CHAPTER 18

REMEMBERING AND FORGETTING

K. Geoffrey White

Remembering and forgetting raise the question of how an event at one time influences behavior that occurs at another. In physics, action at a distance used to be a puzzle because it was thought that objects could influence each other only through direct contact. In psychology, the question of action at a temporal distance remains a puzzle. How do people remember and why do people forget? Research on human memory is wide ranging, and naturalistic and laboratory studies of remembering in nonhuman animals are covered by the field called *comparative cognition* (Roberts, 1998). Sometimes the different abilities reveal fascinating species-specific characteristics (Wasserman, 1993), and sometimes the species similarities owe to procedural limits (White, Juhasz, & Wilson, 1973). This chapter is more constrained in scope. In it, I examine the experimental analysis of nonhuman remembering and forgetting in laboratory procedures in which the retention intervals are typically short and in which parametric variation is a main focus. Can an experimental analysis contribute a solution to the puzzle of action at a temporal distance?

In any experiment in which remembering or forgetting is studied, the most important parameter is the temporal distance between original learning and the point of remembering, because the time delay, or retention interval, defines the behavior as remembering or its converse, forgetting. The process used to bridge the temporal gap is loosely referred to as memory, but as I discuss later, this question is a theoretical one that has many different interpretations.

Remembering in both humans and nonhuman animals has been studied for more than 100 years. At about the time that Thorndike (1898) first demonstrated remembering in cats, Ebbinghaus (1885/1964) reported the results of the first systematic experimental study of human remembering. Ebbinghaus recognized the difficulty caused by people's prior learning experiences for a study of remembering. Accordingly, he used nonsense syllables, an innovation that has influenced the study of human memory to the present day. He also varied the duration of the retention interval from minutes to many days. Since then, an enormous number of studies have been devoted to the empirical and theoretical study of remembering in humans. An accessible account was provided by Baddeley (1997) in his book *Human Memory: Theory and Practice*. Several specialist journals cover the area, and many reviews in the *Annual Review of Psychology* have addressed important issues (e.g., Jonides et al., 2008; Nairne, 2002; Roediger, 2008; Wixted, 2004b). The research has identified many variables and conditions that influence remembering, such as the familiarity and repetition of material to be remembered, whether learning is spaced, and whether interfering events occur between learning and recollection. The effects of some variables, however, are relative to the effects of others, making it difficult to establish lawful regularities (Roediger, 2008). None of this extensive research with human subjects is explicitly reviewed here, although it tends to have influenced the direction of research with nonhuman animals.

I thank Glenn Brown for his guidance and advice.

DOI: 10.1037/13937-018
APA Handbook of Behavior Analysis: Vol. 1. Methods and Principles, G. J. Madden (Editor-in-Chief)

OVERVIEW

I begin the chapter with a preliminary description of the main focus of an experimental analysis of remembering. I follow this description with an account of the procedure most often used to study short-term remembering in nonhuman animals (delayed matching to sample) and the advantages of quantifying the forgetting function, the hallmark of a memory study. In the next section, I summarize the empirical research on the effects of variables that influence the forgetting function. These variables are related to the to-be-remembered events: the sample stimuli in delayed matching to sample; the retention interval; the choice response, including its reinforcing consequences; and the intertrial interval. In a subsequent section, I describe the three main behavioral theories of remembering, all of which rely on the effects of reinforcers for remembering and their role in forgetting. In the final section, I consider a behavioral perspective on memory, in which remembering is treated as a discrimination specific to the retention interval at which remembering occurs. My main purpose in this chapter is to document the effects of variables that must be accounted for by successful theories, to demonstrate the empirical and theoretical importance of the consequences for remembering, and to suggest that remembering can be understood in the same terms as discrimination.

EXPERIMENTAL ANALYSIS OF REMEMBERING

From a behavioral perspective, an experimental analysis of remembering has mainly been advanced using nonhuman animals for two reasons. The first is the relative ease of specifying the environmental variables that influence the individual's behavior, especially when variables are manipulated across different values for each individual in the study. The second is that a fundamental element determining the individual's behavior in any task requiring learning and remembering is the reinforcement contingency. Very few studies with humans can easily control the rewards, or reinforcers, for appropriate completion of the task. When studying remembering in nonhuman animals, the task requirements are made explicit through reinforcement contingencies, and a response language is thus developed (Goldiamond, 1966). For these reasons, nearly all of the studies I review in this chapter examine remembering in nonhuman animals.

