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Bayesian change-point analysis reveals developmental change in a classic theory of mind task

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A B S T R A C T

Although learning and development reflect changes situated in an individual brain, most discussions of behavioral change are based on the evidence of group averages. Our reliance on group-averaged data creates a dilemma. On the one hand, we need to use traditional inferential statistics. On the other hand, group averages are highly ambiguous when we need to understand change in the individual; the average pattern of change may characterize all, some, or none of the individuals in the group. Here we present a new method for statistically characterizing developmental change in each individual child we study. Using false-belief tasks, fifty-two children in two cohorts were repeatedly tested for varying lengths of time between 3 and 5 years of age. Using a novel Bayesian change point analysis, we determined both the presence and—just as importantly—the absence of change in individual longitudinal cumulative records. Whenever the analysis supports a change conclusion, it identifies in that child's record the most likely point at which change occurred. Results show striking variability in patterns of change and stability across individual children. We then group the individuals by their various patterns of change or no change. The resulting patterns provide scarce support for sudden changes in competence and shed new light on the concepts of "passing" and "failing" in developmental studies.

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1. Introduction

Change is a ubiquitous yet recalcitrant problem for psychology. We would like to understand processes of change in many different areas from changes due to therapeutic or pedagogical interventions to natural changes wrought by learning and development. Yet all too often we are limited to comparing 'before and after snapshots' and filling the gap with speculation, or worse, with unexamined assumption.

Developmental change in children is often studied by comparing performance in cross-sectional time slices (between subjects) or by repeated longitudinal testing of the same individuals over lengthy periods. In either case, the study of change has relied on group data and this methodological constraint has served to forge theories of groups rather than of individuals (Estes, 1956). Group data are used because of the necessity of drawing statistical conclusions based on sufficiently large samples. Unfortunately, however, there is no such thing as a group brain. There are only individual brains wherein developmental and learning changes occur.

As Estes (1956) pointed out long ago, we cannot derive valid generalizations about the course of change in individuals from the course of change in a group average. The context for Estes' remarks were the many studies of learning in rats and other animals that show the familiar smooth, gradually incrementing learning curves predicted by associative learning theory that reflect the gradual strengthening of responses from baseline to asymptote as a function of number of learning trials. The problem with this picture, Estes pointed out, is that the gradual learning curve required by associative theory is seen only in the group curve averaged across many individuals. The curves of individual animals, by contrast, showed that learning was not gradual but occurred with sudden change. More recently, Gallistel, Fairhurst, & Balsam (2006) confirmed and quantified the abruptness of onset of conditioned learning in individual animals.

The first obstacle to understanding processes of developmental and many other kinds of change is that we typically lack even basic facts about what change looks like in the locus of change, the individual. We begin by confronting the fact, long recognized, but seldom addressed, that group-averaged data tells us almost nothing about variable developmental profiles of the individuals who make up the studied group. We then describe a method whereby repeated measures collected longitudinally from the same individual are combined with a new method of analysis, which we call, *Bayesian change-point analysis*. Each child in a cohort is repeatedly tested on a task in order to derive a cumulative record for that child of their performance over the period of testing. Cumulative records are ideal because each point in the record is a summary of past performance up to and including that point, while any change in performance produces a change in the slope of the curve. We then use a recently developed statistical method to discover and identify any point of change there may be in the record, which we call, *Bayesian change-point analysis* (Gallistel et al., 2004; Papachristos & Gallistel, 2006). The method of analysis is Bayesian; this has the important advantage of allowing us to demonstrate statistically not only points of change but also patterns of *no change* (Gallistel, 2009). This analysis yields an inferential statistic, the Bayes Factor, for a given individual's record without the need for group averaging. The Bayes Factor reflects the relative fit of a model to the individual's profile. Using the Bayes Factor as our guide, we are able to test the relative fit of two contrasting developmental models: either a change occurred in the individual's performance, or a change did not occur in the individual's performance. In other words, we can quantify our confidence that change occurred for an individual record. Just as importantly, for a given individual's record, the Bayes Factor will quantify our confidence that change did *not* occur, allowing us to distinguish *both* change *and* no-change from the case where an individual's record was simply uninformative. Additionally, this analysis will identify the point or points in the record where, with maximum likelihood, change or changes actually occurred.

Finally, to assess the replicability and generalizability of the methods and findings, we present two cohorts of single-case studies, from the US and the UK. By collecting a cohort of such single-case studies, we can derive unambiguous group descriptions based upon well-characterized individual cases without obscuring any individual differences. Here we apply these methods to the classic theory of mind shift in preschoolers. We reveal for the first time what performance looks like when this shift