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Is there variation across individuals in processing? Bayesian analysis for systems factorial technology☆

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HIGHLIGHTS

- We propose Bayesian hierarchical models for systems factorial technology.
- We develop analysis including Bayes factor model-comparison algorithms.
- We investigate whether chunking in working memory changes processing architecture.
- We find no variation in processing architecture across people or across the tasks.

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ABSTRACT

Systems factorial technology (Townsend and Nozawa, 1995) is a leading methodology for assessing the processing of multiple-feature items. By using certain experimental designs and analyses, researchers can assess whether features are processed in serial, in parallel, or coactively. Current practice is to categorize each individual as displaying one of these three architectures. We argue this approach implicitly assumes heterogeneity of processing strategies across participants. A more scientifically meaningful approach may be to first ask whether all people are serial or parallel or coactive before assuming heterogeneity. We develop a series of Bayesian hierarchical models that captures both situations where everyone follows a common architecture and, alternatively, where there is heterogeneity in architecture. These models use g-prior structures that make computation of Bayes factors convenient. We report an application to investigate Miller's (1956) notion of chunking. We asked participants to compare objects that are composed of separable features simultaneously, a perception task, and sequentially, a memory task. We assessed whether processing changed across the perception and memory tasks with the notion that participants might have to chunk features to store them, and that this chunking might make processing more efficient. The answer is "no." We find a serial architecture for processing for highly separable features (size of circle and the orientation of its diameter) in both the perception and memory tasks. We also find parallel processing for less separable features (first and second digits in a two-digit number) in both perception and memory tasks. Taken together, while processing may depend on the separability of features, it does not vary across perception and memory. As importantly, we find that all people had the same processing strategy; that is models that stated no heterogeneity outperformed those with heterogeneity. This result indicates that architecture may be universal in this setting and not under strategic control.

The goal of this paper is to describe a new approach to evaluate evidence for equality and order constraints in psychological data. We use this new approach for inference in systems factorial technology, a method used to determine the mental architecture underlying processing in experimental tasks. In turn, we use a

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variant of systems factorial technology to address the question of whether the architecture of perception is the same as that of working memory. This paper, therefore, sits at the interface of three stories: a statistical story about how evidence should be evaluated, a methodological story about how architecture is determined, and a substantive story about perception and working memory. We take each in turn.

We think the most important contribution here is the statistical story. Here is the background: Often, researchers are concerned with average effects. For example, if a researcher thinks an interaction between two variables is theoretically important, they may compute the appropriate t-test value, which is a measure of the significance of the average interaction contrast. An improvement on this approach comes from the psychometrics tradition where individuals provide so much data that they are effectively experiments unto themselves. For example, if we are interested in the sign of the interaction of two variables, as we will be with systems factorial technology, we may manipulate both variables in a within-subject design where each individual observes many trials in each cell. We then can compute a t-test value for each individual and classify each as significantly negative, nonsignificant, or significantly positive. Examples of classifying people this way include Little, Nosofsky, and Denton (2011). The same basic logic has been enhanced by using explicit Bayesian mixture models where individuals are classified into psychologically distinct modes of processing (Houpt & Fific, in press; Kary, Taylor, & Donkin, 2016; Rouder, Morey, Speckman, & Pratte, 2007). This Bayesian approach, though more intellectually defensible, shares the basic property of being an approach for classifying individuals.

We think classifying individuals is not necessarily the best way to proceed. Let us start with a focus on the sign of an interaction term. We assume that this sign, whether positive, zero, or negative has theoretical importance. In this paper, where we use systems factorial technology, the sign of the interaction will be an indicator of the architecture. The details are provided subsequently, but parallel, serial, and coactive processing implies true interaction contrast terms that are negative, zero, and positive, respectively (Fific, Nosofsky, & Townsend, 2008). A search for lawfulness here takes the form of asking whether there is a common architecture in a task for all individuals. If all individuals approach a task with the same architecture, then we might view this architecture as more of a primitive—perhaps that it is biological or automatic, and not under volitional control. If not, that is if there is true variation in architecture across people, then perhaps the choice of architecture is under strategic control. Such a result leads to follow-up questions about why certain people with certain characteristics chose certain architectures.