An experimental analysis of remembering emphasizes observable behavior and the description of variables of which the behavior is a function. Much of this chapter concerns such variables, but as I noted earlier, the most important variable is the retention interval—the temporal gap between original learning and later remembering. Without a time delay, researchers would be studying perceiving and would see no need to refer to memory. An additional consideration for an experimental analysis of behavior is that the effects of the experimental variables are demonstrated in each individual (Sidman, 1960). The effects of a variable are shown by altering it across several values. Most of the studies reviewed in this chapter follow these principles.

From a behavioral perspective, remembering can be placed in the broader context of discrimination and generalization. Remembering typically requires a discrimination between concurrently available response alternatives. A choice is followed by reinforcement depending on the event or stimulus to be remembered. In recognition procedures, one or more of the stimuli to be remembered is presented again at the time of choice. In recall procedures, the to-be-remembered stimulus is not presented again but is associated with a choice alternative. The discrimination thus involves both the stimulus or event to be remembered and the stimuli associated with the choice alternatives. It is a conditional discrimination because the reinforced choice response is conditional on the to-be-remembered stimulus. Because the to-be-remembered stimulus exerts its influence on the subsequent choice after some delay, accurate remembering shows delayed stimulus control (Catania, 1992), which implies that the discrimination occurs at the time of remembering, not at the time at which the to-be-remembered event was presented (Berryman, Cumming, & Nevin, 1963; White, 2001).

DELAYED MATCHING TASK

Fifty years ago, two innovative procedures were reported for studying remembering over short delays (generally 20 seconds or less). One, by Peterson and Peterson (1959), was designed to study human memory. The other, by Blough (1959), was designed to study remembering in nonhumans. Although I do not consider research on human memory in this chapter, the two tasks are similar. Peterson and Peterson asked human participants to repeat three consonants after a delay lasting several seconds. During the delay, the participant counted down in threes from a number provided by the experimenter. The result was very rapid forgetting of the consonants, interpreted by the Petersons as trace decay, a process specific to short-term memory. As it happens, the distinction between short-term and long-term forgetting that followed from the Petersons' experiment has little substance (Nairne, 2002; Suprenant & Neath, 2009). Instead, it is best understood simply in terms of the relative lengths of delays being studied (short vs. long), and the same principles can apply to remembering over both the short and the long term. The study by Peterson and Peterson has been very influential in stimulating a large body of research on human short-term memory (Jonides et al., 2008), and the theoretical ideas have been transferred to account for remembering over short delays by nonhuman animals (Kendrick, Rilling, & Denny, 1986; Roberts, 1998). Wixted (1989) observed that in the study of nonhuman short-term memory, "the ratio of theory to data often seems unacceptably high, and efforts to identify common empirical principles of memory are relatively rare" (p. 409). I aim to improve this ratio in this chapter.

The other innovative procedure, delayed matching-to-sample, was reported by Blough (1959) with pigeons as subjects. As with the task devised by Peterson and Peterson (1959), the delayed matching task was performed trial by trial, with delays lasting for several seconds. Each trial began with the presentation of a steady or flickering light on the central response key of a three-key experimental chamber. The two light patterns, the samples, alternated randomly across trials. Responses to the sample darkened the key and led to a delay interval of several seconds, varying from trial to trial. At the end of the delay, the two patterns were presented as comparison stimuli on the left and right response keys, with their position alternating randomly across trials. Correct choices of the comparison pattern that matched the sample at the beginning of the trial were followed by delivery of grain. A houselight illuminated the chamber throughout the experimental session. Figure 18.1 illustrates a general version of

