental trajectories in a living organism are exactly, one could plausibly argue they are the patterns of stability and change in its phenotypes as the organism traverses the life course. Mathematically, this could be expressed as f(t), a possibly multivariate function of time t typically taking values in the real numbers for continuous phenotypes or the integers for discrete phenotypes. There are a few different ways to think about patterns of stability and change (see Figure 1). Consider measuring the height of all youth in a 6th-grade class, once in the fall at the beginning of the school year and once again in the spring at the end of the school year. A common first step may be to compare the class's average height values obtained at these two different measurement occasions. This comparison of the average scores for the same group of individuals at multiple time points is referred to as "mean-level" stability, as it provides information about continuity and change over time for an outcome of interest, aggregated across members of a group.

In contrast, "between-individual" stability and change could be assessed, e.g., by calculating the Spearman correlation between the values obtained at different time points (e.g., 'height in the fall' with 'height in the spring'). This analysis focuses on the degree to which individuals retain their relative placement in a group across time. Consider