Journal of Mathematical Psychology 59 (2014) 95–113

Contents lists available at ScienceDirect

Journal of Mathematical Psychology

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

Modeling perceptual discrimination in dynamic noise: Time-changed diffusion and release from inhibition

Philip L. Smith [a,*], Roger Ratcliff [b], David K. Sewell [a]

[a] Melbourne School of Psychological Sciences, The University of Melbourne, VIC 3010, Australia
[b] The Ohio State University, Columbus, OH, United States

HIGHLIGHTS

- Dynamic noise impairs performance and shifts RT distributions on the time axis.
- We describe two diffusion process models for discrimination in dynamic noise.
- The integrated system model is based on a time-changed diffusion process.
- The release from inhibition model is based on known physiological processes.
- Both models gave good accounts of the RT distributions and accuracy from the task.

ARTICLE INFO

Article history:
Available online 29 July 2013

Keywords:
Decision-making
Sequential-sampling
Response time
Reaction time
Discrimination
Signal detection

ABSTRACT

The speed and accuracy of discrimination of featurally-defined stimuli such as letters, oriented bars, and Gabor patches are reduced when they are embedded in dynamic visual noise, but, unlike other discriminability manipulations, dynamic noise produces significant shifts of RT distributions on the time axis. These shifts appear to be associated with a delay in the onset of evidence accumulation by a decision process until a stable perceptual representation of the stimulus has formed. We consider two models for this task, which assume that evidence accumulation and perceptual processes are dynamically coupled. One is a time-changed diffusion model in which the drift and diffusion coefficient grow in proportion to one another. The other is a release from inhibition model, in which the emerging perceptual representation modulates an Ornstein–Uhlenbeck decay coefficient. Both models successfully reproduce the families of RT distributions found in the dynamic noise task, including the shifts in the leading edge of the distribution and the pattern of fast errors. We conclude that both models are plausible psychological models for this task.

1. Introduction

In contributing an article to honor William Estes as one of the creators of mathematical psychology, we begin by reflecting on what it means to have done as Estes did, and created a discipline where none was before. Estes made numerous deep and influential contributions during his long and distinguished career, but, arguably, none had greater or more enduring significance for the future of the discipline than his original seminal work in animal learning, stimulus sampling theory (Estes, 1950, 1955a,b; Estes & Burke, 1953). In creating stimulus sampling theory, Estes not only constructed an elegant and powerful theory of learning, but also showed by example just what it means to develop and test a process model of a psychological phenomenon. Stimulus sampling theory first confronted the issue that has confronted every process model since then, namely, the inherent variability of behavior: the fact that organisms, whether human or nonhuman, do not exhibit the same behavior from trial to trial or from one presentation of a stimulus to the next. Consequently, a process model for learning must be expressed at the level of operators that show how choice probabilities evolve from trial to trial. Such probabilistic variation is not just a layering of a measurement error model on top of a deterministic process, but is integral to the theory itself.

Those of us who work with process models for psychological phenomena belong to a tradition begun by Estes and are profoundly indebted to him. From his example we understand that the development of a process model is the discipline of expressing a psychological explanation in quantitative terms and, in so doing, of determining precisely what its empirical consequences might be. It is also the discipline of testing a quantitatively expressed explanation against empirical data. Like all applied mathematics, it is the art of making complex problems tractable. In this, it is

* Corresponding author.
E-mail address: philipls@unimelb.edu.au (P.L. Smith).

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http://dx.doi.org/10.1016/j.jmp.2013.05.007

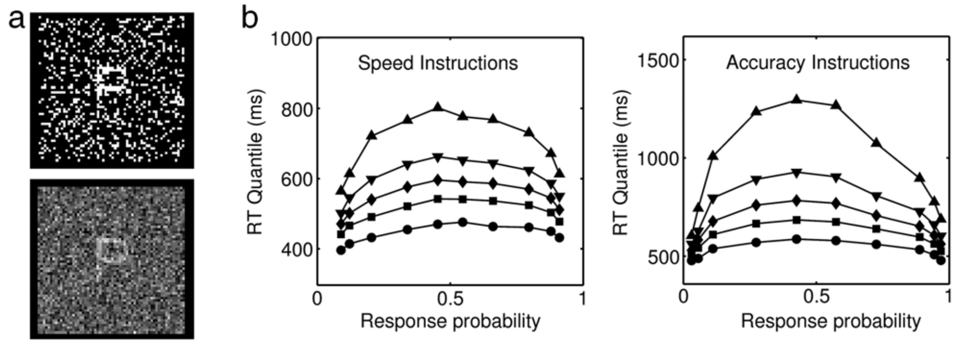

Fig. 1. Letter discrimination in dynamic noise. (a) Example stimulus. The upper panel shows a single frame in which 0.35 of the pixels have been inverted. The lower panel shows an average over 10 frames. Because stimuli would have been integrated by early visual filters, the lower panel provides a better indication of the perceptual experience of the task. (b) Quantile probability plots for five levels of discriminability presented under speed or accuracy instructions. The lines on the graph, bottom to top, are the 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles of the RT distributions. The response probabilities on the *x*-axis are the probabilities of correct responses, *p*, and error responses, $1 - p$. The five distributions on the right in each panel are the distributions of correct responses; the five distributions on the left are the distributions of errors. The data are quantile averages over participants. Note the different *y*-axis scaling for the two conditions.