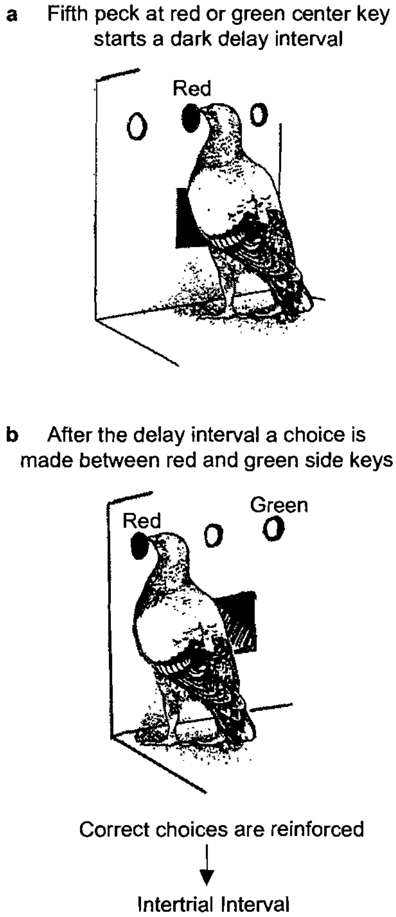

FIGURE 18.1. Illustration of the delayed matching-to-sample procedure involving three response keys that can display different stimuli (e.g., red and green keylights). From "Psychophysics of Remembering: The Discrimination Hypothesis," by K. G. White, 2002, *Current Directions in Psychological Science, 11,* p. 142. Copyright 2002 by the Association for Psychological Science. Adapted with permission.

the delayed matching-to-sample procedure (in which the delay and intertrial interval are usually dark). In Blough's study, the percentage of correct matching responses decreased with increasing duration of the delay, just as in the experiment with humans reported by Peterson and Peterson. Enhanced accuracy was interestingly correlated with whether different stereotyped behaviors, such as bobbing up and down, occurred during the delay.

Blough's (1959) observations of mediating behaviors suggested a behavioral answer to the question of how the temporal gap was bridged. Mediating behaviors, however, may not always be obvious. Berryman et al. (1963) charted the development of delayed matching to sample but were unable to identify mediating behaviors. Whereas Blough gradually increased the duration of the delays, Berryman et al. ensured that exposure to each of the different delays was equal throughout training. Berryman et al. suggested that the mediating behaviors in Blough's study were more likely to have developed as a result of gradually lengthening the delays. Apart from a few studies in which responding on a lit center key during the delay differed after two sample stimuli (e.g., Jones & White, 1994; Wasserman, Grosch, & Nevin, 1982) or behavioral observations during the delay were systematically recorded (Urcuioli & DeMarse, 1997), there is a dearth of studies of mediating behavior during the delay. Human short-term memory studies have shown renewed interest in the process of rehearsal and its prevention during the delay (Berman, Jonides, & Lewis, 2009). The study of mediating behaviors in the retention interval of nonhuman forgetting procedures, and their relation to accurate remembering under a variety of conditions already shown to influence accuracy, could be a productive avenue for future research.

Most studies of delayed matching to sample begin by training the animal to respond to the choice stimuli as a first step, with alternating responses producing reinforcers. The next step is to introduce the sample stimuli, which precede the choice stimuli without delay. After a few days of such training, a very short delay is introduced. In some early studies, training with no delay was followed by a series of test sessions with several different delays (Roberts, 1972). The sudden introduction of nonzero delays can result in chance performance at all nonzero delays for some individuals, or a generalization decrement from the zero delay (Rayburn-Reeves & Zentall, 2019; Sargisson & White, 2001). Similarly, when one delay is arranged for all trials within a session, accuracy can be low or at chance level (Harnett, McCarthy, & Davison, 1984), confounded by large response bias (Jones & White, 1992), and the averaged forgetting function can appear hyperbolic in form. To maintain high accuracy at short delays and minimize the development of response bias at long delays, a successful strategy is to gradually lengthen the delays as training progresses and to retain a zero or near-zero delay in all sets of delays (Jones & White, 1994; Sargisson & White, 2001). The absence of bias at long delays means that the reinforcer proportion remains at its arranged value, typically 0.5, and the discrimination is not influenced by fluctuations in reinforcer proportions. Attempts to control the reinforcer proportion (McCarthy & Davison, 1991) can result in large reductions in the levels of obtained reinforcers at long delays and large bias for other dimensions of the choice between comparison stimuli (Alsop & Jones, 2008; Brown & White, 2009a; Jones & White, 1992; White & Wixted, 1999). Inclusion of a very short delay at all stages of training minimizes response bias at medium and long delays (White, 1985). The procedural advantages of varying delay within experimental sessions yields an interesting major empirical benefit—the mapping of the forgetting function for individual subjects.

