Cognitive Psychology 104 (2018) 29–56

Contents lists available at ScienceDirect

Cognitive Psychology

journal homepage: www.elsevier.com/locate/cogpsych

Dynamic cognitive models of intertemporal choice[☆,☆☆]

Junyi Dai[a,b,*], Timothy J. Pleskac[b], Thorsten Pachur[b]

[a] Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou, China
[b] Center for Adaptive Rationality, Max Planck Institute for Human Development, Berlin, Germany

ARTICLE INFO

Keywords:
Intertemporal choice
Dynamic models
Random utility
Discrimination threshold
Decision field theory

ABSTRACT

Traditionally, descriptive accounts of intertemporal choice have relied on static and deterministic models that assume alternative-wise processing of the options. Recent research, by contrast, has highlighted the dynamic and probabilistic nature of intertemporal choice and provided support for attribute-wise processing. Currently, dynamic models of intertemporal choice—which account for both the resulting choice and the time course over which the construction of a choice develops—rely exclusively on the framework of evidence accumulation. In this article, we develop and rigorously compare several candidate schemes for dynamic models of intertemporal choice. Specifically, we consider an existing dynamic modeling scheme based on decision field theory and develop two novel modeling schemes—one assuming lexicographic, non-compensatory processing, and the other built on the classical concepts of random utility in economics and discrimination thresholds in psychophysics. We show that all three modeling schemes can accommodate key behavioral regularities in intertemporal choice. When empirical choice and response time data were fit simultaneously, the models built on random utility and discrimination thresholds performed best. The results also indicated substantial individual differences in the dynamics underlying intertemporal choice. Finally, model recovery analyses demonstrated the benefits of including both choice and response time data for more accurate model selection on the individual level. The present work shows how the classical concept of random utility can be extended to incorporate response dynamics in intertemporal choice. Moreover, the results suggest that this approach offers a successful alternative to the dominating evidence accumulation approach when modeling the dynamics of decision making.

1. Introduction

When people decide between options, the outcomes do not always materialize immediately—and when the outcomes materialize can differ between options. Decisions between these types of options are commonly referred to as *intertemporal choices*. Empirical research on such decisions has identified a number of behavioral regularities (e.g., Loewenstein & Prelec, 1992). To account for these regularities, several important developments in the formal modeling of intertemporal choice have recently been explored (Doyle, 2013; Frederick, Loewenstein, & O'Donoghue, 2002). In particular, research has challenged the time-honored notion of delay

☆ We are grateful to Susannah Goss and Kate Pleskac for editing the manuscript.

☆☆ Junyi Dai, Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou, China and Center for Adaptive Rationality, Max Planck Institute for Human Development, Berlin, Germany. Timothy J. Pleskac and Thorsten Pachur, Center for Adaptive Rationality, Max Planck Institute for Human Development, Berlin, Germany. All authors contributed to the conceptualization of the study and the development of the models. J. Dai carried out the formal analyses of the models. J. Dai wrote the original draft. All authors wrote, reviewed, and edited the final manuscript.

* Corresponding author at: Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou, China.
E-mail addresses: junyidai@zju.edu.cn (J. Dai), pleskac@mpib-berlin.mpg.de (T.J. Pleskac), pachur@mpib-berlin.mpg.de (T. Pachur).

https://doi.org/10.1016/j.cogpsych.2018.03.001
Accepted 3 March 2018

discounting, according to which the subjective value (or discounted utility) of a payoff declines as it is delayed (e.g., Green & Myerson, 2004; Mazur, 1987; Rachlin, 2006; Samuelson, 1937). Instead, the empirical evidence suggests that people make intertemporal choices by trading off the advantage on one attribute (e.g., payoff amount) against the disadvantage on the other (e.g., delay duration), a so-called attribute-based process (e.g., Cheng & González-Vallejo, 2016; Scholten & Read, 2010; Scholten, Read, & Sanborn, 2014). In addition—and more important for this article—there have been proposals of how to also take into account the dynamic nature of intertemporal choice, thus tackling the question of how decisions unfold over time (e.g., Dai & Busemeyer, 2014; Rodriguez, Turner, & Mcclure, 2014).

