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# OPERANT VARIABILITY

*Allen Neuringer and Greg Jensen*

During almost the entirety of a documentary film featuring Pablo Picasso (Clouzot, 1956), the camera is focused on the rear of a large glass screen that serves as a canvas. As viewers watch, each paint stroke appears and a theme emerges, only to be transformed in surprising ways. In many of the paintings, what started out as the subject is modified, sometimes many times. Erasures; new colors; alterations of size; and, indeed, the very subject of the painting flow into one another. Each painting can readily be identified as a Picasso, but the process seems to be filled with unplanned and unpredictable turns. Uncertainty and surprise characterize other arts as well. A fugue may be instantly recognizable as a composition by J. S. Bach, and yet the transitions within the fugue may astound the listener, even after many hearings. Leonard Bernstein wrote of the importance of establishing expectancies in musical compositions and then surprising the listener. Fiction writers describe their desires to complete novels to find out what the characters will do because the authors can be as uncertain about their creations as are their readers.

Everyday behaviors may similarly be described in terms of generativity and unpredictability. Listen carefully to the meanderings of a conversation. Watch as an individual walks back and forth in his or her office, the tilt of the head, the slight changes in pace or direction. Monitor the seemingly unpredictable transitions in one's daydreams or images. Science is generally thought to be a search for predictable relationship—if A then B—but throughout history, some have argued that to understand the

world, including mind and behavior, scientists must appreciate the reality of unpredictability. From Epicurus in the 3rd century BC, who hypothesized random swerves of atoms, to contemporary quantum physicists, some have posited that nature contains within it unpredictable aspects that cannot be explained by if-A-then-B causal relationships, no matter how complex those relationships might be.

In this chapter, we discuss the unpredictability of behavior and focus on one aspect of it. When reinforcers are contingent on variability, or more precisely on a level of operant–response variability (with levels ranging from easily predictable responding to randomlike), the specified level will be generated and maintained. Stated differently, response unpredictability can be reinforced. Stated yet another way, variability is an operant dimension of behavior. *Operant dimension* implies a bidirectional relationship between behavior and reinforcer. Responses influence (or cause) the reinforcers, and reinforcers influence (or cause) recurrence of the responses. The same bidirectional relationship is sometimes true of response dimensions as well. For example, when food pellets are contingent on rats' lever presses, a minimum force must be exerted in a particular direction at a particular location. Force, direction, and location are response dimensions that are involved in the control of reinforcers and come to be controlled by the reinforcers. Variability is related to reinforcement in the same way. We refer to this capacity as the *operant nature of variability* or by the shorthand *operant variability*.

The very idea of operant variability is surprising to many and, at first blush, seems counterintuitive. Does variability not indicate noise? How can noise be reinforced? In fact, does reinforcement not constrain and organize responses—by definition—and is that definition not confirmed by observation? As we show, the answers are sometimes yes, but not always. Operant variability provides an important exception, one that may be a factor in the emission of voluntary operant responses generally.

The chapter is organized broadly as follows. We discuss

- Experimental evidence showing that reinforcers and discriminative stimuli control behavioral variability;
- Relationships between reinforcement of variability and other influences;
- Explanations: When variability is reinforced, what in fact is being reinforced?
- How operant variability applies in such areas as creativity, problem solving, and psychopathology; and
- How reinforced variability helps to explain the voluntary nature of operant behavior generally.

## REINFORCEMENT OF VARIABILITY

As a way to describe the phenomenon, we begin with descriptions of some of the methods that have been successfully used to reinforce variability.

### Recency-Based Methods

Imagine that a response earns a reinforcer only if it has not been emitted recently. Page and Neuringer (1985) applied this recency method, based on Schwartz (1980, 1988), to pigeons' response sequences across two illuminated keys, left (L) and right (R). Each trial consisted of eight responses, yielding 256 (or  $2^8$ ) different possible patterns of L and R, for example, LLRLRRRR. In the initial variability-reinforcing (or VAR) phase of the experiment, a pattern was reinforced only if it had not occurred for some number of trials, referred to as the *lag*. A trial terminated with food only if the

sequence of eight L and R responses in that trial differed from those in each of the previous 50 trials (as evaluated across a moving window). This contingency was referred to as *lag 50*. If the current sequence repeated any one (or more) of the previous 50, then a brief time out (darkening of all lights) resulted, and food was withheld. After food or time out, the keylights were again illuminated, and another trial initiated. Sequences during the first 50 trials of a session were checked against the trials at the end of the previous session, that is, performance was evaluated continuously across sessions. Approximately 25 sessions were provided under these VAR contingencies.

Let us consider some possible outcomes. One would be that the birds stopped responding—responding extinguished—because the lag 50 requirement was too demanding. At the other end of the possibility spectrum, the birds cycled across at least 51 patterns and by so doing were reinforced 100% of the time, with each sequence being different from every one of the previous 50. Although unlikely for pigeons, one way to solve lag contingencies is to count in binary, with L = 0 and R = 1, then LLLLLLLL followed by LLLLLLLR, followed by LLLLLLRL, then LLLLLLRR, and so on. Lag procedures have also been used with human participants, and therefore such sophisticated counting behavior must be considered. A third possible result would be alternations between a few preferred sequences (these would not be reinforced because of their high frequencies but would fill the lag window) and an occasional “do something else” (leading to reinforcement). The fourth possibility would be that L and R responses were generated in randomlike fashion, or stochastically,<sup>1</sup> as if the birds were flipping a coin.

This last alternative best describes the results. One piece of evidence was that reinforcement occurred on approximately 70% of the trials (with the other 30% leading to time-outs; Page & Neuringer, 1985). The pigeons' performances were compared with the results of a simulated model in which a computer-based random-number generator produced L and R responses under exactly the same

<sup>1</sup>Throughout this chapter, we use *stochastic* and *random* interchangeably.

reinforcement contingencies experienced by the pigeons. The simulation showed that the model was reinforced on 80% of trials because, by chance, response sequences were repeated within the window of the lag 50 approximately 20% of the time. Thus, the pigeons' performances were similar to, although not quite as good as, that of a random response model.

A second source of support for approximations to random generation was provided by statistical analyses of the sequences, namely by the  $U$  statistic (Page & Neuringer, 1985). That statistic is a measure of uncertainty or entropy and is calculated from the relative frequencies of a set of items using the equation

$$U = - \sum_n \frac{RF_i \cdot \log(RF_i)}{\log(n)} \quad (1)$$

Here,  $RF_i$  refers to the relative frequency of element  $i$ , out of  $n$  total elements. As a convention, every  $RF_i = 0.0$  is considered to contribute a value of 0.0 to the sum, without an attempt to resolve  $\log(RF_i)$ . When all elements occur with equal frequency,  $U$  is maximal with a value of 1.0; if any single element has a frequency of 1.0 (and all others are 0.0), then  $U$  is minimal with a value of 0.0.

In the Page and Neuringer (1985) study, three levels of  $U$  value were analyzed at the end of each session.  $U$  value was calculated for the relative frequencies of L and R; for relative frequencies of dyads (namely LL, LR, RR, and RL); and for triads (e.g., LLL, LLR, LRL . . .). The birds'  $U$  values were compared with those from the random model. As expected, the random model produced  $U$  values close to 1.0 at each level of analysis, and the pigeons'  $U$  values also approached 1.0, although not quite as closely as the random model. Thus, in this case, the results can best be described as randomlike but discriminably different from a true random source. Rather than responding equiprobably, the birds demonstrated biases, for example, favoring one key over another or favoring repetition over switching. We return later to a more detailed discussion of whether operant responses can be generated stochastically when the reinforcement contingencies are more demanding.

If Page and Neuringer's (1985) experiment had stopped at this point, there would be uncertainty as to why responses varied. The issue is tricky because it involves more than whether the lag procedure resulted in response variability (which it clearly did). Rather, was variability directly reinforced, or could the results be explained differently? Variability could have resulted from extrinsic sources (noise in the environment) or intrinsic sources (within the organism), or it could have been caused by experimental error, an insufficient flow of reinforcers, or any number of other things. To show that variability depended on the "if vary, then reinforce" contingency, a control procedure provided reinforcers after some eight-response trials and time outs after others, just as in the VAR condition, but these reinforcers were now unrelated to the pigeon's sequence variations. Under this control, reinforcers and time outs were yoked to those delivered during the VAR phase. In other words, the yoke condition was identical to the VAR condition (eight responses per trial, and trials were followed by food or time out at exactly the same rates as during VAR), except that the pigeon received food and time outs whether or not the variability contingency had been met. Each pigeon's terminal six sessions under the lag 50 VAR contingencies provided the trial-by-trial schedule for its reinforcements and time outs under the yoke condition.

The yoke procedure produced large and consistent effects. Levels of variability fell rapidly and remained low under the yoke condition.  $U$  values that had approached the 1.0 of a random model in the VAR condition dropped to values closer to 0.50, indicating substantially more sequence repetition. Other statistics confirmed the increased repetitiveness and predictability of responding. These effects were replicated with an A-B-A-B design (VAR-yoke-VAR-yoke), yielding a conclusion that direct reinforcement of variability was responsible for the high variability (see Figure 22.1).

Lag contingencies have been used with other species, including humans, monkeys, rats, budgerigars, and fish (see Neuringer, 2002, for a review). With rats, four-response trials across L and R levers are often used, in which case 16 (or  $2^4$ ) different sequences are possible. Here, too, high sequence variability is observed. In an example of a human

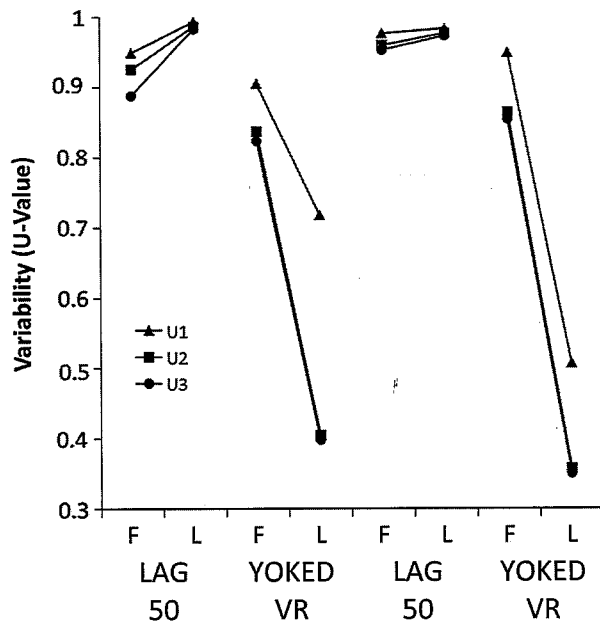


FIGURE 22.1. Three levels of the  $U$  statistic, an index of behavioral variability ( $U_1$  based on number of left [L] and right [R] responses;  $U_2$  on LL, LR, RR, and RL dyads; and  $U_3$  based on triads), during the lag 50 reinforcement-of-variability phases and yoke d-VR phases. VR = variable ratio; F = first session in each phase; L = last session in each phase. Adapted from "Variability Is an Operant," by S. Page and A. Neuringer, 1985, *Journal of Experimental Psychology: Animal Behavior Processes*, 11, p. 445. Copyright 1985 by the American Psychological Association.

procedure, Stokes and Harrison (2002) presented on a computer screen a triangle consisting of one location at the top, two locations in the next row down, three in the third, and so on until the sixth row, which contained six locations. A trial involved moving from the top row to the bottom, thereby requiring five responses, with 32 possible patterns. These five-response sequences were reinforced under lag contingencies, and high levels of variability often resulted. In this procedure, however, as well as others with humans, some (albeit rarely observed) participants use a different strategy of cycling through a subset of sequences, such as a binary counting strategy. Another problem with lag procedures is that they never reinforce repetitions, and a random generator sometimes repeats (e.g., if 16 sequences are possible, then for a random generator, the probability of two identical back-to-back sequences is .0625). An alternative method that bases reinforcement on

response frequencies (rather than recency) provides a partial solution, and we describe it next.

### Frequency-Based Methods

In these procedures, reinforcement is contingent on low overall relative frequencies. As one example, rats' responses were reinforced on the basis of four-response trials (across L and R levers), with, as we indicated, 16 different possible sequences (LLLL, LLLR, LLRL, LLRR, etc.; Denney & Neuringer, 1998). Frequencies of these sequences were updated throughout each session in 16 separate counters, or bins, and a sequence was reinforced only if its relative frequency—the number of times that it was emitted divided by the total number of sequences—was less than some designated threshold value. Reinforcement of low relative frequency sequences has the advantage of permitting occasional reinforcement of repetitions. This procedure has several technical aspects. For example, after each trial, all bins are multiplied by an exponent, for example, 0.95, which results in recent sequences having more weight than those emitted in the past, a kind of memory decay (see Denney & Neuringer, 1998, for details). The important point is that, as with lag, highly variable responding was generated. The procedure has been used in many experiments with yoke serving as the control (Neuringer, 2002).