FORGETTING OVER DELAYS

Blough's (1959) study can be seen as the beginning of an experimental analysis of remembering. Delayed matching to sample is the most frequently used procedure in the study of nonhuman short-term remembering, and it has been studied among a wide range of species (White, Ruske, & Colombo, 1996). Examples include humans (Adamson, Foster, & McEwan, 2000; Lane, Cherek, & Tcheremissine, 2005), monkeys (D'Amato, 1973), dolphins (Herman, 1975), mice (Goto, Kurashima, & Watanabe, 2010), and rats (Dunnett & Martel, 1990; Harper, 2000; Ruske & White, 1999). The trial-by-trial procedure allows the direct translation of the main procedural elements (sample, delay, choice) into the terms of the cognitive psychology of human remembering (encoding, storage, retrieval). It also allows the study of the effects on matching accuracy in pigeons of variables that corresponded to main effects in human short-term remembering such as repetition, rehearsal, proactive interference, retroactive interference, and spaced practice (Roberts, 1972; Roberts & Grant, 1976). Most important, the delayed matching-to-sample procedure allows within-subject variation of the fundamental variable that defines the procedure as a memory procedure—the delay or retention interval. Because the function relating accuracy to delay duration typically decreases with increasing time, the function is referred to as a *forgetting function* (White, 1985, 2001). In the absence of delay interval variation, a single data point at a given delay confounds potential differences in the intercept of a forgetting function with its slope.

I consider the effects on forgetting functions of the sample stimuli, delay interval conditions, choice, and intertrial interval in delayed matching to sample in the sections that follow. Quantifying the forgetting function in terms of the intercept and slope of fitted functions reveals that some variables influence the intercept and others the slope. Additionally, quantification is a hallmark of an experimental analysis of behavior, and the ability to fit functions to data provides another level of analysis in the search for order (Mazur, 2006). An excellent example is the comparison of auditory memory in humans and starlings in a delayed matching task in which samples were pure tones and starling song motifs (Zokoll, Naue, Herrmann, & Langemann, 2008). The forgetting functions were well described by exponential functions that did not differ in intercept for the tones versus motifs. Repetition of the samples increased intercepts for the starlings but not for the humans, and rate of forgetting was greater for the starlings. Thus, the higher order description in terms of intercepts and slopes of forgetting functions facilitated an illuminating cross-species comparison.

QUANTIFYING FORGETTING

The beauty of the forgetting function is that it measures performance across a wide range of levels of accuracy, from high at very short retention intervals to low at very long intervals. Percentage of correct choice in delayed matching to sample is the standard and most basic measure of performance at each retention interval, but increasingly a measure of discriminability is used. The problem with percentage correct is that it is bounded at 1.0 and can suffer from ceiling effects. By transforming proportion correct (p) to logit p, using logit $p = \log_{10} [p/(1 - p)]$, the problem of ceiling effects can be avoided. Logit p is a ratio-based measure that varies on an equal-interval scale, as do measures of discriminability. As a result, the slopes of different forgetting functions can be compared without encountering the problem that slope differences can be generated by non–equal-interval measurement scales (Loftus, 1985; Wixted, 1990). Technically, logit p can be influenced by response bias, whereas the discriminability measures d', log α, and log d estimate discriminability separately from response bias. Macmillan and Creelman (1991) provided a comprehensive account of signal detection theory's d' and log α from choice theory. Log d (Davison & Tustin, 1978; Nevin, 1981) is the same as log α except that it uses log to base 10. Both logit p and log d express discriminability as the log of the ratio of correct responses to errors and are equal when there is no response bias. The log d measure is easy to calculate: log $d = 0.5\log_{10}$ [(correct after S1 × correct after S2) / (errors after S1 × errors after S2)], S1 and S2 are the two stimuli. When there are no errors, log d cannot be determined. Brown and White (2005b) used a computationally intensive analysis to show that the optimal correction in such cases is achieved by adding 0.25 to the response totals in each of the four cells of the response matrix (correct and error responses after S1 and S2).