The above emphasis on lawfulness leads to questions like, "what is the strength of evidence from the data for the proposition that all true values are positive (or zero or negative)?" These questions cannot be answered by classifying individuals. Instead, they are questions about global patterns, particularly about the possibility of multiple order and equality constraints holding simultaneously. They are most deftly answered by comparing models that impose varying constraints. Traditionally, comparing the fit of models with multiple order-constraints has proven difficult because calculations of the sampling distributions of relevant test statistics is not theoretically or computationally convenient (Robertson, Wright, & Dykstra, 1988). Heuristic approaches such as AIC and BIC are also difficult as the penalty terms depend on the number of parameters but not restrictions of the space (Klugkist & Hoijtink, 2007). To address these difficulties, we develop a Bayes factor approach to assess the strength of evidence for models with multiple simultaneous order restrictions. This development is broadly applicable and provides the answer to the question, "*Does everyone?*", For example, it may be used for questions like, "does everyone identify bright flashes faster than dim ones", or "does everyone show a Simon interference effect?"

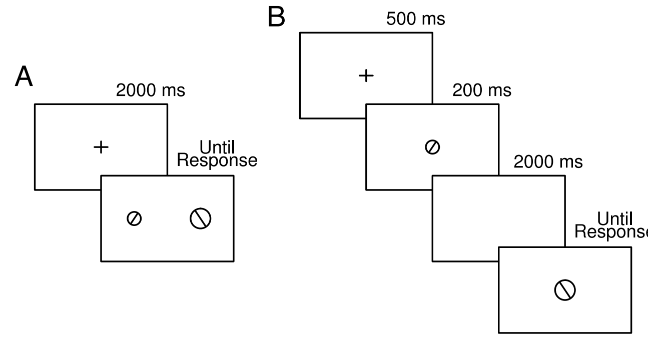

Fig. 1. Paradigm for Experiment 1. **A.** Schematic of trials in the perception task. The participant decides if the screwheads differ in both size and slot orientation. **B.** Schematic of trials in the memory task.

The second story, about methodology, goes as follows: One of the key questions across cognitive psychology is the nature of latent processing that underlies various information-processing tasks. Consider the perception of objects that can be described by their features. How these features are combined into coherent wholes remains timely and topical. This question has generated a long and fruitful mathematical-psychology literature on formal methods for understanding and querying processing architecture. A selective list includes Garner and Felfoldy (1970), Liu (1996), Schweikert and Townsend (1989), Sternberg (1969), Townsend (1990), and Townsend and Ashby (1982).

To make the situation concrete, consider the stimuli presented in Fig. 1. We call these stimuli *screwheads* because they resemble the top view of a flathead screw. The stimuli are defined by two features: the size of the screwhead and the orientation of the slot. The question is how these two features are processed. Perhaps the most common approach is to consider three different architectures: 1. *Serial processing*, where features are processed one-at-a-time in sequence; 2. *Parallel processing*, where features are processed independently and simultaneously and with unlimited capacity; and 3. *Coactive processing*, where the processing of one feature facilitates the processing of the others.

The approach we take to assess architecture is Townsend and Nozawa (1995) *Systems Factorial Technology*. Systems factorial technology refers to a collection of approaches developed by Townsend and his students (see Townsend & Wenger, 2004 for a review). The specific one used here is the logical-rules variant (Fific et al., 2008). Using this approach, Fific, Little, and colleagues have found the following two results: First, simple objects with separable features, such as the screwheads, are seemingly mediated by serial processing for most people (Fific, Little, & Nosofsky, 2010; Little et al., 2011). Second, objects with integral features such color patches comprised of hue and saturation are seemingly mediated by coactive processing (Little, Nosofsky, Donkin, & Denton, 2013).

The third story we consider is the substantive one. We ask whether the architecture mediating perception is the same as that mediating working memory. We use simple objects with separable features for both perception and working memory tasks. Following Fific et al. (2010) and Little et al. (2011), we expect serial processing for these types of stimuli. The main question is about the effect of holding these objects in working memory. On one hand, one can think that storing, maintaining and recalling stimuli from working memory does not change processing much, and there is a tradition of thinking of memory as reexperiencing the object, albeit as a noisier and perhaps systematically distorted copy (Estes, 1997; Hebb & Foord, 1945). A modern version of this view is that memory is the