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Environmental dynamics modulate covariation of choice and timing

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ABSTRACT

Response allocation between delayed reinforcers is presumably a function of the discrimination of those delays. In the present experiment, we analyzed the functional relation between response allocation and temporal discrimination across different environmental dynamics. Three pigeons pecked for food in a concurrent-chain schedule. Concurrent variable-interval initial links produced fixed-interval (FI) terminal links. Start and stop times, single-trial measures of temporal discrimination, were obtained from occasional 'no-food' terminal links. In dynamic, rapid-acquisition conditions, terminal links were FI 10 s and 20 s and the location of the initial link leading to the shorter terminal link varied unpredictably across sessions. In the static conditions, both terminal links were either "uniform" FI 15-s schedules or one terminal link was "fixed" at FI 10 s and the other at 20 s. Response allocation and start and stop times adjusted within sessions in dynamic conditions and across sessions of static conditions. Residuals from regressions of expected on programmed immediacy ratios were positively correlated to a greater magnitude in dynamic than static conditions. This change in residual covariation demonstrated that environmental dynamics modulated the relation between choice and timing.

1. Choice, temporal discrimination, and environmental dynamics

Choice is the allocation of time, effort, or other resources among sources of reinforcement (Baum and Rachlin, 1969). Given a reinforcer that is available after a short delay from one source and also available following a longer delay from another source, animals allocate more responses to the source that provides more immediate access to reinforcement (Chung and Herrnstein, 1967). Ostensibly, the animal learns the specific delays to reinforcement and responds in proportion to relative expected immediacy of two alternatives. Indeed, greater response allocation to immediate over delayed reinforcers is a function of the learned time to reinforcement, or temporal discrimination (Grace, 2002). There is an extensive body of research on the functional relation between response allocation and temporal discrimination, but the extent to which these behavioral processes relate differs depending on whether delays to reinforcement stay the same for several sessions (e.g., Grace and Nevin, 1999) or whether they change unpredictably (e.g., Kyonka and Grace, 2007).

Animals are sometimes faced with situations in which reinforcer availability is predictable, and at other times with situations in which reinforcer availability is less predictable. For example, delays to food in different patches might change over the course of a year. Patch A might be consistently more abundant in the summer months, Patch B the more abundant in the winter, and the relative availability of food might be less predictable and change more rapidly when the seasons change. Identifying how dynamics affect the functional relation between response allocation and temporal discrimination may lead to a better understanding of the adaptation of choice behavior. The purpose of the present study was a direct test of whether that functional relation differs depending on the frequency of change in relative reinforcer immediacy.

Choice between delayed reinforcers is often studied using concurrent-chain schedules (Autor, 1960/1969). In one arrangement, the chain consists of concurrent variable-interval (VI)-VI "initial links" and fixed-interval (FI) "terminal links" (e.g., Omino and Ito, 1993). The concurrent initial links are a choice phase for which the terminal link is the consequence. When the requirements of a VI schedule operating in initial links are satisfied, the terminal-link FI associated with that initial link begins. Reinforcement is available for a response after a fixed interval has passed since terminal-link onset.

For concurrent-chain schedules in which terminal-link FIs determine rates of reinforcement, the generalized matching relation (Baum, 1974, 1979; Staddon, 1968) holds that initial-link

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response ratio is a power function of relative terminal-link immediacy (i.e., the reciprocal of delay). When response and immediacy ratios are log-transformed, the relation between log response ratio and log immediacy ratio is linear, making parameters more easily interpretable. In an arrangement in which the initial links are left and right operanda, generalized matching states that:

$$\log\frac{B_L}{B_R} = a\log\frac{\left(1/D_L\right)}{\left(1/D_R\right)} + \log b, \qquad (1)$$

where B denotes response rate and D denotes the terminal-link delay, with subscripts referring to the left and right alternatives. The terms a (slope) and b (y-intercept) are empirically derived parameters that estimate sensitivity to the relative immediacy and bias for one alternative over another unaccounted for by immediacy, respectively.

The generalized matching relation forms the basis for a class of models that describe over 90% of the variance in response allocation in studies using concurrent (Baum, 1979) and concurrent-chain (Grace, 1994) schedules. Although generalized matching is a well-established description of choice, response allocation is a function of more than reinforcer immediacy alone. For example, response allocation is influenced by overall duration of initial and terminal links (Fantino, 1969; Grace and Savastano, 2000) and the discriminability of relative terminal-link immediacy (Kyonka, 2014). A number of dynamic factors may determine the relative value of terminal-link stimuli. One such factor, relative expected immediacy, largely drives choice in the initial link of concurrent chains with FI terminal links (Grace, 2002). Relative expected immediacy is a relative measure of terminal-link temporal discrimination in concurrent chains. Kyonka and Grace (2007) suggested that initial- and terminal-link behavior are based on a common representation of delay. Delay representation can be defined using empirically derived parameters as,