In an interesting variant of the procedure, Donald Blough (1966) reinforced variable interresponse times (IRTs). Blough's goal was a difficult one, namely, to see whether pigeons could learn to behave like an emitter of atomic particles, the most random of physical phenomena (or, put another way, to respond as would a Geiger counter). For a random-in-time responder, the likelihood of a response is independent of whether a previous response had occurred recently. To accomplish this, Blough created a series of IRT bins, such that a random responder would be expected to have an equal number of IRTs in each bin. A moving window of 150 responses was analyzed in real time, with each response allocated into one of 16 bins, depending on its IRT. Blough then only reinforced an IRT falling in the bin with the lowest current relative frequency, that is, he reinforced only for the least frequent<sup>2</sup> IRT

<sup>2</sup>As such, this contingency is called a *least frequent contingency*.

in a given window. The procedure resulted in the pigeons learning to approximate the IRT distributions of a truly random generator, that is, to distribute pecks (with some minor exceptions resulting from double pecks) much as a Geiger counter would respond.

### Statistical Feedback Methods

If the goal is to test whether animals and people can respond truly randomly, then both recency and frequency methods have a potential weakness. As indicated earlier, systematic strategies, such as binary counting, can provide higher frequencies of reinforcement than responding stochastically. Although sometimes present in animals, this type of strategy is most commonly observed in human participants. Note that exploiting weaknesses in the variability-reinforcing contingencies—by responding in a systematic way that maximizes reinforcement—is not a sign of insensitivity to the schedule requirements. If anything, it is precisely the opposite. An additional problem is that all statistical tests of randomness (and therefore reinforcement contingencies based on randomlike responding) have certain blind spots that result in false positives. Therefore, researchers sought an alternative procedure, one that was better at detecting, and therefore not reinforcing, strategic or patterned responding. It seemed reasonable to hypothesize that if a reinforcement contingency was based on a multiplicity of different measures of variability, it might be less likely to reward exploitative strategies and potentially lead more reliably to approximations to random outputs, especially in human participants.

Before we describe the relevant experiment, note that the attempt to reinforce randomness flies in the face of more than 50 years of research in which people were asked to generate random sequences (e.g., “Pretend you are flipping a coin”). The consistent conclusion from this large body of studies was that people do not respond randomly when so requested (Brugger, 1997), and indeed, some researchers concluded that people cannot respond randomly. (The literature on human randomness rarely references nonhuman animal studies.) This conclusion is fundamentally important because randomness implies absence of identifiable causes and independence from determination. Most psychologists assume that

all behaviors are strictly determined—by inheritance, experiences, stimuli, responses, and the like—and therefore that random behavior is not possible, certainly not when voluntarily attempted.

However, none of the earlier studies tried to reinforce randomlike behavior directly. This approach was accomplished with a procedure that required students to enter tens of thousands of responses at a computer terminal (Neuringer, 1986). A trial consisted of 100 responses across two keys (which we refer to as 1 and 2) with feedback, based on common statistical tests of randomness, presented at the end of each trial. At first, satisfying one statistical test was reinforced, then two tests had to be satisfied, and then three, and so on—with graphical feedback showing each statistic relative to that expected from a true random source—until participants were passing 10 evaluations of random sequences.

The challenge confronting the participants was even greater than just described. Participants were required to generate a distribution of statistical values that would be expected from a random source (Neuringer, 1986). To take a simple example, across many trials of 100 responses each, random generation of 1s and 2s shows a distribution of proportions of 1s and 2s. The most likely outcome would be approximately equal numbers of 1s and 2s, or 50% each, but some trials would occur in which, for example, there were 40% 1s and 60% 2s, or vice versa, and fewer trials of, say, 30% 1s (or 2s). The participants’ task, therefore, was not simply to match the average of a random distribution but more precisely to approximate the randomly generated distributions. This task required many weeks of training, but all participants learned to approximate the random model according to 10 simultaneously applied statistics, and some participants (but not all) were able to pass additional tests as well.

How should this research be interpreted? Because so much training was necessary, it would seem that the ability to respond unpredictably is unnatural, but that would be a misinterpretation. If you, the reader, were to call out 100 instances of heads and tails and try to do so unpredictably, it is unlikely that an observer of your behaviors, even with access to sophisticated statistical analyses,

could predict your responses with a high degree of accuracy. You can, without training, respond quite unpredictably. The requirement to pass 10 statistical tests, however, demands equivalence, over the long run, of instances, dyads, triads, and the like and absence of all biases. To use a rat's operant response as an analogy, it is quite easy to train a rat to press a lever for food pellets. Indeed, that can often be accomplished in an hour-long session. To train a rat to respond precisely at some given force, or with precise interresponse intervals, may take weeks or months of training. In similar fashion, approximating true randomness is difficult to attain, but responding variably, and to large extent unpredictably, is readily achieved. In rats, for example, highly variable operant responding is obtained within a few sessions (McElroy & Neuringer, 1990).

### Novelty-Based Methods

To evaluate variability, each of the methods discussed to this point requires that a set of possibilities be explicitly defined—responses, sequences, paths, or times. Mathematical definitions of randomness, statistical analyses, and reinforcement contingencies depend on such specification. However, in many outside-of-lab situations, the set may not be known, and an alternative method allocates reinforcers for novel, or not previously emitted (e.g., within a session or ever) responses. Reinforcement of novel responses was first used by Pryor, Haag, and O'Reilly (1969) in research with porpoises. At the beginning of each session, Pryor et al. waited until they observed some behavior not previously emitted by the porpoise and then selected the new behavior for consistent reinforcement during the session. This procedure resulted in the porpoise

emitting an unprecedented range of behaviors, including aerial flips, gliding with the tail out of the water, and “skidding” on the tank floor, some of which were as complex as responses normally produced by shaping techniques, and many of which were quite unlike anything seen in . . . any other porpoise. (p. 653)

One problem with long-term use of this procedure, however, is that, over time, it becomes increasingly

difficult for the subject to produce never-before-seen behaviors and increasingly difficult for the observer to discriminate among the various behaviors being emitted. At least over the short run, however, reinforcing novel responses led to an exceedingly high level of unpredictable behaviors.

The Pryor et al. (1969) study was followed by an analogous one with preschool children (Goetz & Baer, 1973). The children were rewarded for block constructions that differed from any that had previously been observed during the session. As training proceeded, the children built increasingly varied forms, including ones never before made by the child. Similar results were obtained with the drawing of color pictures as the target behavior (Holman, Goetz, & Baer, 1977).

The evidence from many methods has therefore shown control over response variability by directly contingent reinforcers (see also Hachiga & Sakagami, 2010; Machado, 1989, 1992, 1997). Variability is highest when reinforcers follow high variability. In the next section, we show that reinforcers exert even more precise control than that: Levels of variability can be specified, levels that span the range from response repetitions (or stereotypy) to response unpredictability. As such, variability parallels other operant dimensions in which reinforcers influence exactly how fast to respond or when, with what force, or at which location.

### Levels of Variability

Other experiments in the Page and Neuringer (1985) article described earlier applied different lag values in different phases, from lag 1 (the current sequence of eight responses had to differ from the single previous sequence) to lag 50 (the current sequence had to differ from each of the previous 50 sequences). As the lag increased, requiring that sequences be withheld for an increasing number of trials, responses generally became increasingly unpredictable (as assessed by *U* values, number of different sequences per session, and other statistics; see also Machado, 1989). Frequency-based methods show similar control over levels. For example, Grunow and Neuringer (2002) used a different threshold reinforcement criterion with each of four groups of rats: one that required rats to distribute



three-response sequences (across three different operanda) in a way that paralleled a random generator (high variability), another that required medium-high variability, another that required medium-low variability, and the last that permitted frequent repetitions. Levels of variability were again controlled by these specific requirements, as shown by the leftmost points in Figure 22.2 (the other points in the figure are discussed later). Several additional studies have demonstrated reinforcement control over precise levels of variability in pigeons (Neuringer, 1992) and people (G. Jensen, Miller, & Neuringer, 2006).

Precisely controlled levels of behavioral (un)predictability can be observed in many natural situations. Variable behaviors are used to attract attention, as when male songbirds increase the variability of their songs in the presence of a receptive female (Catchpole & Slater, 1995). During play and games, animals and people modulate levels of

variability as a function of the reactions of their playmates. When entertaining a child, the actions of an adult sometimes include surprises, such as tickling, as well as repetitions, such as repeatedly bouncing a child on one's lap, and the child's reactions influence the action's (un)predictability. Similarly, in conversations, the speaker is (often) sensitive to the reaction of the listener with variations in topic as well as in prosody, loudness, and speed. Unpredictability is particularly important in competitive situations. Consider the example of table tennis: When a skilled player (S) plays with a beginner (B), S will often return the ball in a way that B can easily predict, but as B becomes increasingly capable, S will vary ball placement and speed until a high level of unpredictability is (sometimes) manifest. Precise control of levels of unpredictability plays a substantial role in game theory, under the rubric of mixed strategies (see Glimcher, 2003; Smith, 1982). These examples are only a few of the commonplace variations in

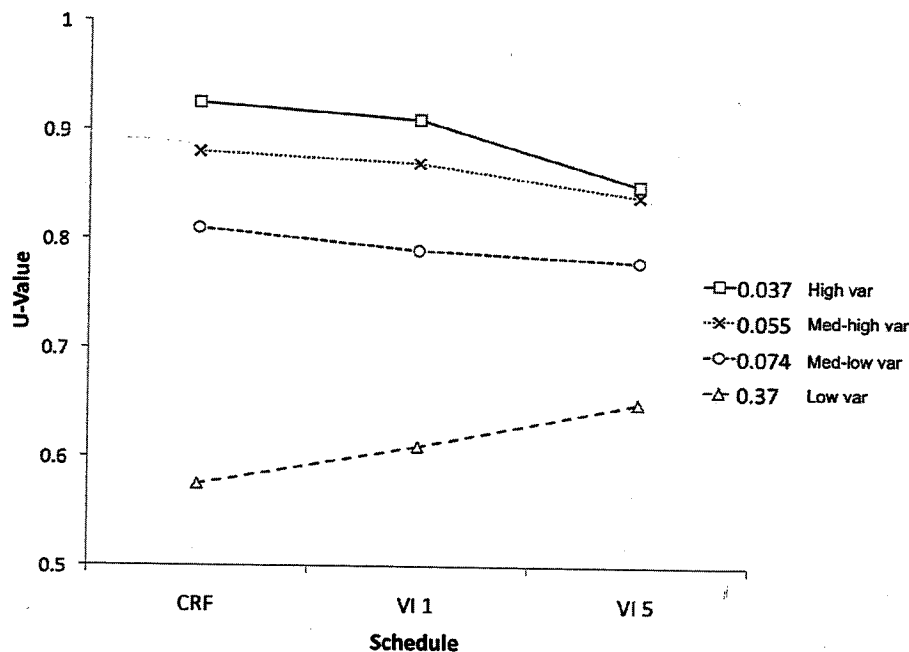


FIGURE 22.2. *U* value as a function of reinforcement frequencies. Each line represents a different group: .037 = very high variability (var) required for reinforcement; .37 = very low variability required; .055 and .074 = intermediate levels required. CRF = continuous reinforcement, or reinforcement every time variability contingencies were met; VI 1 = variable-interval reinforcement for meeting variability contingencies no more than once per minute, on average; VI 5 = variable-interval reinforcement no more than once every 5 minutes. From "Learning to Vary and Varying to Learn," by A. Grunow and A. Neuringer, 2002, *Psychonomic Bulletin and Review*, 9, p. 252. Copyright 2002 by the Psychonomic Society, Inc. Adapted with permission.

levels of response (un)predictability that characterize many real-world operant behaviors, variations that are controlled by consequences. We discuss additional real-world applications later.

### Orthogonal Dimensions

As indicated in the introduction, reinforcement often depends on a combination of many aspects of a response. For example, a child may receive a reinforcer for saying “thank you” but only when the child (a) speaks slowly and (b) makes eye contact. Because responses can vary across many dimensions independently from one another, one can readily imagine circumstances in which it might be functional to vary some dimensions of behavior while keeping others highly predictable.

A demonstration of the independent reinforcement of variability and predictability along independent dimensions was provided by Ross and Neuringer (2002). They instructed college students to earn points in a video game involving drawing rectangles on a computer screen. Three dimensions

of the rectangles were evaluated: area (the number of pixels enclosed by the rectangle), location (the position of its center point), and shape (its height-to-width ratio). To be reinforced, the rectangles had to vary along two of these dimensions while repeating along the third. The participants were told nothing about these criteria, and the only instructions were to gain points by drawing rectangles. Participants were randomly assigned to one of three groups, with rewards delivered in one group when the areas of the drawn rectangles were approximately the same, trial after trial, but locations and shapes varied. The other two groups had analogous contingencies, but for one, locations had to repeat, and for the other, shapes had to repeat. All participants learned to meet their respective three-part contingencies, varying and repeating as required (Figure 22.3). Thus, binary feedback—reinforcement or not—influenced variability and repetitions along three orthogonal dimensions and did so independently, thereby highlighting the precise, multifaceted way in which reinforcers control variability.

