



# Quantitative, steady-state properties of Catania's computational model of the operant reserve

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## ABSTRACT

Catania (2005) found that a computational model of the operant reserve (Skinner, 1938) produced realistic behavior in initial, exploratory analyses. Although Catania's operant reserve computational model demonstrated potential to simulate varied behavioral phenomena, the model was not systematically tested. The current project replicated and extended the Catania model, clarified its capabilities through systematic testing, and determined the extent to which it produces behavior corresponding to matching theory. Significant departures from both classic and modern matching theory were found in behavior generated by the model across all conditions. The results suggest that a simple, dynamic operant model of the reflex reserve does not simulate realistic steady state behavior.

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## 1. Introduction

### 1.1. The Catania operant reserve computational model

Catania (2005) presented a computational model of behavior based on Skinner's (1938) theory of the operant reserve. The model used only low level, theoretically based rules to animate a digital organism's behavior. In brief, the principle of the operant reserve is that organisms have a "reserve" of responses that contains the total remaining responses for a particular behavior. When the reserve is empty, the behavior is extinguished. When the reserve is full, the organism will emit responses at a high rate, which will decline by an amount proportional to the level of the reserve. Responses deplete the reserve, while reinforcements replenish it (Skinner, 1938).

Using this relatively simple concept, Catania (2005) developed a computational model of behavior. Some details were operationalized differently from the original Skinnerian model, however. First, rate of behavior emission was implemented by specifying that the probability of emission at any time-point was a direct function of reserve level. With a full reserve, there was a 100% probability of behavior being emitted. Likewise a reserve that was 50% full would correspond to a 50% probability of a behavior being emitted and so on. Second, although the amount each behavior emission depleted the reserved was fixed, Catania used a type of memory decay function to determine how much each reinforcement replen-

ished the reserve. The decay function determined the amount the reserve level increased as a function of responses that immediately preceded reinforcement. This essentially gave the digital organism short term memory. Because the function decreased with time (i.e., decayed), responses closest in time to the reinforcement added more to the operant reserve than did responses that occurred further back in time. At some point, determined by the decay function, a previous response would add nothing to the operant reserve because it was too distant from the time at which reinforcement occurred. To avoid overlapping decay functions, Catania did not extend the decay function past a previous reinforcement. Thus if reinforcement occurred at Time 1, followed shortly by another reinforcement at Time 2, the behaviors previous to the Time 1 reinforcement would not contribute to the Time 2 reinforcement.

Catania (2005) used the reciprocal decay function,

$$\rho = \frac{c}{d_0}, \quad (1)$$

where  $\rho$  is the incremental contribution of a response,  $c$  is the maximum possible incremental contribution of a response, and  $d_0$  is the time from the reinforcement event to the response. Reinforcement events were understood to occur at the time-step immediately following a response, making the minimum value of  $d_0$  equal to one. The total increment to the reserve at each reinforcement event was the summation of the individual contributions of all previous responses, provided a previous reinforcement event did not truncate the decay function. Catania considered alternative function forms such as exponential and hyperbolic but implemented the reciprocal form for computational simplicity.

Catania (2005) simulated behavior on random interval (RI), random ratio (RR), fixed interval (FI), concurrent, and several other

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**Table 1**  
Simple decay function forms and constant,  $c$ , conversion factors.

Function	Equation	Conversion factor
Reciprocal	$\rho = \frac{c}{d_0}$ , (6)	$c = \text{MIC}$
Exponential	$\rho = ce^{-d_0}$ , (7)	$c = e \times \text{MIC}$
Hyperbolic	$\rho = \frac{c}{1 + d_0}$ , (8)	$c = 2 \times \text{MIC}$
Linear	$\rho = -d_0 + c$ , (9)	$c = \text{MIC}$

MIC: maximum individual contribution.

schedules of reinforcement. However, no systematic method was used to run simulations, report data, or evaluate the effectiveness of the model. Catania supported the viability of the model primarily by presenting qualitative observations of extinction curves and response patterns for behavior on various schedules. The published analyses were also not representative of all the model's behavior. Catania admittedly only published selected results that provided evidence the simulated contingencies could be implemented, and that correspondence to live-organism behavior could be obtained. Few analyses were quantitative and those that were primarily consisted of illustrations that some but not all results were similar to live-organism behavior. Catania (2005) did report some consistency with matching theory but again the published analyses were not extensive; they merely demonstrated that successful outcomes were possible. The purpose of the research reported in the present article was to evaluate the viability of the model more systematically.