The form of the mathematical function that best fits the data from delayed matching-to-sample studies (Rubin & Wenzel, 1996) and whether the fits depend on the measure of accuracy (Wickens, 1998) have been extensively discussed. In practice, functions that differentiate different conditions measured in terms of discriminability equally differentiate them when measured in terms of percentage correct, as long as the different levels of chance performance are recognized (zero for discriminability measures and 50% for percentage correct; White, 2001).

A function that appeals from a behavioral perspective is the simple exponential decay function, $y = a \cdot \exp(-b \cdot t)$, because it is "memoryless." The exponential function is the only mathematical function that has a constant rate of decrement (b), with the property that the reduction in performance between two times depends only on that temporal distance and not on the level of performance at earlier times (White, 2001). The exponential function is memoryless in that performance does not depend on changes in memory that might result from organismic variables. A practical problem with the simple exponential function, however, is that it underestimates accuracy at longer delays. A better fitting exponential function scales time to the square root (White & Harper, 1996) and retains the memoryless properties of the simple exponential function, that is, $y = a \cdot \exp(b \cdot \sqrt{t})$ (White, 2001).

Power functions have also proven useful in quantifying forgetting functions. Wixted (2004a, 2004b), Wixted and Carpenter (2007), and Wixted and Ebbesen (1991) have argued persuasively in favor of the power function, $y = a \cdot (t + 1)^b$, because of its consistency with the notion of consolidation and Jost's law (Woodworth & Schlosberg, 1954, pp. 730–731). The power function is difficult to discriminate from the exponential function with time scaled as $\sqrt{t}$ in terms of their accurate description of forgetting functions (White, 2001). Indeed, apart from theoretical reasons, which particular function is used for descriptive purposes does not matter greatly as long as it provides a reasonable fit to the data.

The advantages of fitting functions to data are that the entire forgetting function can be quantified in terms of the parameters of the fitted function, typically intercept and slope, and that comparisons can be made between different experimental conditions in terms of their effects on either or both of the two parameters (White, 1985; Wixted, 1990). Where functions are fitted to data in this chapter, I used the exponential function in the square root of time. In the following sections, I describe the results of varying the different components of the delayed matching task: the sample stimuli, the retention intervals, the comparison stimuli and choice response, and the intertrial interval. The results of fitting functions to the data from the wide range of studies I summarize suggest some impressive regularities: Variation in attributes of the sample stimulus influence the intercept of the forgetting function, whereas conditions during the retention interval and at the time of remembering influence the slope of the forgetting function.

VARIATIONS IN SAMPLE STIMULI

The initial impetus for studying the effects of variation in sample-stimulus parameters in studies of nonhuman delayed matching tasks was provided by the analogy with processes of human short-term memory—distinctiveness, complexity, repetition, and rehearsal of the to-be-remembered events. The results, however, established many basic findings that can now be described in terms of their effects on forgetting functions. The main feature that these different variables have in common is that they affect the overall difficulty of discrimination, as shown by changes in the intercept parameter of the forgetting function. In other words, the different aspects of the sample stimuli influence the discrimination independently of time.

Sample Stimulus Disparity

Roberts (1972) showed that percentage of correct matching was overall higher for an easier color discrimination than for a harder color discrimination, although comparison stimuli also differed owing to the identical nature of samples and comparisons. White (1985) described forgetting functions for two levels of wavelength disparity between the samples, with disparity between comparison stimuli held constant. Figure 18.2 shows discriminability, log d, averaged over five pigeons in the experiment, recalculated from data in White's Table 1, and with the exponential function in the square root of time fitted to the data. The fits suggest that variations in the disparity of the sample stimuli produce a change in the intercepts of the fitted function without affecting their slope.