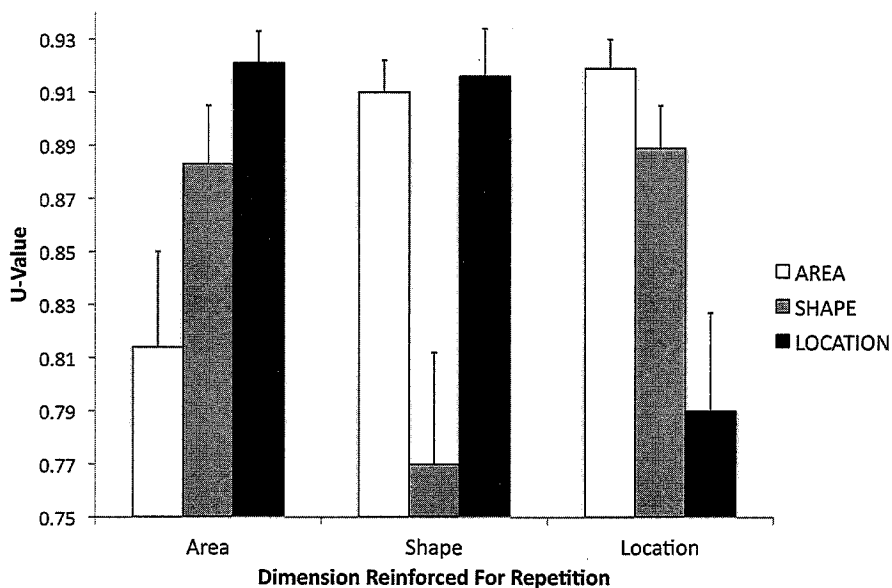


FIGURE 22.3. *U* values for each of three dimensions of rectangles drawn by participants in three separate groups. One group was required to repeat the areas of their rectangles while varying shapes and locations (left set of bars), a second group was required to repeat shape while varying areas and locations (middle set of bars), and a third group was required to repeat location while varying areas and shapes (right set of bars). Error bars indicate standard errors. From “Reinforcement of Variations and Repetitions Along Three Independent Response Dimensions,” by C. Ross and A. Neuringer, 2002, *Behavioural Processes*, 57, p. 206. Copyright 2002 by Elsevier B.V. Adapted with permission.

As we show in the next section, reinforcers exert other simultaneous influences: They select the set or class of responses from which instances emerge and, simultaneously, the required level of variation.

### Response Sets and Variations

Whenever variability is reinforced, a set of appropriate responses is also strengthened. Reinforcers select the set from which variations emerge. Mook and Neuringer (1994) provided experimental evidence for this point. In the first phase, rats' variable four-response sequences across L and R levers (lag schedule) were reinforced. In the second phase, only sequences that began with two right responses, RR, were reinforced. Thus, now only RRLL, RRLR, RRRL, and RRRR patterns were effective. In the first phase, all 16 possible sequences were emitted, whereas in the second phase, most sequences began with two right responses, RR. Thus, the reinforcement contingency generated behaviors that satisfied the appropriate set definition while simultaneously producing a required level of variability within that set. In another experimental example (Neuringer, Kornell, & Olufs, 2001), rats responded in chambers containing five operanda: left lever, right lever, left key, center key, and right key. In one phase, reinforcers were contingent on variations across only three of the operanda (left and right levers and center key), and the rats learned to respond variably across only those three. A binary event—reinforce or not—can function simultaneously to define a response class and levels of (un)predictability along multiple dimensions of the within-class instances. This result shows an extraordinary diversity of control by simple reinforcement operations.

### Discriminative Stimuli

Operant responses are generally influenced by discriminative stimuli, that is, cues that indicate reinforcer availability. If pigeon pecks are intermittently reinforced when the keylight is red but not when it is green, the birds learn to peck almost exclusively when the keylight is red. Discriminative stimuli control levels of variability as well. For example, Page and Neuringer (1985, Experiment 6) reinforced repetitions of a single sequence of key pecks, LRLL, in the presence of blue keylights, whereas variable

sequences were reinforced in the presence of red keylights (lag schedule). Blue and red alternated after every 10 reinforcers under what is referred to as a *multiple schedule* (two different reinforcement contingencies presented successively, each correlated with a distinct stimulus). The birds learned to repeat in the presence of blue and to vary in the presence of red, and when the stimulus relationships were reversed, the birds varied in the presence of blue while repeating in the presence of red. In another experiment, rats learned to emit variable four-response sequences across L and R levers in the presence of one set of lights and tones and repeated a single pattern, LLRR, in the presence of different stimuli (Cohen, Neuringer, & Rhodes, 1990). In an even more stringent test by Denney and Neuringer (1998), rats' variable sequences were reinforced in one stimulus, whereas in a yoke stimulus, reinforcers were delivered at exactly the same rate and distribution but independent of variability. The cues came to exert strong differential control, and when variability was required, the animals varied; when variability was not required but permitted in yoke, response sequences became more repetitive and predictable. These results indicate that an individual may behave in a habitual and predictable manner in one context, whereas in a different context, perhaps occurring only a few moments later, the same individual will respond unpredictably or in novel ways. The results further indicate (along with other VAR-yoke comparisons described earlier) that to engender highly variable behaviors, it may be necessary to reinforce variability explicitly rather than, as in *laissez-faire* environments, simply permit individuals the freedom to vary. To the extent that individual freedom depends on the possibility of variation, reinforcement plays an important role (a topic to which we return in the final sections of this chapter).

### Endogenous Stimulus Control

The discriminative stimuli described in the previous section were external to the organism and publicly observable. Another form of discriminative control depends on the interactions of an organism with a reinforcement schedule. An example of such endogenous stimulus control is seen in the pauses that follow reinforcers under fixed-interval schedules.

The reinforcers serve as indicators that for some period of time, reinforcement is not possible. Hopson, Burt, and Neuringer (2002) showed that response-reinforcer relationships exert discriminative control over levels of variability as well (see also Neuringer, 2002). Rats' responses were reinforced under a schedule in which two periods alternated, VAR and repetition (REP), but these periods were not cued by external stimuli (technically, a mixed schedule). In the VAR period, four-response sequences of L and R lever presses were reinforced if they met a threshold variability contingency; in the REP period, only repetitions of LLLL were reinforced. (Probabilities of reinforcement were equalized in the two periods by intermittent reinforcement of LLLL in REP.) After the schedule transitioned into the VAR component, responding began to vary within a few trials, and variations continued until the schedule transitioned into REP, with responding soon reverting to LLLL. These results indicate that the variability produced when reinforcement is withheld for short periods, as when a new response is being shaped, may partly be discriminatively controlled despite absence of external cues; that is, animals and people may learn when it is functional to vary, and some of the cues may come from response-outcome relationships.

## NONCONTINGENT EFFECTS

Until this point, we have focused on contingencies that directly relate reinforcers to variability. All operant responses are also influenced by events that are not directly contingent on the responses, sometimes referred to as eliciting or inducing influences, respondents, or establishing operations. For example, levels of deprivation, injections of drugs, and ambient room temperature can all influence learning and maintenance of operant responses. Even noncontingent aspects of the reinforcement operation itself may have important effects, for example, attributes such as the quality and quantity of food (referring here to when these do not change as a function of behavior). Thus, to understand operant responding, including operant variability, these other influences must be considered. We turn to a discussion of effects of noncontingent events on operant variability. As we describe at the end of this section,

noncontingent influences often interact in important ways with variability-contingent reinforcers.

## Random Events

Many behavioral trajectories are initiated by the accidental confluence of the organism with one or more environmental happenings. Hurricanes, earthquakes, and wars change behaviors in ways that cannot readily be anticipated. Winning a lottery is a happier example. Another might be happening to sit next to a particular individual on a cross-country flight, which leads to a long-term romantic relationship (see Bandura, 1982; Taleb, 2007). These events, although randomly related to the individual's behavior, have important long-term influences.

Random events have been purposively used throughout history to guide behaviors, for example, throws of dice, randomly selected sticks, cards, bones, or organs. Today, a referee flips a coin at the beginning of a football game to decide which team can choose whether to kick the ball; a computer's random-number generator assists scientists with avoiding biases in assigning subjects to experimental groups; and alleotory events are used in modern art, music, and literature. *The Dice Man* by Rhinehart (1998) provides a fictional example of intentional use of random artifacts. The protagonist, bored with life, writes a number of possible actions on slips of paper and then periodically selects one blindly and behaves accordingly. These examples show that random events that are independent of an individual's actions may be used to avoid biases, engender unlikely responses, and break out of behavioral ruts.

## Evolved Responses

Modes of unpredictable behavior have evolved that permit organisms to escape from or avoid predators or aggressors. These behaviors have been referred to as *protean behaviors* that are "sufficiently unsystematic in appearance to prevent a reactor predicting in detail the position or actions of the actor" (Driver & Humphries, 1988, p. 36). Examples include the random zigzags of butterflies, stickleback fish, rabbits, and antelopes when being attacked. One consequence of evolved protean behavior is that it interferes with a predator species' evolving a response to a specific escape or avoidance pattern. In brief,

protean behaviors demonstrate evolved randomlike responses to eliciting stimuli.

### Schedules of Reinforcement and Expectancy

Both in the laboratory and in the real world, it is common for responses to be intermittently (or occasionally) reinforced. Much operant conditioning research is devoted to documenting the effects of such schedules. To take one example, under a fixed-ratio schedule of reinforcement, a fixed number of responses (say, 30) is required to gain access to a pellet of food. After receipt of each pellet, it is impossible to obtain another immediately, because 30 additional responses are required. As was the case for the fixed-interval schedules mentioned earlier, pauses are generally observed after reinforcement, or lower rates of responding, as compared with later in the ratio, when access to reinforcement is possible.

In addition to these effects on response rate, response variability is also found to change under similar reinforcement schedules. In the cases discussed here, variability plays no role in the contingency, that is, reinforcers do not depend on response variations. However, responding tends to become increasingly repetitive and predictable as an anticipated reinforcer is approached in time or number. This tendency was shown for variability across two levers when a fixed sequence of responses was the operant (Cherot, Jones, & Neuringer, 1996), for variability of lever-press durations also under ratio schedules (Gharib, Gade, & Roberts, 2004), and for variability of movements across a chamber space when access to a potential sexual reinforcer is approached (Atkins, Domjan, & Gutierrez, 1994). In each of these cases, variability is relatively high when reinforcers are distant with respect to effort, time, or space, and responding becomes more predictable as reinforcers are neared (see also Craig, 1918). These changes in response predictability are said to be induced by the schedule of reinforcement.

Another variable shown to induce differences in response variability is reinforcement frequency. In general, response variability is high when reinforcers are infrequent and low under high-density reinforcement (Lee, Sturmeijer, & Fields, 2007). One

interpretation of these effects is that low expectation (or anticipation) of reinforcers induces variability (Gharib et al., 2004). Whatever the explanation, it is important to be able to identify whether variability is selected by reinforcers or pushed by states of the body (endogenous inducers) or environmental events, including noncontingent effects of reinforcers. Discriminating between selection and induction will facilitate the modification of variability when that is desirable.

### Experience

Thorndike (1911) and Guthrie and Horton (1946) described the responses of cats that had been confined in a puzzle box and who received food contingent on escape. Response topographies were highly variable at first but, over trials and rewards, became increasingly predictable and stereotyped. Antonitis (1951) studied nose pokes by rats along a long horizontal slit. When pokes produced access to food, location variability decreased across trials. Notterman and Mintz (1965) measured the force exerted by rats on a response lever and found that across training, force decreased, approaching the minimum level necessary to operate the lever, with force variability decreasing as well. Brener and Mitchell (1989) extended these results to the total energy expended by a rat in an operant conditioning chamber. A last example comes from Vogel and Annau (1973), who reinforced pecking three times on a left key and three times on a right key, in any order. Across sessions, a marked increase occurred in the predictability (stereotypy) of the pigeons' patterns of response. A general consensus has therefore emerged: Variability of operant behavior decreases with experience. This conclusion, however, may apply mainly to situations in which every response or sequence leads to a reinforcing consequence and to situations in which high variability is not differentially reinforced.

### Extinction

After long-term experience in which responses produce reinforcers, suddenly withholding reinforcers—referred to as *extinction of responding*—increases variability. In the experiment by Antonitis (1951) noted earlier, after the rats were accustomed to

producing food reinforcers by poking their noses anywhere along a horizontal opening, food was withheld, which caused an increase in location variability. Extinction-induced variability has been seen along many other response dimensions: location (Eckerman & Lanson, 1969), force (Notterman & Mintz, 1965), topography (Stokes, 1995), and number (Mechner, 1958). One contrary result is often cited, namely a study by Herrnstein (1961) in which variability of the location of pigeon pecks along a continuous strip was reported to decrease during a period of extinction. However, the extinction in that study followed a phase in which every response was reinforced (continuous reinforcement) in an A-B design (first a reinforcement phase, then extinction, without return to the first phase). Experience may therefore have confounded the results. In general, extinction causes variability to increase.

