Trends in Cognitive Sciences

Feature Review

# Diffusion Decision Model: Current Issues and History

Roger Ratcliff,[1,*] Philip L. Smith,[2] Scott D. Brown,[3] and Gail McKoon[1]

**There is growing interest in diffusion models to represent the cognitive and neural processes of speeded decision making. Sequential-sampling models like the diffusion model have a long history in psychology. They view decision making as a process of noisy accumulation of evidence from a stimulus. The standard model assumes that evidence accumulates at a constant rate during the second or two it takes to make a decision. This process can be linked to the behaviors of populations of neurons and to theories of optimality. Diffusion models have been used successfully in a range of cognitive tasks and as psychometric tools in clinical research to examine individual differences. In this review, we relate the models to both earlier and more recent research in psychology.**

## Trends

Diffusion models with drift and boundaries constant over time account for accuracy and correct and error response time distributions for many types of two-choice tasks in many populations of participants.

Collapsing decision bounds implement optimal decision making in certain cases, but fits to data show humans use constant boundaries.

Brief stimulus presentation produces time varying input, but data suggest that evidence is integrated to produce constant drift in the decision process. (Other tasks can produce nonstationary evidence.)

Evidence is assumed to vary from trial to trial, as in signal detection theory. This explains why incorrect decisions are often slower than correct decisions.

It is not clear if variability in a sequence of stimulus elements in expanded judgment tasks is equivalent to moment-by-moment internal noise in tasks with a single stationary stimulus.

## Modeling Simple Decision Making

Decision making is intimately involved in all of our everyday activities. Many decisions are made rapidly and at a low level cognitively, for example, deciding whether to drive left or right round a car in front. Others, such as deciding which candidate to vote for or which car to buy, are made at a higher level with prolonged deliberation. The diffusion models we discuss are of the former type. In the real world, they involve a rapid matching of a perceptual representation to stored knowledge in memory, which allows us to identify things in our immediate surroundings and determine how we should respond to them. Much of what we have learned about such decisions comes from laboratory tasks in which people are asked to make fast two-choice decisions. The measures of performance are typically response times (RTs) and the probabilities of making the two choices. Researchers are usually interested in how and why RTs and choice probabilities change across experimental conditions, for example, whether a person tries to respond as quickly as possible or as accurately as possible.

There have been a moderate number of models for these tasks and most assume accumulation of noisy evidence to decision criteria representing each of the two choices. The models can include one versus two **accumulators** (see Glossary), decision rules that are relative or absolute, models with drift rate constant or varying over time, discrete or continuous time evidence, stochastic versus deterministic evidence, and models with inhibition and decay. Ratcliff and Smith [1] showed the relationships between the models along with a detailed evaluation of the models (Figure 1, Key Figure).

The standard model that we will discuss was developed by Ratcliff in the 1970s [2] and has only changed in assuming a single diffusion process instead of racing processes [3] and in adding **across trial variability** in starting point [4,5] and **nondecision time** [6]. In this model (Figure 2A), evidence about a stimulus from perception or memory accumulates from a starting point to a boundary or **threshold** (i.e., a criterion), one boundary for each choice. The boundaries represent the amount of evidence that must be accumulated before a response

[1]Department of Psychology, The Ohio State University, 1835 Neil Avenue, Columbus, OH, 43210, USA
[2]Melbourne School of Psychological Sciences, Level 12, Redmond Barry Building 115, University of Melbourne, Parkville, VIC 3010, Australia
[3]School of Psychology, University of Newcastle, Australia, Aviation Building, Callaghan, NSW 2308, Australia

*Correspondence: ratcliff.22@osu.edu (R. Ratcliff).