$$\mathrm{DREP}_i = \mathrm{FI}_i + \epsilon_i, \qquad (2)$$

where delay representation is a function of the FI schedule value correlated with i initial or terminal link and an error term representing deviations in behavior from the FI, sometimes referred to as encoding error. Relative delay representation of two FI schedules (i.e., $(1/\mathrm{DREP_L})/(1/\mathrm{DREP_R})$) can then replace immediacy ratios in Eq. (1) as a determinant of response allocation. Kyonka and Grace argued that when the same representation of delay controls different behavior, all behaviors would have the same encoding error. Specifically, if initial- and terminal-link responding were determined by a common representation of delay, encoding error from terminal links (ε_i; Eq. (2)) would contribute to initial-link response allocation and predict some of the variance not accounted for by generalized matching (Eq. (1)). That is, after the functional relations with terminal-link immediacy have been partialed out, error variance in log initial-link response ratio and log expected immediacy ratio attributable to encoding error should be positively correlated.

A number of theories support the view that delay representation in temporal discrimination is an important dynamic factor determining choice. In their decision model, Grace and McLean (2006) and Christensen and Grace (2010) suggested that the value of terminal-link stimuli, and thus response allocation, is determined by relative expected immediacy (defined by estimates of temporal discrimination toward terminal-link schedules expressed as a ratio). Similarly, an information-processing theory of learning, rate estimation theory (Gallistel and Gibbon, 2000) holds that relative expected immediacy drives response allocation. Gallistel and Gibbon provided evidence that animals estimate rates of reinforcement when first exposed to conditioning procedures. The specific intervals of time in conditioning procedures become the content of learning through scalar timing theory (Gibbon, 1991). Temporal information and the representation of delays thus form the basis of all conditioning processes, including response allocation.

1.1. Choice and temporal discrimination in static environments

Grace and Nevin (1999) assessed the functional relation between response allocation and temporal discrimination in a relatively stable environment. They exposed pigeons to four conditions: 1) a multiple peak-interval (PI) schedule (e.g., Roberts, 1981) in which no-food trials alternated pseudorandomly with signaled FI 10- and FI 20-s schedules; 2) a concurrent chain with VI initial links and terminal links identical to the PI schedule in Condition 1; 3) a replication of the PI schedule in Condition 1 with signaled FI 20- and FI 40-s schedules; and 4) a replication of the concurrent chain in Condition 2 with terminal links identical to Condition 3. Peak times (i.e., medians of response distributions in PI trials) were comparable when a PI schedule operated alone (Condition 1) and when the PI schedule was embedded into terminal links of concurrent chains (Condition 2). Further, initial-link response allocation favored the shorter terminal link in the concurrent chain (Condition 2). Temporal discrimination rapidly adjusted to the new FI schedule values when the PI schedule was re-presented in Condition 3. In the concurrent-chain replication, Condition 4, terminal-link peak times adjusted to the change in FI schedule within two sessions, but initial-link response allocation gradually adjusted over 25 sessions. If response allocation in the initial links was a function of terminal-link immediacy and peak times were a function of the time from terminal-link onset to food delivery, peak-time ratios (a measure of relative expected immediacy) would be better predictors of initial-link response ratios than programmed terminal-link immediacy ratios. Instead, response ratios at the beginning of Condition 4 were consistent with the value of those stimuli in Condition 2. The acquisition of stable response allocation lagged behind temporal discrimination; processes other than temporal discrimination determined response allocation in the beginning of Condition 4.

Related work on identifying the relation between response allocation and temporal discrimination (Berg and Grace, 2006; Grace, 2002; Grace et al., 2006) also challenged the notion that a common representation of delay determines choice and timing behavior. For example, Berg and Grace (2006) found that changing the terminal-link FI schedule values in concurrent chains led to rapid adjustment of relative expected immediacy, while choice in initial links adjusted more gradually. Similarly, in concurrent temporal discrimination tasks, Jozefowiez et al. (2005, 2006) found that temporal regulation of responding and response allocation were independent processes. These experiments all had one factor in common: The schedules of reinforcement were in effect for several sessions.

1.2. Choice and temporal discrimination in dynamic environments

Although there is evidence that response allocation and temporal discrimination in concurrent and concurrent-chain schedules are less related than decision and information processing models assume, positive covariation of different measures of temporal discrimination (e.g., wait times, peak times, start and stop times) and response allocation has been reported in other studies. For instance, Cerutti and Staddon (2004) measured wait times, or the latency to the first response in initial links of concurrent chains. Their dynamic modified time-left procedure led to strong, positive correlations between initial-link response allocation and wait-time. The strong relation between response allocation and wait time may have been a function of frequent changes in the schedule of reinforcement, or environmental dynamics.