The variations induced by extinction generally emerge from the class of responses established during original learning. For example, if lever pressing produced food pellets, a rat may vary the ways in which it presses when food is withheld, but much of the behavior will be directed toward the lever (e.g., Stokes, 1995). Neuringer et al. (2001) quantified the bounded nature of extinction-induced variability that was observed after rats had been rewarded for repeating a single sequence across two levers and a key: left lever, key, right lever (LKR), in that order. The top panel of Figure 22.4 shows the distribution of the relative frequencies of each of the possible sequences (proportions of occurrences) during the conditioning, or reinforcement, phases (filled circles) and during extinction (open circles). The LKR sequence was, of course, most frequent during the reinforcement phase, with other, somewhat similar sequences falling off in terms of their frequencies. The LKR sequence was also most frequent throughout the extinction phase—during which time response rates fell to low levels—with the two curves being quite similar. (Note that these curves show relative frequencies. Absolute rates of response were much lower during extinction than during the reinforcement phase.) Also shown at the bottom of the figure are the ratios of response proportions during the reinforcement and extinction phases (i.e.,

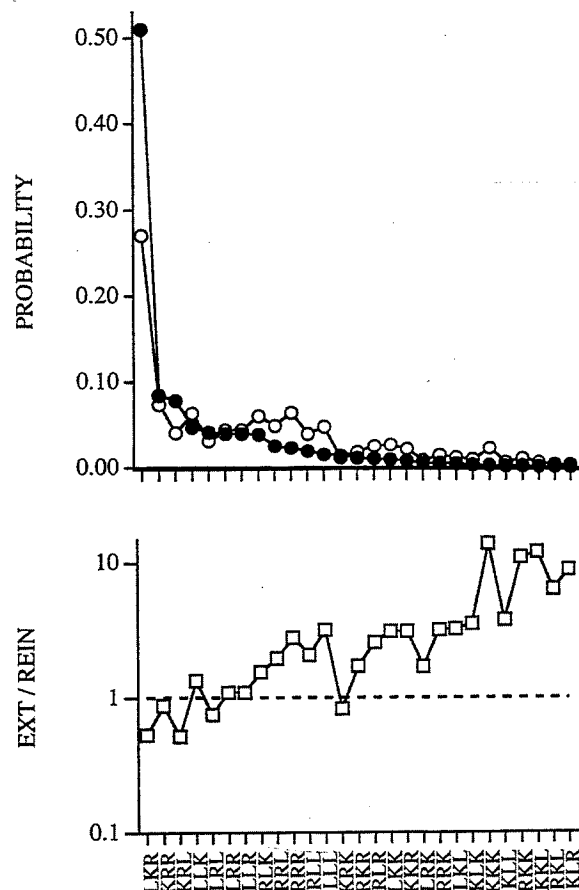


FIGURE 22.4. The top graph shows the proportion (or probability) of occurrences of the three-response patterns shown along the x-axis during a period when a single sequence (left lever, key, right lever) was being reinforced (filled circles) and during a period of extinction, when reinforcers were withheld completely (open circles). The bottom graph shows the ratio of responding during extinction (EXT) to responding during reinforcement (REIN; i.e., the ratio of the two curves in the upper graph). Together, the graphs show that patterns of responding during extinction were similar to those during reinforcement, but high-frequency sequences decreased and low-frequency sequences increased during the extinction phase. Adapted from "Stability and Variability in Extinction," by A. Neuringer, N. Kornell, and M. Olufs, 2001, *Journal of Experimental Psychology: Animal Behavior Processes*, 27, p. 89. Copyright 2001 by the American Psychological Association.

the ratio of the two curves in the upper graph). The take-home message is that the basic form of the behavior was maintained during extinction, and variability increased because of the generation of unusual or highly unlikely sequences (for related

findings, see Bouton, 1994). Extinction was therefore characterized as resulting in a “combination of generally doing what worked before but occasionally doing something very different. . . . [This] may maximize the possibility of reinforcement from a previously bountiful source while providing necessary variations for new learning” (Neuringer et al., 2001, p. 79). Knowledge of these effects can be applied to one’s own behavior as well as to others. When in a rut, or unproductive or dissatisfied, avoiding those reinforcers that had been produced by habitual behaviors may help.

### Interactions

Noncontingent inducers often interact with variability-contingent reinforcers to control levels of response variability. Additional phases in the Grunow and Neuringer (2002) experiment described in the Levels of Variability section provide one example. In the first phase of that experiment, recall that high, medium-high, medium-low, and low levels of response-sequence variability were reinforced across groups of rats, resulting in different levels of response variability across the four groups. Two additional phases followed in which, although the four different variability criteria were unchanged, overall frequencies of reinforcement were systematically lowered by providing reinforcement only intermittently. In particular, a variable-interval (VI) schedule of reinforcement was superimposed on the variability contingency: first a VI 1 minute (such that food pellets were limited to an average of once per minute, with unpredictable gaps of time between food deliveries) and then VI 5 minute (limiting food pellets to no more than once, on average, every 5 minutes). Under the VI schedules, after an interval elapsed, the first trial to meet the variability contingency ended with a reinforcer. All other trials ended with a brief time out (whether or not the variability requirement had been satisfied).

As reinforcement frequencies were lowered, response rates fell in all four groups and did so equally, that is, all groups responded much more slowly when varying sequences were reinforced on average once every 5 minutes than when they were reinforced each time that they met the contingencies. However, different results were obtained for

variability, indicated by the  $U$  values in Figure 22.2. The individual curves represent the four variability thresholds, and the  $x$ -axis represents frequencies of reinforcement. The four thresholds exerted primary control, that is, the groups differed in variability throughout the experiment. Effects of reinforcement frequency were more subtle and depended on the threshold requirements, an interaction effect. When the contingencies were lenient and low levels of variability sufficed for reinforcement, variability increased as reinforcement rates fell (from continuous reinforcement to VI 1 to VI 5). When the contingencies were demanding and high levels of variability were reinforced, the opposite occurred, that is, variability decreased with decreasing reinforcements. The intermediate groups showed intermediate effects. A similar interaction was obtained when delays were introduced between the end of a varying sequence and reinforcement (Wagner & Neuringer, 2006). Thus, when reinforcers are contingent on variability, the contingency exerts a strong—and often primary—effect, but that effect is modified by noncontingent influences, including reinforcement rates and delays. Levels of response variability depend on both contingent and noncontingent influences.

Interactions between variability-contingent and variability-noncontingent reinforcement may help to explain effects seen outside of the lab. Repetitive behaviors are required for many workers (e.g., factory workers, mail carriers, fare collectors), but for others, variable (and unpredictable) behaviors are the norm (e.g., inventors, fashion designers, artists). Lowering pay or withholding positive feedback may affect behaviors differently in these two cases. Thus, to predict effects on behavioral variability, one must know both contingent and noncontingent relationships.

Cherot et al. (1996) described a different interaction that may also help to illuminate real-world effects. In that experiment, repeated response sequences across two levers were reinforced in one group of rats (REP) and sequence variability was reinforced in another group (VAR). Not every sequence that met the VAR or REP contingency gained reinforcement, however; rather, a superordinate fixed-ratio 4 also had to be satisfied. That is, the REP group had to successfully repeat a sequence

four times to get a single reinforcer, and the VAR group had to successfully vary a sequence the same number of times. For example, in the REP group, one animal may have emitted LLLR in the first trial after a reinforcer, but that correct sequence caused only a signal indicating *correct*. No food was given. If the next trial also contained LLLR, the *correct* signal was again provided. If the following trial was LLLL, then a brief time out was given. This process continued until the fourth correct LLLR sequence produced the signal plus a food pellet. Exactly the same procedure was in place for the VAR animals, except they were correct only when they met a lag variability contingency.

As shown in Figure 22.5 (bottom), the main result was that the VAR animals responded much more variably overall than did the REP animals, again indicating primary control by the variability and repetition contingencies. However, as reinforcement was approached (i.e., as the last of the four successful sequences was neared), levels of variability decreased for both VAR and REP groups. Recall the expectancy-of-reinforcement effects described in the section Schedules of Reinforcement and Expectancy earlier in this chapter. In this case as well, variability decreased as reinforcers were approached, thereby facilitating correct responding in the REP group but interfering with it in the VAR group (Figure 22.5, top panel). Let us pause for a moment to consider this surprising finding. Despite the fact that variability was being reinforced in the VAR group, as the reinforcer was neared, the likelihood of varying decreased. It is important to note again that reinforcement of variability generated much higher levels of variation overall than did reinforcement of repetitions, a variability-contingent effect, but superimposed was an expectancy-inducing decrease in variability. Similar interactions may help to explain effects of reinforcers on other types of behavior, including creative behaviors, a topic that we discuss in the Applications section.

## MEMORIAL AND STOCHASTIC EXPLANATIONS

We have described types of events that result in variable behaviors. Now, we examine two commonly

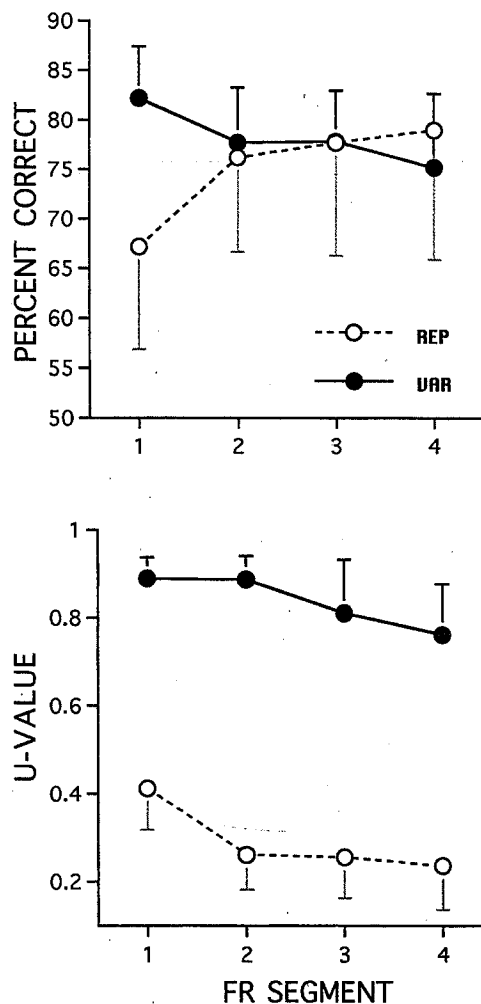


FIGURE 22.5. The top graph shows percentages of sequences that met variability (VAR) or repetition (REP) contingencies as a function of location within a fixed-ratio 4 (FR 4) schedule. The lines connect means for groups of rats, and the error bars indicate standard deviations. The lower graph shows *U* values, an index of sequence variability, for the two groups across the FR schedule. Adapted from "Reinforced Variability Decreases With Approach to Reinforcers," by C. Cherot, A. Jones, and A. Neuringer, 1996, *Journal of Experimental Psychology: Animal Behavior Processes*, 22, p. 500. Copyright 1996 by the American Psychological Association.

discussed explanations of operant variability, namely memorial and stochastic processes. According to the memorial explanation, each response can be related to or predicted from prior stimuli or responses. According to the stochastic-generator hypothesis,



individual responses are unpredictable because of the nature of a random process. That is, individual responses do not have identifiable individual causes, a hypothesis that many consider problematic. We consider each of these explanations and argue that the evidence for both of these hypotheses is good and therefore that behaving (more or less) unpredictably derives from multiple sources.

### Memory-Based Variability

*Memory* is a shorthand way to refer to the influence of past events that are separated in time from a current response. The term is not intended to connote conscious awareness (although that might be involved) but rather potentially identifiable influences (or causes). To the extent that memorial processes are responsible for variability generation, prediction of individual responses is possible, even when the overall output is variable; thus, each member of a variable sequence could be said to be determined by prior events.

At the outset of this chapter, we indicated that under lag 50 schedules, in which the current response sequence must differ from each of the previous 50 sequences, responding was highly variable and, indeed, approached that expected of a stochastic generator. However, behaviors are often quite different under lag 1 or 2 schedules. In these cases, the current sequence must differ from only the previous one or two, and memory-based response strategies frequently emerge: Animals and people sometimes cycle repeatedly through two or three sequences, apparently basing a current response sequence on the just-emitted sequences. The cycling strategy produces reinforcement for every sequence, which is a better rate of return than responding in a stochastic-like manner.<sup>3</sup> The advantage is, however, only conferred when the memory demands are within the subject's capacity.

In a demonstration of the latter point, Machado (1993) studied pigeons pecking L and R keys under a frequency-dependent variability contingency. Under this schedule, if the sequence is composed of just one response, then pecking the key that had been pecked least frequently in the past will be

reinforced. By alternating, LRLRLR . . . , every response is reinforced, and birds developed just such an alternation strategy. When the sequence consisted of two responses, the birds again developed memory-based sequences, for example, repeating RLLRLL. However, when the sequence was increased to three responses, such that reinforcement was given for responses in the least frequent three-response bin, the birds apparently could not develop the optimal fixed pattern of RRLLRLL . . . but instead reverted to randomlike behavior (Machado, 1993, p. 103). Thus, a memory-based strategy was used when that was possible, but when the memory demands became too high, stochastic responding emerged. A similar pattern was seen with songs generated by a songbird, a budgerigar, under lag contingencies of reinforcement (Manabe, Staddon, & Cleaveland, 1997). Under lag 1, the birds tended to alternate between two songs; under lag 2, they cycled among three songs. When the lag was increased to 3, however, song diversity and variability increased appreciably. Thus, under recency- and frequency-based methods of variability reinforcement, variable responses are generated via memorial processes when possible, but reversion to stochastic-like emission is seen when memory requirements exceed the organism's capacity.