the art of distinguishing the essential from the superfluous and the simple from the simplistic. Anyone who does work of this kind knows what the benefits of this undertaking can be. The attempt to express a psychological principle in quantitative terms is usually, in the first instance, a process of discovering that the things you thought were precise are in fact not so. It is also a way of flushing out unexamined assumptions and of exposing them to critical scrutiny.

Estes began his long career during the ascendancy of behaviorism and finished it long after the cognitive revolution had become the cognitive orthodoxy. The evolution of his research interests over time reflected the change in the conceptual landscape, from learning, which was the driving force for behaviorism, to perception, memory, categorization, and decision-making. These are topics that remain of central concern to mathematical psychologists today. A number of his later papers focused on the problem of determining whether variables that affect performance in visual recognition tasks do so by affecting perceptual or decision processes (Bjork & Estes, 1973; Estes, 1972, 1975, 1982). Estes was profoundly aware of the contribution made by decision processes, which match incoming sensory information against task representations in immediate memory, to performance in simple cognitive tasks. He was also aware of the hazards of theorizing about perceptual and decision processes in isolation, arguing that a proper understanding could only be gained by considering how they act in concert. That question, although framed in somewhat different terms, is the focus of this article.

1.1. Two-choice perceptual discrimination in dynamic noise

In a sequence of 12 experiments, Ratcliff and Smith (2010) investigated performance in a novel two-choice discrimination task in which letter stimuli were degraded by embedding them in dynamic visual noise. In their task, a randomly-chosen proportion of the pixels in the letter and the background were inverted in each consecutive frame of the display. Like other manipulations of discriminability, dynamic noise increased response time (RT) and reduced accuracy, but unlike other manipulations, it also produced significant shifts of the RT distribution on the time axis. These were manifested as changes in the distribution's leading edge, as indexed by its 0.10 quantile. Changes in the 0.10 quantile depend only on the fastest 10% of responses in the distribution and are relatively independent of changes in its variance or higher moments. Ratcliff and Smith found that dynamic noise shifted the leading edge of the distribution by more than 100 ms in the most difficult as compared to the easiest condition.

Fig. 1 shows examples of the stimuli used by Ratcliff and Smith (2010) in their Experiment 1, together with a quantile–probability plot (Ratcliff & Tuerlinckx, 2002) of group data from an unpublished experiment that used the same task. The details of the method can be found in Appendix A. Participants performed the task under speed and accuracy instructions in alternating blocks at five levels of stimulus discriminability, formed by inverting 0.35, 0.40, 0.425, 0.45, 0.475 of the pixels in the display. (When 0.5 of the pixels are inverted, the display becomes a homogeneous, random field of black and white pixels that carries no stimulus information.) In quantile probability plots, selected quantiles of the RT distributions for correct responses and errors are plotted against the choice probabilities, p_i and $1 - p_i$, for each condition, *i*. Such plots show how distribution shape, response accuracy, and the relationship between mean RTs for correct responses and errors all change as stimulus discriminability is varied. The distributions in Fig. 1 have been summarized using their 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles.

The unusual result in Fig. 1 is the systematic change in the leading edge of the distribution as a function of noise, which appears as a bowing of the curve representing the 0.1 quantile (the bottom curve in the plot) in both the speed and accuracy conditions. This is unlike the results found in the vast majority of speeded two-choice decision tasks. In most tasks, most of the changes in the distributions are in the upper quantiles; the leading edge is relatively unaffected and the curve representing the 0.1 quantile is almost flat (Ratcliff & Smith, 2004). Following Ratcliff and Smith (2010), we refer to the bowing of the 0.1 quantile function in Fig. 1 as the *leading edge effect.*

The leading edge effect in Ratcliff and Smith's (2010) study was found only with letter discrimination in dynamic noise. There was no leading edge effect in a brightness discrimination task with dynamic noise, in which participants were required to judge whether the average proportion of light pixels in the display was greater or less than 50%. There was no leading edge effect in a letter discrimination task, in which letters were degraded by a simultaneous structure mask composed of random letter fragments in the same stroke font as the stimuli. There was a smaller leading edge effect in the letter discrimination task when the noise was static rather than dynamic.

Ratcliff and Smith (2010) attributed the leading edge effect to a delay in the onset of information accumulation by a decision process until a stable perceptual representation of the stimulus had formed. The phenomenological basis for this interpretation is compelling: When letters are viewed in dynamic noise, they appear to emerge slowly out of the noise. The perceptual experience is quite unlike that in the masking-by-structure discrimination task, in which the stimuli seem to appear instantaneously.