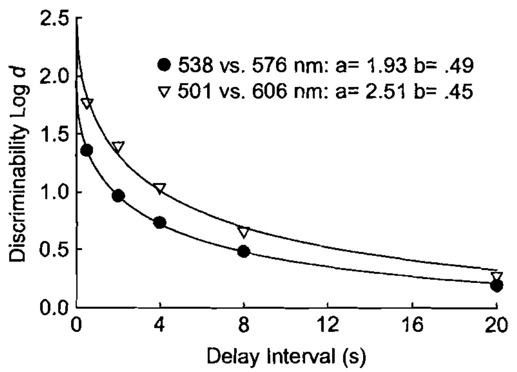

FIGURE 18.2. Discriminability as a function of delay for two conditions of wavelength disparity between sample stimuli. Smooth curves are nonlinear least-squares fits of $y = a \cdot \exp(b \cdot \sqrt{t})$. Data from White (1985, Table 1).

Fixed-Ratio Requirement

Repeating a to-be-remembered item can increase accuracy. In the delayed matching task, repetition can be achieved by repeated presentations of the sample (Kangas, Vaidya, & Branch, 2010; Roberts & Grant, 1976; Zokoll et al., 2008), extending its duration, or requiring repeated observing responses to the sample. Roberts (1972) varied the fixed ratio (FR) response requirement for pigeons' pecks on the sample key in a delayed matching-to-sample task in which retention intervals were varied over 0, 1, 3, and 6 seconds. The FR values in different conditions were 1, 5, and 15 (i.e., required 1, 5, and 15 responses, respectively). This manipulation, along with variation in the exposure duration of the sample, was seen as affecting repetition. White (1985, Figure 13) fitted simple exponential functions to the logit *p* transform of Roberts' data and found that the intercept of the fitted functions increased systematically and the slope decreased with increasing FR value. Both White (1985) and White and Wixted (1999) compared the effects of FR 1 and FR 5 requirements for sample-key responding across a range of delay intervals and reported higher intercepts for fitted exponential functions for FR 5 than for FR 1 without any systematic change in slope.

Sample Duration

Grant (1976) varied the exposure duration of sample stimuli over four values ranging from 1 second to 14 seconds and also used delays longer than in most studies—up to 60 seconds. His data, transformed to logit *p* values, are plotted in Figure 18.3. The intercepts of fitted exponential functions in the square root of time increased systematically with increasing sample duration, without an obvious change in slope.

Foster, Temple, Mackenzie, DeMello, and Poling (1995) varied independently both the FR requirement (0, 1, 3, 7, 10) and sample duration (2 seconds, 5 seconds, 10 seconds) in a delayed matching procedure with hens as subjects. Although Foster et al. arranged just one delay interval in the delayed matching task, their data clearly demonstrated that increases in both FR and sample duration had independent effects in increasing discriminability.

Serial Compound Sample Stimuli

In the delayed paired-comparison task arranged by Shimp and Moffitt (1977), two stimuli were presented in succession and with a delay between them. At the same time as the second stimulus was presented, a choice was made available—peck left if the stimuli were the same, or peck right if they differed. The procedure is a choice version of successive matching to sample (Nelson & Wasserman, 1978). In White's (1974) version of the task, the choice response follows the second stimulus. In all three procedures, lengthening the time between successive presentation of the two stimuli decreases accuracy. The stimulus associated with a correct response is actually a compound or abstract stimulus—same

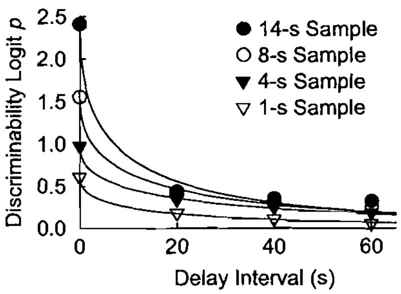

FIGURE 18.3. Discriminability as a function of delay and sample stimulus duration. Smooth curves are nonlinear least-squares fits of $y = a \cdot \exp(b \cdot \sqrt{t})$. Data from Grant (1976). DRO = differential reinforcement of other behavior; FR = fixed ratio.

versus different. By increasing the temporal separation between elements of the compound, the discrimination is made more difficult. White and McKenzie (1982) held constant the time between successive stimuli and varied the retention, or delay, interval between the second stimulus and the choice. They also compared the forgetting functions for the same or different compound with forgetting functions for the element stimuli (red and green) making up the compound. These functions differed only in intercept, not in slope. In particular, the intercept for the compound stimuli was lower. That is, the discrimination of same versus different was more difficult than the discrimination of the elements making up the compound, and increasing the retention interval resulted in a similar decrement in discriminability in both cases.