### Chaotic Responding

Memory-based strategies can be used in other ways as well. For example, chaotic processes generate outputs that are so noisy that it is exceedingly difficult to distinguish them from stochastically generated ones. "Chaos [is] a technical term . . . refer[ring] to the irregular, unpredictable behavior of deterministic, nonlinear systems" (R. V. Jensen, 1987, p. 168). Chaotic behavior is both highly variable and precisely controlled by prior events (Hoyert, 1992; Mosekilde, Larsen, & Sterman, 1991; Townsend, 1992). A study by Neuringer and Voss (1993) asked whether people could learn to generate chaotic-like responses. They used one example of a chaotic function, the logistic difference function:

$$R_n = t \cdot R_{n-1} \cdot (1 - R_{n-1}). \quad (2)$$

<sup>3</sup>For example, stochastic responding on two alternatives under a lag 1 contingency earns 50% reinforcement, whereas alternating earns 100%.

Here,  $R_n$  refers to the  $n$ th iteration in a series, each  $R$  is a value between 0.0 and 1.0, and  $t$  is a constant between 1.0 and 4.0. The current value of the logistic difference function ( $R_n$ ) is based on the previously generated value ( $R_{n-1}$ ). The process begins with an arbitrary seed value for the  $R_0$  between 0 and 1, which is used to calculate  $R_1$ . Apart from the initial seed value, the function is completely self-generated, with each value determined by the just-prior value, together with the constant parameters.

Chaotic outputs have two identifying characteristics. First, given a constant value for  $t$  that approaches 4, for example, 3.98, the generated sequence approximates a random one, that is, it passes many tests for randomness. Outputs are noisy and apparently unpredictable. However, second, if the current value of  $R_n$  is plotted as a function of the just prior value,  $R_{n-1}$ , a predictive structure can be identified. In the particular case of the logistic difference function, the form of this autocorrelated relationship is a parabola (different chaotic functions show different types of internal structures). Thus—and this is the identifying attribute of chaotic processes—a deterministic mathematical function can generate randomlike outputs with prediction of each value of the function possible given precise knowledge of parameters and prior values. The outputs are extremely noisy and, at the same time, identifiably determined.

In the Neuringer and Voss (1993) study, college students were shown, after each response, the difference between their responses and that of the iterated logistic difference model. With training, the students became increasingly adept at responding in chaoticlike fashion—the students' responses matched closely the iterations of the logistic function—and their autocorrelations increasingly approximated a parabola (Figure 22.6). Because each iteration in the logistic difference sequence is based on the prior output, Neuringer and Voss hypothesized that the human subjects also remembered prior responses. Put simply, the subjects may have learned (or memorized) a long series of "if the previous response was value A, then the current response must be value B" pairs, a suggestion made by Metzger (1994) and by Ward and West (1994).

To test this memory hypothesis, Neuringer and Voss (2002) interposed pauses (IRTs) between each

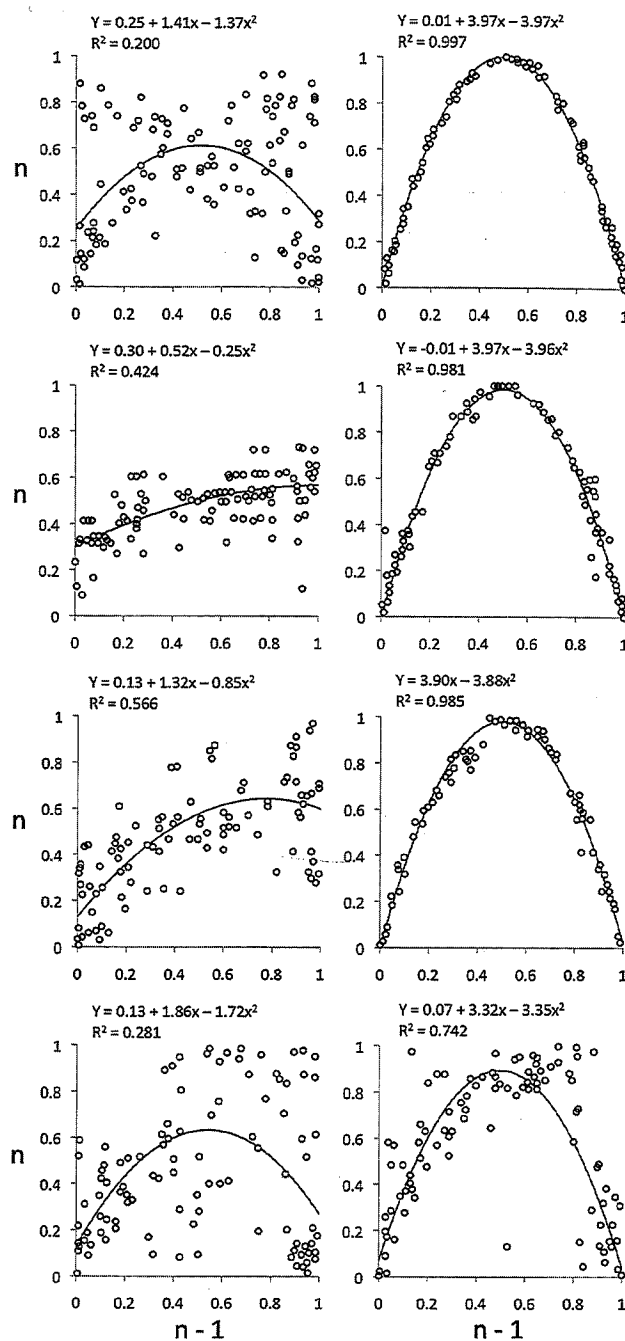


FIGURE 22.6. Responses in trial  $n$  as a function of responses in trial  $n - 1$  during the first 120 responses of the experiment (left column) and final 120 responses (right column). Each row of graphs represents data from a single participant. The drawn lines show the best-fitting parabolas. From "Approximating Chaotic Behavior," by A. Neuringer and C. Voss, 1993, *Psychological Science*, 4, p. 115. Copyright 1993 by the Association for Psychological Science. Adapted with permission.

response, that is, they slowed responding (see also Neuringer, 2002). As IRT durations increased, the difference between the subjects' sequences and the model's chaotic output increased, and the underlying parabolic structure was disrupted, providing evidence that the highly variable responding was memory based.

### Stochastic Generation

Stochastic generation has been hypothesized at numerous points in the chapter. Here we discuss in more detail what the stochastic hypothesis involves and possible ways to test it. The issue is complex, difficult, and important. If variable operant responses are generated stochastically, then it may not be possible to predict individual responses at greater than chance levels. Stochastic generation may also be relevant to operant responses generally and to explanations of their voluntary nature, as we discuss later. A researcher confronts many problems, however, in attempting to decide whether a particular response stream is random or not and confronts additional difficulties when trying to determine whether it has been generated by a random process (see Nickerson, 2002).

To get an intuitive sense of what *random* implies, imagine an urn filled with 1,000 colored balls. The urn is well shaken, and one ball is blindly selected. After selection, the ball's color is noted, the ball is returned to the urn, and the selection process is repeated. If the urn contains an equal number of blue and red balls, then prediction of each ball's color will be no better than chance; that is, the probability of a correct prediction would be .50. The repeated selections represent a random process<sup>4</sup> with the resulting output being a random sequence. Note that predictions can be better than 50% for random processes, as shown by the following: If the urn was filled with an uneven number of different colored balls, prediction could become increasingly accurate. For example, if the urn contained 900 red balls and 100 blue balls, then prediction accuracy would rise to .90 (if one always predicted red). However, the process and output are still referred to as stochastic. Thus, stochastic outputs are more or less predictable depending on the relative frequencies

of the items (the two colors, in our example). It is also true that the greater the number of different item classes, for example, different colors, the less predictable any given instance will be. If the urn contained equal numbers of 20 different colors, for example, then the chance level of prediction would be .05 (rather than .50 in the two-color case). Discussion of these concepts in historical context can be found in Gigerenzer et al. (1989).

When trying to ascertain whether a finite sequence of outputs was randomly generated, the best one can do is to estimate the probability that a random process is involved. For example, if 100 selected balls were all blue, it would be unlikely but not impossible that the balls were selected randomly from an urn containing an equal number of red and blue balls. Given a random generating process, any subsequence of any length is possible, and every particular sequence of outcomes of a given length is exactly as likely as any other (see Lopes, 1982). These considerations indicate the impossibility of proving that a particular finite sequence deviates from random: The observed sequence may have been selected from an infinite random series (see Chaitin, 1975). However, the probability of 100 blue balls is extremely low in our example, and the probability is much higher for sequences that contain approximately 50% red and 50% blue. Thus, one can evaluate the probability that a given output was generated by a stochastic process having particular parameters.

A second problem is that as demonstrated by chaos theory, seemingly random outputs may be generated by nonrandom processes. Another example is given by iteration of the digits of pi. Someone could memorize the first 100 digits of pi and use those to generate a randomlike sequence. Thus, behavioral outputs can be highly variable but (given sufficient knowledge by an observer) predictable. How, then, can one test whether highly variable operant responses derive from a stochastic process? The test must involve a comparison—which of two hypotheses is most likely to account for the data?—and the most likely alternative is the one already discussed, namely, memory-based processes under which each response can be predicted from

<sup>4</sup>Specifically, this process is "random with replacement" on account of the act of returning the ball to the urn. All discussions of randomness in this chapter refer to this type of randomness.

knowledge of prior stimuli or responses. A powerful tool for making this comparison is memory interference, that is, the degrading of control by prior events. Availability of memory-interfering procedures leads to the following reasoning: When approximation to a stochastic output is reinforced, if a memory-interfering event degrades performance, it provides evidence against a stochastic generation process. Absence of memory-interfering effects provides evidence consistent with stochastic generation. We have already seen evidence for stochastic-like responding when demands on memory were high (Machado, 1993; Manabe et al., 1997) and turn next to additional tests of the stochastic hypothesis.

Neuringer (1991) compared the effects of memory interference on responding by two groups of rats. One group obtained reinforcers by repeating a single pattern, LLRR. Once that pattern was well learned, blackouts were introduced between each response, the durations ranging from 0.1 second to 20 seconds across different phases of the experiment. Responses were ineffective during the blackout periods. As blackout durations increased, errors increased and reinforcement rates fell. Neuringer hypothesized that the interposed blackouts degraded performance because each response in the LLRR

sequence depended in part on memory for the just-prior response.

Effects of the same blackouts were assessed in a second group of rats that obtained reinforcers for varying four-response sequences under lag contingencies. Neuringer (1991) reasoned that if variable responses were generated by a memory-based process, then performances would be degraded as blackout durations increased, as was the case for the LLRR group. In fact, performances by the variability group actually improved with increasing blackout durations, resulting in higher rates of reinforcement. Some have suggested that absence of memory for prior events is necessary for random responding (Weiss, 1965), implying that memory interferes with random generation. In any event, the results were clearly inconsistent with the memory hypothesis.

In a related study, alcohol was administered to a single group of rats that had learned to respond variably when one stimulus was present and repeat LLRR sequences given a second stimulus (Cohen et al., 1990). The two stimuli alternated throughout each session under a multiple schedule. As alcohol doses increased, performance of the LLRR sequence was seriously impaired, whereas varying under the lag contingency was unaffected (Figure 22.7; see

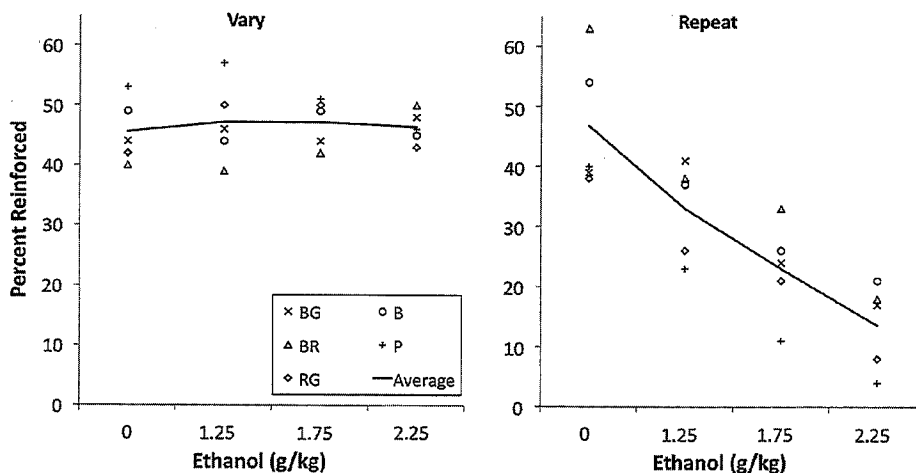


FIGURE 22.7. Percentages of reinforced, or correct, sequences as a function of ethanol dosage for each of five rats. Varying sequences were reinforced under one stimulus condition (left graph), and repetitive LLRR sequences were reinforced under another stimulus (right graph). The lines connect averages of the five subjects (BG, BR, RG, B, and P). From "Effects of Ethanol on Reinforced Variations and Repetitions by Rats Under a Multiple Schedule," by L. Cohen, A. Neuringer, and D. Rhodes, 1990, *Journal of the Experimental Analysis of Behavior*, 54, p. 5. Copyright 1990 by Society for the Experimental Analysis of Behavior, Inc. Adapted with permission.

also Doughty & Lattal, 2001). Thus, within a single session, the drunk rats failed to repeat accurately but were highly proficient when required to vary. Both interposed time delays and alcohol, two ways to affect memory for prior responses; degraded performances of fixed-pattern sequences; and either improved operant variability or left it unaffected.