## Key Figure

### Sequential Sampling Models

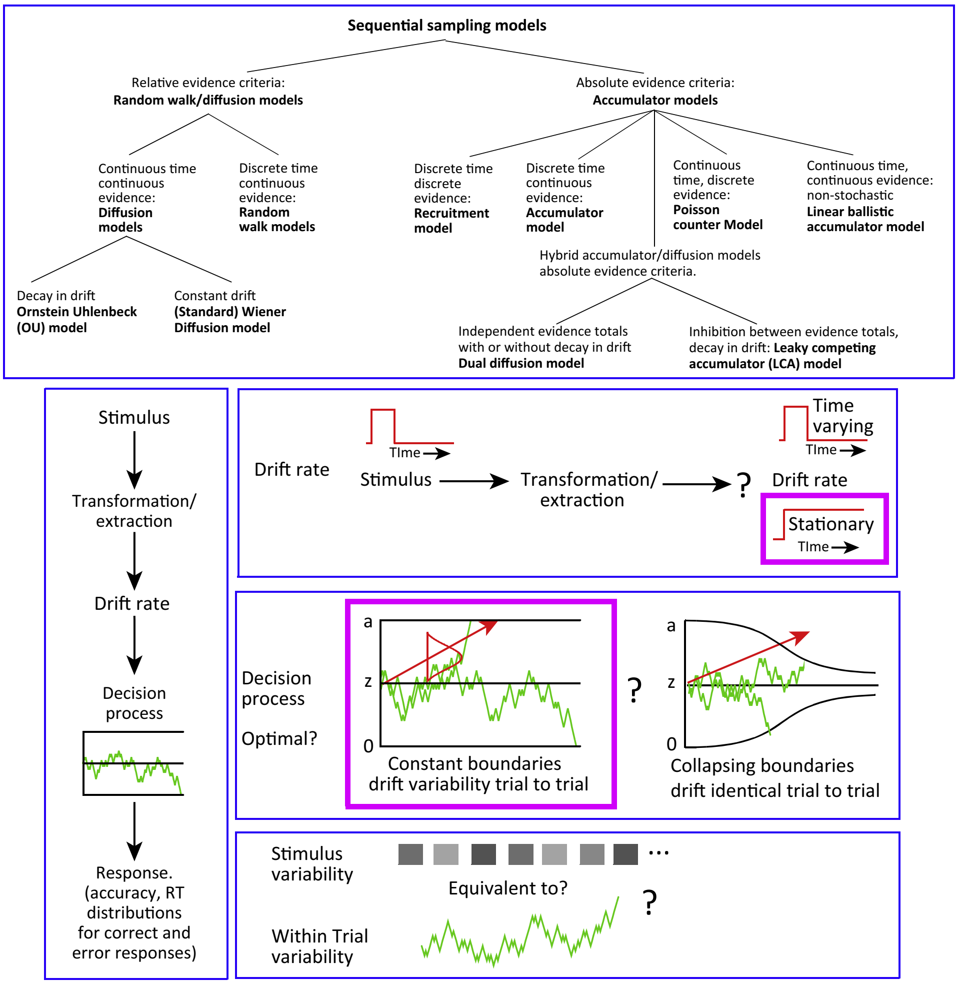


Figure 1. Relationships between the models, a flowchart of processing, and three issues addressed in the article.

is made. The accumulation process is noisy; at each moment in time, the evidence might point to one or the other of the two boundaries, but more often to the correct than the incorrect one.

The main components of the model for the decision process represent the rate of accumulation and the settings of the boundaries. In Figure 2, the boundaries are set at 0 and *a* with starting point *z*. Evidence accumulates in a noisy manner, and the average rate of accumulation is called the 'drift rate'. In addition, there are nondecision components: encoding the evidence from a stimulus that will drive the decision process, extracting the dimension(s) of the stimulus that form the basis of the decision from the stimulus or memory, and executing a response. These nondecision components are combined and labeled the 'nondecision' component, which has a

## Glossary

**Accumulator:** an assumed structure in an evidence accumulation model that has the purpose of gathering evidence in favor of one response.
**Across-trial variability:** the assumption that drift rates vary from decision to decision, motivated by the idea that, even if physical stimulus conditions are identical, the internal representation of the decision-relevant information is not.
**Attractor model:** a network (graph-based) model of interconnected nodes with a dynamic updating process. The updating process causes changes that lead to a stable end state (at the 'attractor').
**Collapsing boundary:** an assumption that the amount of evidence required to trigger a decision (the 'threshold') becomes smaller as the time taken to make the decision increases. This contrasts with the standard assumption that the threshold is unchanging.
**Confidence:** a subjective rating of the likely accuracy of a decision provided by the decision maker.
**Evidence accumulation:** also known as 'sequential sampling'. The idea that decisions are made by gathering evidence from the environment, continuing until sufficient evidence (a 'threshold' amount) is gathered.
**Fast errors:** an empirical phenomenon in which the mean RT for incorrect responses is longer than that for correct responses. Reliably observed when decision making is easy or decision makers stress speed. It has been important for model development because it is inconsistent with many theories of decision making. See also 'slow errors'.
**Hopfield network:** a type of attractor model based on recurrent connections that has been used to model human memory and decision processes, among other things.
**Latency–probability (LP) and quantile–probability (QP) plots:** parametric plots that show the relationship between the probabilities of different classes of responses and the timing of those responses. Response times can be plotted either as means (LP) or as quantiles (QP).
**Nondecision time:** the component of RT that is not due to evidence accumulation. Usually modeled as