A question of interest is whether the function relating discriminability to retention interval has the same slope as the function relating discriminability to the time between successive stimuli. Data relevant to this question were reported by Urcuioli and DeMarse (1997). When pigeons chose left versus right response keys according to whether two successively presented stimuli were the same or different, discriminability with increasing delay between successive stimuli decreased at a faster rate than did discriminability with increasing time between the second stimulus of a pair and the choice. This result suggests that the two intervals have different functions. One relates to the pairing of the elements to form a discriminable compound (Wixted, 1989), and the other relates to the delayed control by the compound over the subsequent choice response.

Categorized Samples

Extensive research has documented the ability of nonhuman animals to discriminate categories of natural and artificial objects at different levels (e.g., Sands, Lincoln, & Wright, 1982; Vonk & MacDonald, 2004; Wasserman, Kiedinger, & Bhatt, 1988). Lazareva and Wasserman (2009) examined the choice responses of pigeons to samples categorized at basic levels (cars, chairs, flowers, people) or superordinate levels (natural vs. artificial) after three delays (0, 1, and 4 seconds). Discriminability was lower for the basic categories at all delays, consistent with the lower intercept for elements than for serial compounds in the same–different discriminations. The forgetting function for basic categories also tended to have a greater slope than that for the superordinate categories, although confirmation of this trend relies on analysis of functions fitted to individual data.

Asymmetrical Samples

Technically, delayed matching to sample is a two-alternative forced-choice procedure. When the samples are symmetrical, there should be no reason to prefer one sample over the other. A variant of the standard procedure involves asymmetrical samples, in which the choice responses are associated with whether a sample was present or absent. Preference to report the absence of the sample increases with increasing duration of the retention interval (Dougherty & Wixted, 1996; Wixted, 1993). Similarly, when samples are two different durations of a stimulus, the tendency to report the shorter of the two durations increases as the retention interval lengthens—the "choose-short" effect (Spetch & Wilkie, 1982, 1983). Gaitan and Wixted (2000) have shown that short durations seem to function in the same way as absent samples. The effect generalizes to number, the "choose-few" effect (Fetterman & MacEwan, 1989), and to the effects of prior training with one of the samples (Grant, 2006). Hypotheses to account for the effect range from subjective shortening (Spetch & Wilkie, 1983) to ambiguity between delay and intertrial intervals (Sherburne, Zentall, & Kaiser, 1998).

Ward and Odum (2007) convincingly demonstrated that the choose-short effect can be accounted for in terms of overall control by the sample stimuli and not by mechanisms such as subjective shortening. In a delayed matching task with just one 0-second delay, pigeons chose one comparison stimulus after four generally short delays and another comparison after four longer delays. The psychometric functions relating choice accuracy to sample duration were asymmetrical, like those of Fetterman (1995). Various disruptors affected accuracy on long-duration trials (a choose-short effect). Ward and Odum used Blough's (1996) model to analyze their data, owing to its ability to separate stimulus control factors from other influences. Their conclusion is consistent with the emphasis emerging from this chapter, that sample-stimulus variation affects overall stimulus control, as reflected in the intercept of the forgetting functions.

Research on the choose-short effect tends to examine functions for the two sample stimuli separately. Of interest is comparing full forgetting functions that plot discriminability as a function of retention interval (thus combining the effects of the two samples) for duration samples and color samples or for a range of duration samples that differ in relative duration. The latter comparison was reported by Fetterman (1995). Reanalysis of Fetterman's data (White, 2001) showed that for samples that differed in duration but that were otherwise closely separated or more distant, forgetting functions for the easier discriminations were characterized by higher intercepts.