Additional evidence for the difference between memory-based and stochastic responding was provided by Neuringer and Voss (2002; see also Neuringer, 2002). College students learned to generate chaotic-like sequences (according to the logistic difference chaos function described in Equation 2) as well as to generate stochastic-like sequences (given feedback from eight statistical tests, as in Neuringer, 1986). These two ways of responding variably were alternated, with the stimulus control, throughout each session. Memory interference was later introduced in a rather complex way. In the chaos phase of the experiment, subjects were required to generate four separate chaotic functions, each differing from the other. In the stochastic phase, four uncorrelated response sequences were required. In essence, chaotic responses were used to interfere with one another, and stochastic responses were used similarly. Results showed that performances were significantly degraded during the four-segment chaotic phases. Chaotic responses interfered with one another. A different result was obtained from the stochastic portion of the experiment. For one subject, seven of eight statistics were closer to a random model during the interference phase than at the end of the original training with a single sequence; for the second subject, all eight statistics were closer. These results are consistent with the hypothesis that a memory-based process controls chaotic variability and that a stochastic process, not dependent on memory, controls stochastic variability. (For additional evidence, see G. Jensen et al., 2006; Page & Neuringer, 1985.) The importance of this experiment is that it demonstrated the two modes of variability generation, one memory based, the other stochastic, under a procedure that controlled for extraneous variables.

## APPLICATIONS

We have described experiments on the reinforcement of predictable and unpredictable responding

and the underlying processes. Results from these laboratory experiments may help to explain unpredictable operant behaviors in many nonlaboratory cases in which variability contingencies occur naturally. In this section, we continue to describe laboratory-based studies but ones with direct relevance to real-world conditions.

## Training New Responses

Skinner (1981) hypothesized a parallel between evolutionary processes and selection by reinforcers of operant responses from a substrate of varying behaviors (see also Baum, 1994; Hull, Langman, & Glenn, 2001; Staddon & Simmelhag, 1971). As described in the Reinforcement of Variability section earlier in this chapter, the reinforcers whose delivery is directly contingent on that variability, something not anticipated by Skinner. One question that has potential importance for applications is whether reinforced variability facilitates acquisition of new responses, especially difficult-to-learn ones.

Neuringer, Deiss, and Olson (2000) reinforced variable five-response sequences across L and R levers while concurrently reinforcing a target sequence that rats find difficult to learn, namely RLLRL. Reinforcement for varying was limited to once per minute, whereas the target sequence RLLRL was reinforced whenever it occurred. Thus, if the rats learned to emit the target, reinforcement was much more frequent than if they only varied. The question was whether concurrent reinforcement of variations would facilitate acquisition of the target sequence, and the answer was obtained through a comparison with two other groups of rats. In one group, the same RLLRL target sequence was reinforced whenever it occurred, but varying was never reinforced. These target-only animals stopped responding altogether—responses extinguished because reinforcer frequencies were low or zero—and they did not learn the target (shown by the control [CON] data in Figure 22:8, top panel). In a second control group, the RLLRL target was also reinforced whenever it occurred. In addition, five-response sequences were reinforced at a rate yoked to that obtained by the experimental animals; note that these reinforcers could follow any sequence and

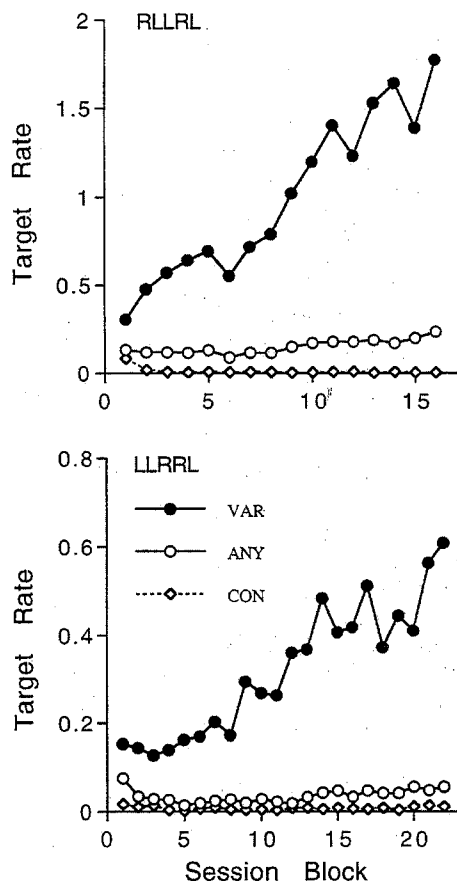


FIGURE 22.8. Rates of emission of a difficult-to-learn target sequence (RLLRL on top and LLRRL on bottom) for three groups of rats as a function of blocks of sessions (each session block shows the average of five sessions). In all groups, the target sequence was reinforced whenever it occurred. For one group, reinforcement was additionally arranged for varying sequences (VAR); for a second group, the additional reinforcers occurred at the same rate as in VAR but independent of variability (ANY); a third group did not receive additional reinforcement for any sequence other than the target sequences (CON). Adapted from "Reinforced Variability and Operant Learning," by A. Neuringer, C. Deiss, and G. Olson, 2000, *Journal of Experimental Psychology: Animal Behavior Processes*, 26, p. 107. Copyright 2000 by the American Psychological Association.

did not depend on variations. These animals continued to respond throughout (the yoke reinforcers maintained high response strength) but as shown by the independent-of-variability (ANY) data in the top

panel of Figure 22.8, these rats too did not learn the target. Only the experimental animals who concurrently received reinforcers for variable responding (VAR) learned to emit the RLLRL sequence at high rates. Thus, it appeared that concurrent reinforcement of variations facilitated acquisition of a difficult-to-learn sequence, a potentially important finding. The experiment was replicated with a second difficult sequence with the same results (bottom panel of Figure 22.8) and in a separate study with rats as well (Neuringer, 1993).

However, attempts in two laboratories to replicate these effects with human participants failed (Bizo & Doolan, 2008; Maes & van der Goot, 2006). In both cases, the target-only group (with no additional reinforcers presented) learned most rapidly. Several possible explanations have been suggested, including differences in relative frequencies of reinforcements for target responses versus variations, differences in levels of motivation in the animal versus human studies, and the "figure out what's going on" type of instructions provided to the human participants, but why or when concurrent reinforcement of variations facilitates versus interferes with learning of new responses is not yet clear (see Neuringer, 2009).

### Problem Solving

Arnesen (2000; see also Neuringer, 2004) studied whether a history of explicit reinforcement of variations would facilitate later problem solving. Using a rat model, she provided food pellets to rats in an experimental group for varying their responses to arbitrarily selected objects. For example, a soup can was placed in the chamber, and responding to it in a variety of ways was reinforced. Each session provided a different object, with response variability being reinforced throughout. Members of a yoked control group experienced the same objects but received food pellets independent of their interactions. A second control group was simply handled for a period each day. After training, each rat was placed alone in a problem space, a room approximately 6 feet by 8 feet, on the floor of which were 30 objects—for example, a toy truck, metal plumbing pipes, a hair brush, a doll's chest of drawers—arbitrarily chosen but different from those used

during the training phase. Hidden in each object was a small piece of food, and the hungry rats were permitted to explore freely for 20 minutes. The question was how many food pellets would be discovered and consumed. The experimental animals found significantly more pellets than either of the control groups, which did not differ from one another. Furthermore, the experimental rats explored more—they seemed bolder—and interacted more with the objects than did the control rats, many of whom showed signs of fear. Thus, prior reinforcement of response variations transferred to a novel environment and facilitated exploration of novel objects and discovery of reinforcers. The advantages incurred by variations are discussed in the human literature (e.g., brainstorming), but tests of direct reinforcement-of-variability procedures for problem solving more generally have been few.

### Creativity

Although creative production requires more than variation, Donald Campbell (1960) argued that variations, and indeed random variations, are necessary. If so, then operant variability may make important contributions to creativity. Support comes from studies in which creativity was directly reinforced (e.g., Eisenberger & Armeli, 1997; Holman et al., 1977; Pryor et al., 1969; see also Stokes, 2001). Other studies, however, have indicated that reinforcement interferes with, or degrades, creative output (e.g., Amabile, 1983). This literature is deeply controversial and has been reviewed in several articles (e.g., Cameron & Pierce, 1994; Deci, Koestner, & Ryan, 1999; Lepper & Henderlong, 2000), but the research listed earlier may contribute to a resolution. As shown by Cherot et al. (1996) and others (Wagner & Neuringer, 2006), reinforcement of variations has two effects: As a reinforcer is approached, variability declines. Thus, situations that potentiate the anticipation of consequences on the basis of completion may interfere with creative activities. The contingencies may at the same time, however, maintain high overall levels of creativity. Consideration of both induced effects (anticipation of reinforcement) and contingency effects (reinforced variability and creativity) may help explain reinforcement's contribution to creativity (see Neuringer, 2003).

### Psychopathology

Behavioral and psychological disabilities are sometimes associated with reduced control of variability. In autism and depression, for example, behaviors tend to be repetitive or stereotyped even when variations are desirable. In attention-deficit/hyperactivity disorder (ADHD), the opposite is true, with abnormally high variability observed when focused and repetitive responses are adaptive. All three of these disorders share a common characteristic, however: an apparent inability to move from one end or the other of the variability continuum. One question is whether reinforcement contingencies can modify abnormal levels of variability. The answer to this question may differ with respect to depression and autism, on the one hand, and ADHD, on the other.

**Depression.** Hopkinson and Neuringer (2003) asked whether the low behavioral variability associated with depression (Channon & Baker, 1996; Horne, Evans, & Orne, 1982; Lapp, Marinier, & Pihl, 1982) could be increased by direct reinforcement. College students were separated into mildly depressed and not depressed on the basis of Center for Epidemiological Studies Depression Scale scores (Radloff, 1991). Each participant played a computer game in which sequences of responses were first reinforced independently of variability or probabilistically (PROB), as in the yoke procedures we have described, after which variable sequences were directly reinforced (VAR). Figure 22.9 shows that under PROB, the depressed students' variability ( $U$  values) was significantly lower than that of the nondepressed students. When variability was explicitly reinforced, however, levels of variability increased in both groups and to the same high levels. This result, if general, is important because it indicates that variability can be explicitly reinforced in people manifesting mild depression (see also Beck, 1976).

**Autism.** In an experiment conducted by Miller and Neuringer (2000), five individuals diagnosed with autism and nine control subjects received reinforcers independent of variability in a baseline phase (PROB), followed by a phase in which sequence variations were directly reinforced. Subjects with autism behaved less variably than the control subjects in both phases; however, variability increased

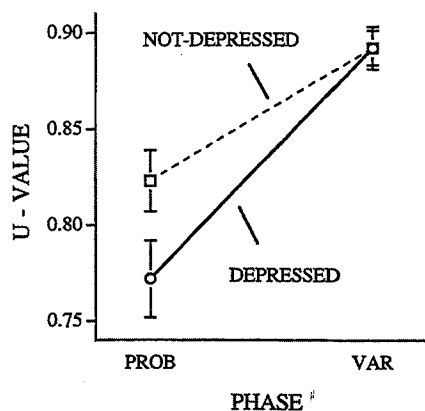


FIGURE 22.9. Levels of variability (indicated by  $U$  values) for depressed and nondepressed college students when reinforcers were provided independent of response variability (PROB phase) versus when variations were required (VAR phase). Standard errors are shown by the error bars. From "Modifying Behavioral Variability in Moderately Depressed Students," by J. Hopkinson and A. Neuringer, 2003, *Behavior Modification*, 27, p. 260. Copyright 2003 by Sage Publications, Inc. Adapted with permission.

significantly in both groups when it was reinforced. Thus, individuals with autism, although relatively repetitive in their responding, acquired high levels of operant varying. Ronald Lee and coworkers (Lee, McComas, & Jawor, 2002; Lee & Sturmey, 2006) extended this work. Under a lag schedule, individuals with autism received reinforcers for varying verbal responses to questions, and two of three participants in each of two experiments learned to respond appropriately and nonrepetitively. Thus, the experimental evidence, although not extensive, has indicated that the behavior of individuals with autism can benefit from reinforcers contingent on variability. Stated differently, the abnormally low levels of variability characteristic of individuals with autism may at least in part be under the influence of operant contingencies.

**Attention-deficit/hyperactivity disorder.** Things may differ for individuals diagnosed with ADHD. Here, the abnormal levels of variability are at the opposite end of the continuum, with high variability a defining characteristic (Castellanos et al., 2005;

Rubia, Smith, Brammer, & Taylor, 2007). A second common identifier is lack of inhibitory control (Nigg, 2001). Can such behavior be influenced by direct reinforcement? The evidence has indicated that unlike the case for autism, variability may result mainly from noncontingent (i.e., inducing) influences. One example is provided by the beneficial effects of drugs such as methylphenidate (Ritalin). Another is the fact that variability in individuals with ADHD is higher than in control subjects when reinforcement is infrequent, but not when it is frequent (Aase & Sagvolden, 2006). Methylphenidate reduces variability. Low reinforcement frequencies induce high variability, and the effects on those with ADHD may be independent of direct reinforcement-of-variability contingencies. Similarly, when reinforcement is delayed, the responses of subjects with ADHD weaken more than those of control subjects, possibly because of induced increases in variability (Wagner & Neuringer, 2006). Thus, variability may be induced in individuals diagnosed with ADHD by different attributes of reinforcement, but to date little evidence has indicated sensitivity to variability-reinforcing contingencies.

