

cerned primarily with the rate at which associative learning takes place. In contrast, momentum theory is typically considered a steady-state model in that it deals with asymptotic levels of responding. Whether the variables that determine behavioral mass also affect the rate at which that asymptote is reached is not explicitly stated by Nevin & Grace (N&G 2000) in their target article. Yet, resistance to change is by definition a dynamic measure and presumably reflects a dynamic process. The analogy to physical mechanics implies that the mechanisms of associative acquisition and extinction should oppose one another. In other words, variables that facilitate acquisition should impede extinction and vice versa. Moreover, the variables that enhance asymptotic behavioral mass should both decelerate extinction and accelerate acquisition. It should be interesting to see whether such a correlation exists. Research in this vein would encourage the development of behavioral momentum theory as a dynamic model of behavior.

Among the variables known to influence associative learning in Pavlovian situations are conditioned stimulus (CS) intensity, reinforcer magnitude, and CS rate within the context. (It is a separate question whether these specific attributes of experience or just their effects on learning are ultimately retained by the organism.) As predicted by the Rescorla-Wagner (1972) model, CS intensity appears to directly affect the rate but not the asymptote of learning, whereas reinforcer magnitude directly influences both rate and asymptote in the expected manner. In the Rescorla-Wagner model, CS intensity is captured by the learning rate parameter α , and reinforcer magnitude modulates λ , the total amount of learning that can occur, and β , a learning rate parameter for the unconditioned stimulus (US).

Although behavioral momentum theory is silent concerning the effect of CS intensity, reinforcer magnitude and rate are the two main variables the theory has used to establish different baselines of behavioral mass. It is with respect to reinforcer magnitude that the two theories contrast most sharply. Although both theories anticipate that greater reinforcer magnitude will increase the asymptotic strength of learning (mass or associative strength), they make different predictions regarding resistance to extinction following training with reinforcers of different magnitude. The Rescorla-Wagner model implies that during extinction β will be larger for a larger (now-omitted) reinforcer. Therefore, extinction (just like acquisition) of associative strength should proceed faster with the cessation of larger reinforcers than smaller reinforcers, even when baselines are normalized. This rather counterintuitive prediction is, of course, opposite to that of a Pavlovian extension of momentum theory, which anticipates that subjects trained with larger reinforcers will exhibit greater resistance to extinction.

The existing data based on traditional Pavlovian paradigms seem to favor the view of behavioral momentum theory. There is a positive relationship between resistance to extinction and magnitude of reinforcement. For example, Wagner et al. (1964) found more rapid salivary conditioning and greater resistance to extinction when the US consisted of six food pellets rather than one. Annu and Kamin (1961) and Kamin and Brimer (1963), varying the intensity of shock used as a US in conditioned suppression, found that higher intensity shocks facilitated acquisition and retarded extinction. Smith (1968) found that conditioning of the nictitating membrane response of rabbits and its resistance to extinction were directly related to the intensity of a shock US.

However, all of these studies used what would be analogous to continuous reinforcement (CRF) schedules; that is, all trials were reinforced. It is well known that in operant situations a direct relationship between reinforcer magnitude and resistance to change only holds for partial reinforcement (PRF) schedules, in which not every response is reinforced. With CRF schedules, greater magnitude of reinforcer often leads to more rapid extinction. This is an example of the partial reinforcement extinction effect with which behavioral momentum theory has struggled over the years (e.g., Nevin 1988). This latest version of momentum theory borrows the concept of generalization decrement, a mechanism that has been used many times before to explain partial reinforcement

effects (e.g., Sheffield 1949). In fact, N&G's "augmented model" for resistance to extinction (equation 17 in the target article) is basically a formal statement of Capaldi's (1967) account of the interaction between reinforcement schedule and reward magnitude: Effectively, the generalization decrement involved in the transition from continuous reinforcement to extinction outweighs the "reinforcing power" (mass) gained by using a larger reinforcer. With PRF schedules, the amount of generalization decrement is presumably less, allowing the pattern anticipated by behavioral momentum theory to emerge. But a discrepancy remains: Why was there a positive relationship between resistance and US magnitude when all trials were reinforced in the Pavlovian experiments cited above? There is a literature suggesting that the effect of generalization decrement is less pronounced in Pavlovian tasks (e.g., Gormezano 1966) because the short CS-US interval favors a broad stimulus generalization gradient. Therefore, the short intervals typically found between the CS and the US in Pavlovian conditioning mitigate against the partial reinforcement extinction effect, thereby leaving unopposed the effects of reinforcer magnitude on resistance to change.