While current dynamic models represent an important step toward a more complete account of intertemporal choice, they have done so exclusively by relying on an evidence-accumulation framework (e.g., Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006; Ratcliff, Smith, Brown, & McKoon, 2016; Ratcliff & Smith, 2004). A key assumption of evidence-accumulation models is that successive samples of noisy stimulus representations are accumulated until a criterion quantity of evidence is reached (Ratcliff & Smith, 2004). However, there are also other, qualitatively different routes to model the dynamic nature of choice. Our goal in this article is to develop and systematically test various dynamic modeling schemes of intertemporal choice. As we will show, most of the behavioral regularities in intertemporal choice can also be accommodated without relying on the evidence-accumulation framework. Furthermore, one class of alternative modeling schemes can even outperform extant evidence-accumulation models when fitting empirical data at the individual level. This suggests that it is not necessary to assume evidence accumulation when theorizing about the dynamics of intertemporal choice. In fact, the alternative modeling schemes might also be viable competitors to evidence-accumulation models for modeling the dynamics of decision making in other domains.

The remainder of this article is organized as follows. We first discuss the merits of dynamic (rather than static) models of intertemporal choice and sketch potential computational schemes for developing such models. We then summarize key behavioral regularities in intertemporal choice that will serve as benchmarks for the subsequent development and comparison of competing models. Subsequently, we describe the modeling approach of intertemporal choice based on DFT and extend the DFT models proposed in Dai and Busemeyer (2014). Then we discuss two novel schemes—which to different degrees discard the notion of evidence accumulation—for developing probabilistic, dynamic, and attribute-based models. We also illustrate their ability to account for the key behavioral regularities in intertemporal choice. We then compare the computational schemes in a series of quantitative analyses, including quantitative model comparisons, empirical testing of model predictions, model recovery analyses, and parameter recovery analyses. We conclude by discussing the implications of our results for intertemporal choice and beyond.

2. A dynamic approach to modeling intertemporal choice

A critical limitation of most existing models of intertemporal choice is that they only address the final decision but not the time it takes to reach the decision. However, the temporal dynamics of choice in general and response time in particular offer an informative window on the underlying cognitive processes of decision making (e.g., Luce, 1986; Ratcliff & Rouder, 1998; Townsend & Ashby, 1983; Usher & McClelland, 2001). For instance, by analyzing both choices and response times, more information can be extracted from empirical data, potentially revealing new regularities in intertemporal choice. These new regularities, in turn, represent constraints for the development of dynamic models that reflect the underlying cognitive mechanisms. Moreover, by modeling both response time and choice, the identifiability of the underlying mechanism might be improved. In fact, as we will show, relative to using only choice data, using both choice and response time data indeed improves the identifiability of the cognitive processes involved in intertemporal choice.

In one of the first attempts to incorporate response time into models of intertemporal choice, Dai and Busemeyer (2014) proposed a class of probabilistic, dynamic, and attribute-based models built on decision field theory (DFT; Busemeyer & Townsend, 1993). According to these DFT models, to make a choice attention switches back and forth between evaluating the difference in the outcome of the options and the difference in their delay. These evaluations are accumulated over time to form a preference between the options. When the accumulated evidence reaches a threshold, a choice is triggered and the corresponding option is chosen. The time it takes to reach the threshold as well as non-decision components (e.g., motor time) determine the response time.

Dai and Busemeyer (2014) showed that the DFT models were able to accommodate several regularities of intertemporal choice as well as some of the dynamic aspects of the choice process. However, the models are based on a set of processing assumptions, not all of which may be appropriate for intertemporal choice. For instance, one defining feature of DFT models is that they assume a compensatory evaluation mechanism. For an intertemporal choice, this means that all information about each alternative (i.e., monetary outcome and delay duration) is integrated over time to make a decision, and that the advantage of one attribute (e.g., a larger reward) can be offset by the disadvantage of the other (e.g., a longer delay), and vice versa. However, research in several domains of decision making has highlighted the possible operation of lexicographic, noncompensatory processes (e.g., Brandstätter, Gigerenzer, & Hertwig, 2006; Einhorn, 1970; Gigerenzer & Goldstein, 1996; Luan, Schooler, & Gigerenzer, 2014; Payne, Bettman, & Johnson, 1992; Tversky, 1969). It is currently unclear to what extent lexicographic models might be able to account for the dynamics of intertemporal choice. Moreover, although lexicographic models appear consistent with qualitative patterns in response times in inferential choices (Bröder & Gaissmaier, 2007; Pachur, Hertwig, & Rieskamp, 2013), they are typically silent in terms of quantitatively predicting response time distributions. In this article, we propose one way to derive response time distributions for a class of lexicographic models of intertemporal choice.

A second key assumption of DFT—in fact, of any evidence-accumulation model—is that samples of information are accumulated over time. Yet many models of intertemporal choice make no such accumulation assumption. In fact, some of the more successful descriptive accounts, such as the tradeoff model, assume that a choice is made based on a single sample of information (e.g., Scholten