## OPERANT VARIABILITY AND THE EMITTED OPERANT

Reinforced variability may help to explain some unique attributes of operant behavior. Operants are often compared with Pavlovian reflexes, and the two can readily be distinguished at the level of the procedures used to establish them. In Pavlovian conditioning, a conditional relationship exists between a previously neutral stimulus, such as a bell, and an unconditioned stimulus, such as food. The result is that the neutral stimulus becomes a conditioned stimulus that elicits a conditioned response. One view is that operant responses differ in that they depend on a conditional relationship between response and reinforcer. Thus in one case, a conditional relationship exists between two stimuli (if conditioned stimulus, then unconditioned stimulus), whereas in the other, the relationship is between response and reinforcer.

However, according to Thorndike, Guthrie, and others, when a response is made in the presence of a



particular stimulus and the response is reinforced, then over trials, the stimulus takes on the power of an elicitor (Bower & Hilgard, 1981). This finding led some researchers to conclude that both operant and Pavlovian responses were elicited by prior stimuli. That is, in both cases stimulus–response relationships were critical to predicting and explaining the observed behaviors.

Skinner (1935/1959) offered a radically different view of the operant. Skinner's position is difficult to grasp, partly because at times he assumed the point of view of an environmental determinist, whereas at other times he proposed probabilistic (and possibly indeterministic) outcomes. According to Skinner, eliciting stimuli could not be identified for the operant. Although discriminative stimuli signaled the opportunity for reinforcement, no discrete environmental event could be identified to predict the exact time, topography, or occurrence of the response. Skinner described operants as *emitted* to distinguish them from elicited Pavlovian reflexes.

But how is one to understand emission? The term is ambiguous, derived from the Latin *emittere*, meaning “to send out.” To be sent out might imply being caused to leave, but there is a sense of emergence, rather than one-to-one causation, as in the emission of radioactive particles. More important, the term captures, for Skinner and others, the manifest variability of all operant behaviors. Skinner interpreted that variability as follows.

An individual operant response is a member of a class *C* of instances, a generic class, made up of functionally similar (although not necessarily physically similar) actions (Skinner, 1935/1959). An example may help to explain this point. Jackie, a young child, desires a toy from a shelf that is too high for her to reach. Jackie might ask her mom to get the toy, jump to try to reach it, push a chair next to the shelf to climb up to the toy, take a broom from the closet and try to pull the toy from the shelf, or cry. Each of these acts, although differing in physical details, is a member of the same operant class because each potentially serves the same functional relationship between the discriminative stimulus (out-of-reach toy) and the goal (toy in hand). Some responses may be more functional than other members of the class, and cues may indicate which

of these responses is most likely to be reinforced. For example, if Jackie's mother is nearby, the “Mom-mie, get my toy” response might be most likely. Alternatively, if the toy is just beyond reach, the child might be most likely to jump to get it. In many cases, however, the behavior appears to be selected with equal probabilities, and prediction of the instance becomes difficult.

As just suggested, members of a particular class of behaviors may be divided into subclasses, and even here variability may characterize aspects of the response. For example, if “ask for the toy” is the activated subclass, the exact moment of a verbal request, the particular words used, or the rhythm or loudness may all be difficult to predict. Similarly, when a rat is pressing a lever to gain food pellets, the characteristics of the press (one paw vs. both, with short or long latency, with high or low force, etc.) are sometimes predictable, but often are not. Thus, according to a Skinnerian model, functionally equivalent instances emerge unpredictably from within a class or subclass, as though generated by a stochastic process (Skinner, 1938; see also Moxley, 1997). To state this differently, there is variance within the operant, manifested as the emission of instances from a set made up of functionally related but often physically dissimilar behaviors.

Behavioral variability occurs for many reasons, as we have discussed. It decreases with training and experience. It is low when reinforcers are frequent and higher under intermittent schedules of reinforcement. It decreases with expectancy of and proximity to reinforcement. However, consequence-controlled variability may play a special role in explaining the emitted nature of the operant. To see why, we next turn to experiments on volition. The operant is often referred to as the *voluntary operant*, in contrast to the Pavlovian reflex. The question is what about the operant indicates (and helps to explain) volition.

## OPERANT VARIABILITY AND VOLUNTARY BEHAVIOR

Attempts to explain volition have been ongoing for more than 2,000 years, and heated debates continue to this day in philosophy (Kane, 2002), psychology

(Maasen, Prinz, & Roth, 2003; Sebanz & Prinz, 2006; Wegner, 2002), and physiology (Glimcher, 2005; Libet, Freeman, & Sutherland, 1999). These debates often concern the reality of volitional behavior or lack thereof and, if real, how to characterize it. Research on operant variability has suggested that the descriptive term *voluntary* can be usefully applied; that is, voluntary behaviors can be distinguished from accidental reactions, such as stumbles; from elicited responses, such as reflexes, both unconditioned and Pavlovian; from induced ones, such as those caused by drinking alcohol or anticipating a reinforcer; and many other cases. The research has also indicated important ways in which voluntary actions differ from these others.

In large part, the difficulty surrounding attempts to explain voluntary behavior comes from an apparent incompatibility between two often-noted characteristics. On the one hand, voluntary acts are said to be intentional, purposeful, goal directed, rational, or adaptive. These characteristics indicate the functionality of voluntary behaviors, and we use that term as a summarizing descriptor. On the other hand, voluntary actions are described as internally motivated and autonomously controlled. Unpredictability, demonstrated or potential, is offered as empirical evidence for such hypothesized autonomous control. Thus, unpredictability is thought to separate voluntary acts from other functional behaviors (e.g., reflexes) and to separate their explanation from Newtonian causes and effects. Proposed explanations of the unpredictability run the gamut from a soul or a mind that can function apart from physical causes to quantum-mechanical random events, but they are all ultimately motivated by the presumed inability of a knowledgeable (perhaps even supremely knowledgeable) observer to anticipate the particulars of a voluntary act.

How can unpredictability (perhaps even unpredictability in principle) be combined with functionality? That is the critical question facing those of us who would argue that *voluntary* is a useful classification. The problem derives from the (erroneous) assumption that functionality necessarily implies potential predictability. That assumption goes something like this: If an observer knows what an individual is striving for, or attempting to accomplish,

then together with knowledge of the individual's past experiences and current circumstances, at least somewhat accurate predictions can be made about the individual's future goal-directed actions. Thus, because functionality is thought to require an orderly relationship to environmental variables, predictions must be (at least theoretically) possible. Again, though, voluntary acts are often characterized by their unpredictability, with this serving as a sign of autonomous control.

An added complication is that unpredictability alone does not characterize voluntary actions. Researchers do not attribute volition to random events, such as the throw of dice or emission of atomic particles (Dennett, 2003; Popper & Eccles, 1977), and truly random responding would often be maladaptive. Yet another problem is that voluntary behaviors are not always unpredictable—they are quite predictable some of the time and, indeed, exist across the range of predictability. For example, when the traffic light turns red, a driver is likely to step on the brake. When you are asked for your name, you generally answer veridically, and so on. But even in cases of predictable behaviors, if voluntary, these responses can be—and sometimes are—emitted in more or less unpredictable fashion. The red light can cause speeding up, slowing down, or cursing. The name offered might be made up so as to fool the questioner, for example, during a game. In brief, voluntary responses have the potential to move along a variability continuum from highly predictable to unpredictable. A characteristic of all voluntary behaviors is real or potential variations in levels of variability.

Operant variability helps to explain volition by combining functionality with variations in levels of variability. Operant responses are goal directed and functional, and the same holds for voluntary behaviors. (In some cases, researchers say that the voluntary response—and the operant—is intended to be functional because it is governed by previous experiences and because in a variable or uncertain environment, what was once functional may no longer be so.) Operant responses are more or less variable, depending on discriminative stimuli and reinforcement contingencies, and the same is true for voluntary behaviors. Thus, for both operant and voluntary

behaviors, the ability of a knowledgeable observer to predict future occurrences will depend on the circumstances. Voluntary behavior is behavior that is functional (or intended to be so) and sometimes highly predictable, other times unpredictable, with predictability governed by the same functionality requirement as other attributes of operant behavior. We have just summarized a theory of volition referred to as the *operant variability and voluntary action* (OVVA) theory (Neuringer & Jensen, 2010). In the following sections, we provide experimental evidence consistent with OVVA theory. We begin with a discussion of choices under conditions of uncertainty, partly because choices are generally thought to be voluntary and partly because concurrent schedules of reinforcement, a method used to study choice, provided the means to test OVVA theory.

### Choice Under Uncertainty

In some choice situations, one (and only one) of many options provides reinforcement (e.g., the third key from the left in a row of eight keys), and both people and other animals learn to choose correctly and to do so repeatedly. In other cases, a particular pattern of choices is required (e.g., LLRR in a two-lever chamber), and that pattern is learned and repeated. Individual choices in these situations are readily predicted. In many situations, though, fixed choices and patterns are not reinforced, and reinforcer availability is uncertain, both in time and place. As we discuss, these conditions often result in stochastic responding.

Choices under conditions of reinforcement uncertainty have commonly been studied in behavioral laboratories with concurrent schedules of reinforcement. Reinforcers are independently programmed for two (or sometimes more) options, and subjects choose freely among them. Consider the example of concurrent VI schedules. In a VI 1 minute–VI 3 minute procedure, each schedule is applied to one of two response alternatives, left and right. Under this procedure, a reinforcer becomes available (or “sets up”) on average once per minute for responses on the left and independently on average every 3 minutes for choices of the option on the right. Once a reinforcer has set up, it is delivered on the next response to that alternative. Because time to

reinforcement is unpredictable, and the two alternatives are independent of one another, every response has the possibility of producing a reinforcer. However, in general, the left alternative is three times more likely to have reinforcement waiting than the right alternative.

The VI values (or average times between reinforcer setups) generally differ across phases of an experiment. For example, a 1:3 ratio of setup time left to right in one phase might be followed by a 3:1 ratio in another, and a third might use a 2:2 ratio. When the ratios across these alternatives are systematically manipulated, an often observed finding is that the overall ratios of left-to-right choices are functionally related to ratios of left-to-right obtained reinforcers, a relationship commonly described as a power function and referred to as the *generalized matching law* (Baum, 1974):

$$\frac{C_X}{C_Y} = \left( \frac{k_X}{k_Y} \right) \cdot \left( \frac{R_X}{R_Y} \right)^s \quad (3)$$

In Equation 3,  $C_X$  refers to observed choices of alternative  $X$ , and  $R_X$  corresponds to delivered reinforcers ( $C_Y$  and  $R_Y$  correspond to alternative  $Y$ , accordingly). The parameter  $k_X$  refers to bias for  $X$ , with biases—because of side preferences, differences in the operanda, or any number of variables—not thought to be influenced by the reinforcer ratios. The  $s$  parameter refers to the sensitivity of choice ratios to reinforcement ratios. When  $s = 1.0$ , choice ratios exactly match (or equal) reinforcement ratios. With  $s$  parameter values less than 1.0, choice ratios are not as extreme as the ratio of reinforcers, with the opposite for  $s$  more than 1.0 (see the Psychophysical Test section later in this chapter). To the extent that the generalized matching law provides an accurate description (and there is much support for it), it permits predictions of the molar distribution of choice allocation; that is, overall ratios of choices can accurately be described as a function of obtained reinforcer ratios (Davison & McCarthy, 1988).

Another observation from studies of concurrent VI schedules, however, is that individual choices are difficult to predict. Even when they conform to Equation 3, they often appear to be emitted stochastically (Glimcher, 2003, 2005; G. Jensen & Neuringer,

2008; Nevin, 1969; see also Silberberg, Hamilton, Ziriax, & Casey, 1978, for an alternative view). In the VI 1 minute–VI 3 minute example given earlier, an observer might accurately predict that the left option will be chosen three times more frequently than the right but be unable to accurately predict any given choice. A recent example of such stochasticity was observed when pigeons' choices were allocated across three concurrently available sources of reinforcement (G. Jensen & Neuringer, 2008). Figure 22.10 shows that run lengths—defined as the average number of choices on one key before switching to a different key—approximated those expected from a stochastic process.<sup>5</sup> Thus, at the same time that overall choice proportions can readily be predicted, individual choices cannot. This combination of functionally related choice proportions and stochastic emission provided the means to assess the relationship between operant variability and volition. In particular, we asked whether

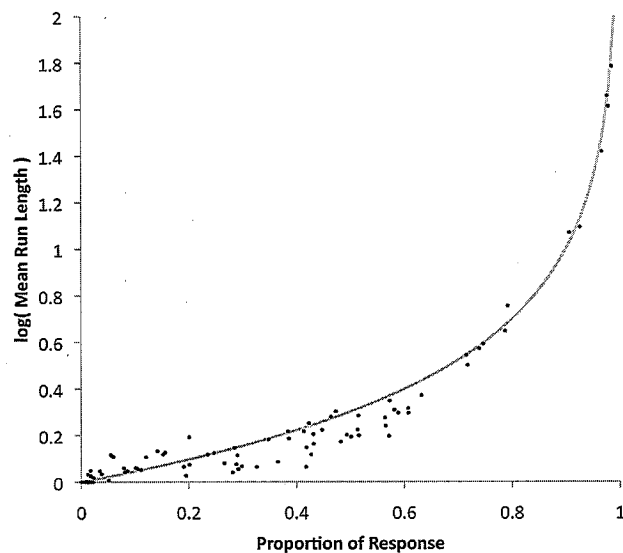


FIGURE 22.10. Mean run lengths by pigeons on each of three response keys as a function of the proportion of responses to that key. The drawn line is the expected function if responses were emitted stochastically. Adapted from “Choice as a Function of Reinforcer ‘Hold’: From Probability Learning to Concurrent Reinforcement,” by G. Jensen and A. Neuringer, 2008, *Journal of Experimental Psychology: Animal Behavior Processes*, 34, p. 44. Copyright 2008 by the American Psychological Association.

functionally varying behaviors yielded a perception of voluntary action.