Leaving these issues aside, N&G draw a strong distinction between learning and performance, a long-known (e.g., Tolman 1932) but often overlooked (e.g., Rescorla & Wagner 1972) dichotomy that we have examined in our laboratory over many years (e.g., Miller & Matzel 1988). Therefore, we welcome N&G drawing attention to this distinction. However, for them, response rate (metaphorical velocity) is influenced by the operant (response-reinforcer) contingency, whereas resistance to change and preference (metaphorical behavioral mass) are influenced primarily by the Pavlovian (stimulus-reinforcer) contingency. Thus, behavioral momentum (resistance to change) and velocity (response rate) appear differentially sensitive to two different contingencies. This is not necessarily the learning-performance distinction, but rather different measures reflecting two different memories. There is ample evidence that organisms learn about both stimulus-reinforcer and response-reinforcer relationships (e.g., Colwill & Rescorla 1985). Simply noting that resistance to change and response rate are sensitive to different variables may not warrant classifying one measure as an indicator of learning while relegating the other to the status of a performance variable, particularly because the authors acknowledge several exceptions to the assumption that resistance to change is determined solely by stimulus-reinforcer relations.

Authors' Response

Behavioral momentum and Pavlovian conditioning

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Abstract: The constructs of behavioral mass in research on the momentum of operant behavior and associative strength in Pavlovian conditioning have some interesting parallels, as suggested by **Savastano & Miller**. Some recent findings challenge the strict separation of operant and Pavlovian determiners of response rate and resistance to change in behavioral momentum, renewing the need for research on the interaction of processes that have traditionally been studied separately. Relatedly, **Furedy** notes that some autonomic responses may be refractory to conditioning, but a combination of operant contingencies and enriched Pavlovian stimulus-reinforcer relations may prove effective.

Our target article suggested that the components of behavioral momentum – an established rate of responding and its resistance to change, which we take to be analogous to velocity and mass in Newtonian physics – were separately determined by operant response-reinforcer contingencies and Pavlovian stimulus-reinforcer relations. Although separate research traditions have evolved for operant and Pavlovian conditioning, with different theories, methods, and even philosophical orientations, ultimately “what is learned” must be related. The defining feature of Pavlovian conditioning may be the stimulus-reinforcer (i.e., CS-US) contingency, but no learning can be detected in the absence of a response. Conversely, the operant response-reinforcer contingency must always occur in a stimulus context. By emphasizing the importance of stimulus-reinforcer contingencies as determiners of resistance to change, behavioral momentum theory (Nevin & Grace 2000) has always recognized the connection between Pavlovian and operant conditioning.

Savastano & Miller return the favor by drawing a parallel between behavioral mass – which according to momentum theory determines the resistance to change of an operant response – and associative strength, the primary learning construct in Pavlovian conditioning. They cite several studies which show that resistance to extinction of Pavlovian conditioning is positively related to reinforcement magnitude. This is important because if we can show that the same variables affect associative strength and behavioral mass in similar ways, then it is plausible that they represent a single construct. In fact, one of the major goals of our target article was to show that behavioral mass and conditioned reinforcement value could be understood in an expanded metaphor of behavioral momentum. The resulting integration of research on resistance to change and preference implies that behavioral mass and conditioned value represent a single construct. Because Pavlovian processes have long been assumed responsible for the acquisition of conditioned value, Savastano & Miller have closed the circle by linking associative strength and behavioral mass. This may help to build more comprehensive models of conditioning, and we thank them for pointing it out.

Savastano & Miller also note that Pavlovian studies have used continuous reinforcement (CRF) procedures, in contrast to most operant research on resistance to extinction, which has used intermittent or partial reinforcement (PRF). The puzzle then is why CRF often produces the opposite result for operant procedures (i.e., greater resistance for the alternative with the smaller reinforcer; see Case 2000). In our target article (Nevin & Grace 2000), we proposed an augmented model for resistance to extinction:

$$\log \frac{Bx}{Bo} = \frac{-x(c + dr)}{r^a}, \quad (1)$$

where Bx and Bo are response rates during extinction and baseline, respectively, x is session number, and r is reinforcement rate (or magnitude), with sensitivity parameter a . The denominator on the right-hand side of Equation (1) is behavioral mass. The disruptive effects of extinction are captured by c , which represents the impact of suspending the response-reinforcer contingency, and d , which multiplies reinforcement rate (or magnitude) to give generalization decrement. To apply Equation (1) to Pavlovian conditioning, c is now interpreted as the effects of sus-

pending the stimulus-reinforcer contingency (e.g., presenting the US with equal probability in the presence and absence of the CS). Equation (1) then predicts increased resistance to extinction for the relatively larger reinforcement magnitude or rate provided that d is relatively low, consistent with Savastano & Miller's suggestion that there is a broad stimulus generalization gradient in Pavlovian conditioning.

Savastano & Miller also question whether it is possible to maintain a strict learning-performance distinction, with resistance to change equated with learning (i.e., effects of reinforcement history) and response rate viewed as a performance variable. Although we originally took the strong position that resistance to change depended solely on the stimulus-reinforcer contingency and was independent of response rate, recent studies suggest that in some cases the response-reinforcer contingency and the resulting response rate may affect resistance to change. Nevin et al. (2001) compared resistance to change and preference for variable interval (VI) and variable ratio (VR) schedules with reinforcement rates equated, and found that response rate was greater for VR but resistance to change was greater for VI responding. Moreover, the VI schedule was preferred in a concurrent-chains preference test. Relatedly, Grace et al. (1998) found that an un signaled delay of reinforcement decreased both response rate and resistance to change relative to immediate reinforcement at the same rate, and, again, immediate reinforcement was preferred (see Nevin & Grace 2000, p. 84). It appears to be that when stimulus-reinforcer contingencies are equated, the response-reinforcer contingency can affect resistance to change in some situations, but when response-reinforcer contingencies are equated (e.g., in a multiple VI VI schedule), differential resistance to change will depend on the stimulus-reinforcer contingency. At present, the relative contributions of operant and Pavlovian contingencies to resistance to change (i.e., behavioral mass or, perhaps, associative strength) are unknown. This issue should be addressed in future research.

Furedy's commentary is also concerned with operant and Pavlovian contingencies, specifically with the failure of certain preparations to establish reliable conditioned responding. However, his “brute facts” simply do not bear on the domain of behavioral momentum theory, which does not attempt to explain the vagaries of acquisition, some of them idiosyncratic and some of them attributable to biological constraints (e.g., the difficulty of maintaining lever pressing by a rat when the reinforcer changes from food to shock avoidance). Our starting point is ongoing operant behavior maintained by an effective reinforcer, and most of the results we cite have been replicated with several species, stimuli, responses, and disruptors. It would be marvelous if we could enunciate a “law” that “fully accounted for the behavior of living organisms” but our goals are more modest.

With respect to biofeedback, **Furedy** asserts that operant and Pavlovian contingencies have no beneficial effect on autonomically controlled cardiac responses. There is, however, evidence that our approach is directly relevant to skeletal muscle relaxation. As described in our target article (Nevin & Grace 2000, p. 86), Tota-Faucette (1991) gave auditory feedback and points to children for meeting a relaxation criterion. In some stimulus conditions, she also gave extra points or candy, independently of how well the

children were performing the relaxation task. These extra reinforcers strengthened the stimulus-reinforcer relation, and when auditory feedback was discontinued (extinction), relaxation was reliably more persistent in the added-reinforcer conditions. The finding exactly parallels results obtained with pigeons, key pecking, and food (Nevin & Grace 2000, p. 77) and replicated many times with other species, responses, and reinforcers, most recently by Ahearn et al. (2003) with autistic children engaged in stereotyped behavior. Thus, our approach can guide effective application. To our knowledge, it has not yet been applied to autonomically mediated cardiac responses but it would be worth trying.

A part of the task of any scientific theory is to identify its domain of applicability, and behavioral momentum theory need not be all-encompassing in order to be useful. For a century, we have known that Newton's laws apply only to macroscopic bodies moving at velocities substantially less than the speed of light, but they still serve superbly for many engineering applications. **Savastano & Miller's** commentary suggests that our approach may apply to a variety of classical conditioning preparations, and we look forward to expanding the domain and the utility of behavioral momentum theory through convergence with other lines of research and theory.

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The letter "r" before author's initials indicates Authors' Response to Continuing Commentary references.

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