### 1.2. Purpose of the current project

The current project attempted to replicate the operant reserve model proposed by Catania (2005), extend the model by testing alternate decay function forms, systematically test the effect of the model's parameters on behavior, and quantitatively evaluate the model's performance.

In addition to the reciprocal decay function used by Catania (2005), simple exponential, hyperbolic, and linear functions were implemented and evaluated for their impact on the model's behavior. Table 1 lists the simple decay functions used in the current project. The exponential and hyperbolic function forms were chosen based on their frequent occurrence in the memory (Page and Norris, 1998) and learning (e.g., Catania and Shimoff, 1996; Killeen, 1994; Mazur, 1987) literatures. In contrast, linear functions traditionally have not been observed in memory decay or delay-to-reinforcement studies. However, some lines of research have pointed to the role of linear decay functions in short term memory and are supported by neurological data (e.g., Tarnow, 2009). Although our understanding of how memory decays, and what function form this decay takes, is limited, dynamic computational models have the advantage of being able to test and directly compare different possibilities because all other parameters can be held constant in the computational environment.

### 1.3. Determining correspondence with live organism data

One challenge with computational models is how to accurately evaluate model performance and determine its correspondence with live organism data. Although there are a number of qualitative methods for evaluating performance, such as visual examination of a cumulative response record, these methods are subject to bias. A quantitative approach using a matching analysis, like that used by McDowell (2004) in his evaluation of a computational model of selection by consequences, provides a more systematic method.

A wide range of live organism behavior at equilibrium has been shown to be described by the mathematical function,

$$R = \frac{kr}{r + r_e}, \quad (2)$$

originally proposed by Herrnstein (1970) (McDowell, 1988). This function is a rectangular hyperbola where  $R$  is the response rate,  $r$  the reinforcement rate,  $k$  the maximum response rate, and  $r_e$  the reinforcement rate due to extraneous behavior. Eq. (2) is one equation of matching theory, which accounts for a large percentage of the variance in single-alternative, live animal data (McDowell, 2005). As is well known, related functions account for behavior on concurrent schedules (Herrnstein, 1970).

Despite the success of matching theory (i.e., Eq. (2)), recent work by McDowell (2005) has shown that the alternative, but related form,

$$R = \frac{kr^a}{r^a + (r_e^a/b)}, \quad (3)$$

consistently outperforms Eq. (1) in terms of percentage variance accounted for (pVAF) and the random distribution of residuals from fits to live organism data. Eqs. (2) and (3) differ in terms of the exponent,  $a$ , and bias parameter,  $b$ . The difference follows from the functions from which Eqs. (2) and (3) were derived. Eq. (2) was derived from the original matching equation,

$$\frac{R_1}{R_1 + R_2} = \frac{r_1}{r_1 + r_2}, \quad (4)$$

where the  $R$ s refer to the rates of responding and the  $r$ s refer to the rates of reinforcement for each alternative of a two-alternative concurrent schedule (Herrnstein, 1970). Although this equation originally provided a good description of live-organism data (Herrnstein, 1961) it could not account for certain types of behavioral phenomena such as undermatching and bias (Baum, 1979). Thus, power function matching,

$$\frac{R_1}{R_2} = b \left( \frac{r_1}{r_2} \right)^a, \quad (5)$$

with the additional parameters,  $a$  and  $b$ , was proposed (Baum, 1974; Staddon, 1968, 1972). Eq. (5) and equations derived from it (including Eq. (3)) have been referred to as "modern matching theory" as opposed to "classic matching theory", which consists of Eq. (4) and equations derived from it (including Eq. (2)) (McDowell, 2005). McDowell argued that classic matching theory was false, but that modern matching theory was consistent with all known data.

In the present study both classic and modern single-alternative matching equations were used to evaluate the performance of the operant reserve model. Two principal criteria were used to evaluate goodness-of-fit, namely,  $R^2$ , and the absence of systematic patterns in the residuals. A systematic pattern in the residuals indicates that a fitted function does not fully account for the variance in the data. Together, these two criteria provide a powerful approach to determining whether the behavior generated by the model is consistent with live organism data.

## 2. Methods

### 2.1. Subject

The participant was a digital organism having one class of behavior that was governed by the principles of an operant reserve. The probability that the behavior would be emitted at each computational tick was directly proportional to the current level of the reserve. Responses decreased the reserve level while contingent reinforcement increased the reserve level.

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