### Psychophysical Test

OVVA theory predicts that responses will appear to be voluntary when levels of (un)predictability vary functionally (purposefully, adaptively). Choices under concurrent schedules of reinforcement provided a way to test this claim. Neuringer, Jensen, and Piff (2007) had human participants observe six different virtual actors (hereinafter called *agents*) as each agent made thousands of choices. The agents differed in how they went about choosing among the available options (the strategies are described in a subsequent paragraph). Each agent's choices were shown separately on an individual computer, with six computers located close to one another on small desks in a laboratory. The participants were free to walk among the computers to compare the agents' choice strategies.

To minimize extraneous cues, such as whether the agent resembled a human figure, choices were represented in a simple manner, namely as dots moving around the screens. Participants were instructed that the agents were choosing among three alternative gambles, similar to slot machine gambles, with each gamble's choice represented by the dot's movement in one of three directions. Whenever a choice led to reinforcement—the agent won that gamble—the dot's color changed as a sign of success. Thus, participants could observe how choices were made in relationship to the reinforcers received. Participants were asked to judge how well the choices made by the agents represented voluntary choices made by a real human player.

Unknown to the participants, the agents' choices were controlled by iterating the generalized matching power function (Equation 3) that was extended to a three-alternative situation (G. Jensen & Neuringer, 2008). Thus, the agents chose probabilistically among the three options on the basis of the proportions of reinforcers that they had received from the three alternatives. These calculations were done in real time, with current choice probabilities depending on previously obtained reinforcers.

<sup>5</sup>See Jensen and Neuringer (2008) for discussion of these findings, including the small divergence of data from the theoretical curve.

Choices by the six agents differed only with respect to the  $s$  exponent of the power functions governing the choices: Some agents had high values for their sensitivity parameters, and others had low values. Participants were told only that the dot movements represented choices of gambles and that their objective was to rate how closely those movements resembled the voluntary choices of real human players. Next, we describe how reinforcer availability was programmed and the effects of  $s$  values on the generated choices.

Reinforcers set up probabilistically (and remained available until collected, as in concurrent VI schedules) for each of the three gambles. There were six different combinations of set-up rates, which participants were told constituted six different games. Thus, in some games, the agent's X choices were most frequently reinforced; in other games, Y choices were most frequently reinforced; in others, the reinforcers were more equally distributed; and so on. Participants were free to observe each agent playing each of the six games for as long as needed to make their evaluation. After observing the choices in all games, the participants judged the degree to which each agent's responses appeared to be those of a human player who was voluntarily choosing among the options. The key question was whether the agents' different choice strategies—caused by differences in the  $s$  exponents—generated systematic differences in participants' judgments of volition.

The  $s$  values, and their effects on the agents' choice allocations, were as follows: For one agent,  $s$  equaled 1.0, and choice proportions therefore strictly matched proportions of received reinforcers. Assume, for example, that this agent had gained a total of 100 reinforcers at some point in the game: 50 reinforcers for option X, 30 for Option Y, and 20 for Option Z. The probability of the agent's next X choice would therefore equal 0.5 (50/100); a Y choice, 0.3 (30/100); and a Z choice, 0.2 (20/100). The  $s = 1.0$  actor therefore distributed its choices probabilistically in exact proportion to its received reinforcers.

Another agent was assigned an  $s$  value of 0.4, the consequence of which was that it tended to choose

among the three options with more equal probabilities than indicated by the reinforcement ratios throughout the six games. In the preceding example, this agent would choose X with probability of .399 (rather than .5 for the exact matcher), choose Y with probability of .325 (rather than .3), and choose Z with probability of .276 (rather than .2). In general, algorithms with  $s$  values less than 1.0 are referred to as *undermatchers*: They distribute choices more equally—and therefore more unpredictably—across the available options than the exact matcher. The opposite was the case for agents with  $s$  values more than 1.0, whose preferences were more extreme than indicated by the reinforcer ratios and were referred to as *overmatchers*. Over the course of several experiments, a wide range of  $s$  values was presented, spanning a range from 0.0 (extreme undermatcher) to 6.0 (extreme overmatcher) in one experiment, a range from 0.1 to 2.0 in another, and a range from 0.1 to 1.9 in a third.

Results were consistent and clear: The strict matcher ( $s = 1.0$ ) was judged to best represent volitional choices. Figure 22.11 shows data from two of the experiments. In one experiment, participants were informed in advance that all of the agents' choices were generated by computer algorithms, and they were asked to rate the algorithms in terms of volitional appearance. In the second, participants were told that some agents' choices were based on computer algorithms, that others depicted voluntary choices of real humans, and that their task was to identify the humans.<sup>6</sup>

As  $s$  values approached 1.0, the agents were rated as providing increasingly good representations of voluntary human choice, suggesting a continuum of more or less apparent volition. From the perspective of the participants, the  $s = 1.0$  strict matcher sometimes responded unpredictably (when reinforcers were equally allocated across the three alternatives), at other times highly predictably (when most reinforcers were obtained from one alternative), and at yet other times at intermediate levels. In each case, however, the agent's choices seemed to be governed by the reinforcement distribution in a particular game environment, an indicator of functional

<sup>6</sup>This task was inspired by the Turing test, considered by many to be the gold standard of artificial intelligence.

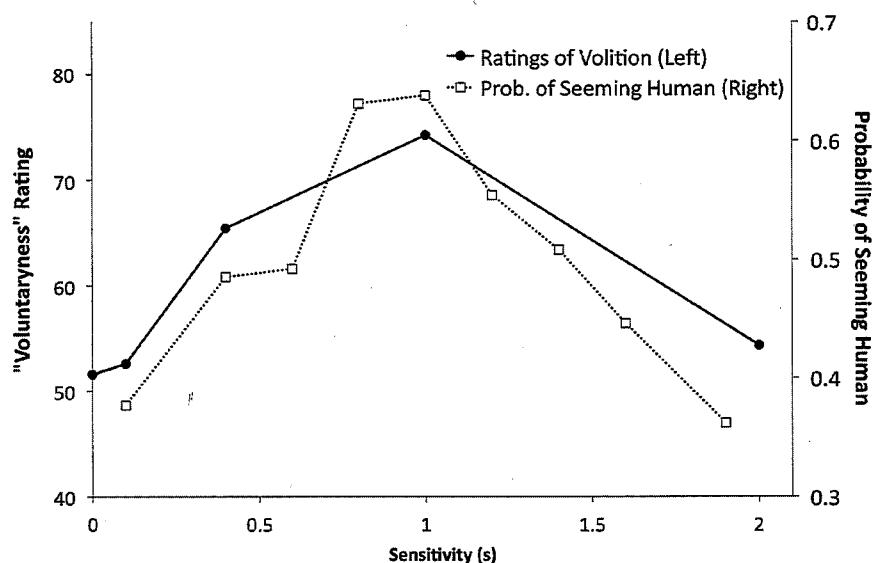


FIGURE 22.11. Judgments of how closely agents' responses approximated voluntary human choices (on left y-axis) and probabilities (prob.) of identifying agents as a voluntarily choosing human player (on right y-axis) as functions of the agents'  $s$ -value exponents. From "Stochastic Matching and the Voluntary Nature of Choice," by A. Neuringer, G. Jensen, and P. Piff, 2007, *Journal of the Experimental Analysis of Behavior*, 88, pp. 7, 13. Copyright 2007 by Society for the Experimental Analysis of Behavior, Inc. Adapted with permission.

changes in behavior. The undermatchers tended to respond less predictably throughout, as we indicated earlier, and the overmatchers more predictably. Thus, the undermatchers demonstrated that unpredictability alone was not sufficient for apparent volition: It was necessary that agents display functional variations in levels of (un)predictability to receive the highest volitional ratings.

A series of control experiments evaluated alternative explanations. For example, rates of reinforcement were overall slightly higher (across games) for the  $s = 1.0$  matcher than for any of the other agents, and one control showed that differences in reinforcement rate were not responsible for the volitional judgments. In the experiment, agents who cheated (i.e., those who appeared to know where to respond for reinforcers) were compared with the strict—probabilistically choosing—matcher, and the matcher was evaluated as substantially more volitional in appearance, despite obtaining fewer reinforcers than the cheaters. An observer might appreciate the individual who gains more reinforcement than another, but that fact alone will not convince the observer that the individual is choosing in a voluntary manner.

Another control experiment tested whether matching alone implied volition (Neuringer et al., 2007). The question was whether the more or less (un)predictable responding contributed at all to the judgments. Stated differently, did matching or predictability or both generate the volitional judgments? Participants were therefore asked to compare two agents, both of which exactly matched choice proportions to reinforcer proportions; however, one agent matched by stochastically allocating its choices (as was done in all of the experiments described to this point), whereas the other agent allocated its choices in an easily predictable fashion. For example, if the stochastic matcher had received reinforcers in a ratio of 5:3:2, it responded to the left alternative with a .5 probability, to the center with a .3 probability, and to the right with a .2 probability. Because they were emitted stochastically, individual choices could not be predicted above chance levels. By contrast, the patterned matcher also matched exactly but did so in a patterned and therefore readily predictable way. In the example just given, it would respond LLLLLCCRR, again and again cycling through the same 5:3:2 strings of responding until there was a change in obtained reinforcer

proportions, at which point it would adjust the length of its strings accordingly. Because both agents matched, both received identical rates of reinforcement. The participants judged the stochastic matcher to significantly better represent a voluntary human player than the patterned one, showing that both functionality (matching, in this case) and stochasticity were jointly necessary for the highest ratings of volition.

The combination of choice distributions (matching) and choice variability (more or less predictability) provided evidence for voluntary behavior. Choice distributions alone did not lead responses to be evaluated as highly voluntary, nor did choice unpredictability alone. Choices were most voluntary in appearance when probabilities and distributions of stochastic responses changed with distributions of reinforcers. According to OVVA theory, functionally changing variable behaviors are voluntary behaviors. Stated differently, voluntary behaviors are members of a class characterized by ability to vary levels of response (un)predictability in a functional manner. The psychophysical evidence just reviewed is consistent with OVVA theory.

To review, the facts of operant variability show that levels, or degrees, of behavioral (un)predictability are guided by environmental consequences. A theory of volition, OVVA, proposes that exactly the same is true for voluntary actions. Voluntary behaviors are sometimes readily predictable, sometimes less predictable, and sometimes quite unpredictable. In all cases, the reasons for the predictability can be identified (given sufficient knowledge), but the precise behaviors may still remain unpredictable. For example, under some circumstances, the response to "How are you?" can readily be predicted for a given acquaintance. Even when the situation warrants unpredictable responses, as when responders wish to conceal their feelings, some veridical predictions can be made: that the response will be verbal, that it will contain particular parts of speech, and so on. The functionality of variability implies a degree of predictability in the resulting behaviors that is related to the activated class of possibilities from which the response emerges. The class can often be predicted on the basis of knowledge of the organism and environmental conditions. However, the

instance may be difficult or impossible to predict, especially for large response classes.

Unpredictability, real or potential, is emphasized in many discussions of volition. Indeed, the size of the active set can be exceedingly large—and functionally so—because if someone was attempting to prove that he or she is a free agent, the set of possibilities might consist of all responses in that person's repertoire (see Scriven, 1965). We return to the fact, though, that voluntary behaviors can be predictable as well as not predictable. The most important characteristic is functionality of variability, or ability to change levels of predictability in response to environmental demands. This is equally an identifying characteristic of operant behavior in which responses are functional and stochastically emitted. Thus, with Skinner, we combine *voluntary* and *operant* in a single phrase, but research has now shown why that is appropriate. Operant responses are voluntary because they combine functionality with (un)predictability.

## CONCLUSION

Aristotle anticipated what many have referred to as the most influential law in psychology (Murray, 1988). When two events co-occur, presentation of one will cause recollection or generation of the other. Although he and many others were wrong in the details, laws of association have been the foundation of theories of mind and behavior throughout the history of Western thought, and the science of psychology and behavior has been well served by the search for them. From the British Associationists, to Pavlov, to Hebb and Rescorla, theoreticians and researchers have documented laws of the form "if A, then B" that help to explain thoughts and behaviors. Evolutionary theory offered a distinctly different type of behavioral law, involving selection from variations, laws that were developed by Skinner (1981) and others (Hull et al., 2001). In this chapter, we provided evidence of how selection interacts with variation: Parameters of variation are selected (via reinforcement of variability), and selections emerge from variations (via stochastic emission). This interaction, of equal importance to that of association, must be deciphered if researchers are to explain, at long last, voluntary behavior.

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