Sample-Specific Responding

When the sample response requirement differs, not only is there a choose-few effect but overall accuracy is also higher than in conditions with the same ratio requirement for sample responses (Fetterman & MacEwan, 1989; Zentall & Sherburne, 1994). Zentall and Sherburne (1994) trained pigeons to respond (FR 10) or not respond (differential reinforcement of other behavior) to color samples in a delayed matching-to-sample task. Their results are replotted in Figure 18.4, with percentage correct transformed to logit *p*. The main difference in the exponential functions fitted to their transformed data is in the intercepts, not the slopes. That is, sample-specific responding enhances overall stimulus control, independent of the delay.

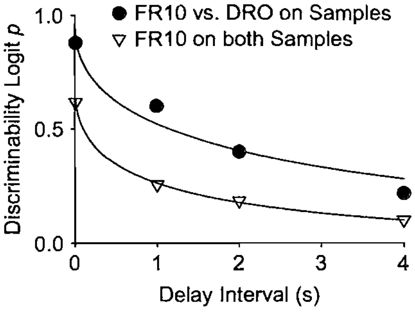

FIGURE 18.4. Discriminability as a function of delay and different sample stimulus response requirements. Smooth curves are nonlinear least-squares fits of $y = a \cdot \exp(b \cdot \sqrt{t})$. FR10 = fixed-ratio 10 responses; DRO = differential reinforcement of other behavior. Data from Zentall and Sherburne (1994).

VARIATIONS IN DELAY INTERVAL CONDITIONS

Conditions during the retention or delay interval that reduce accuracy are described as instances of retroactive interference (Cook, 1980; Grant, 1988). Such conditions include illuminating a houselight in a normally dark delay, introducing other stimulus events, providing food, and reinforcing responses in an alternative task. The general effect of such intruding events is an increase in the slope of the forgetting function. Competition from reinforcers for other tasks can also result in a reduction in the intercept of the forgetting function. That is, competing reinforcers can generate an overall reduction in discrimination accuracy.

Retroactive Interference

When the houselight is illuminated for the duration of a normally dark delay, matching accuracy plummets, as illustrated in Figure 18.5, for logit *p* transformations of data reported by Roberts and Grant (1978). The exponential functions fitted to the data in Figure 18.5 do not differ in intercept but have very different slopes, or rates of forgetting. The same effect was reported for pigeons by White (1985) and

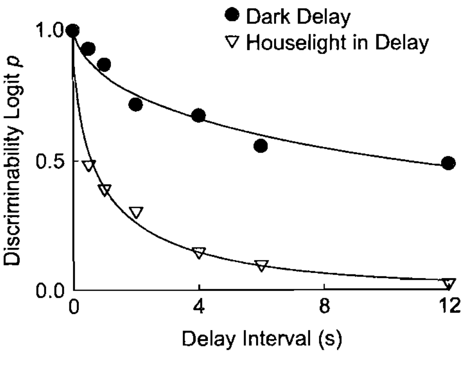

FIGURE 18.5. Discriminability as a function of delay for dark delays and illuminated delays. Smooth curves are nonlinear least-squares fits of $y = a \cdot \exp(b \cdot \sqrt{t})$. Data from Roberts and Grant (1978).

Harper and White (1997), for monkeys by D'Amato and O'Neill (1971), and for humans with delays filled by interfering noise (Zokoll et al., 2008). Roberts and Grant (1978, Experiment 2) varied the duration of houselight interpolated in a 10-second delay interval and found that accuracy decreased with increasing houselight duration. Other studies that introduced various stimuli in the delay, including food presentations (Jans & Catania, 1980) and geometric forms (Wilkie, Summers, & Spetch, 1981), have reported the same general result.

Harper and White (1997) argued that the increased rate of forgetting observed when the houselight is illuminated is caused by the increasing duration of houselight that is otherwise normally correlated with the increasing duration of the retention interval. When they included a constant 1.5-second illumination of the houselight at the end of each delay interval, the forgetting function (not including the shortest delay) had the same slope as the function for delays that were dark throughout. The effects of houselight illumination during the delay for pigeons are not surprising because once the light is on, the birds tend to peck at irrelevant objects and find grain spilled from the hopper when the reinforcers were delivered. Such behaviors during the delay interval, presumably maintained by reinforcers extraneous to the remembering task, are likely to compete with any possible mediating behavior during the delay.

Competing Reinforcers

An explicit competing alternative in the delay interval was arranged by Brown and White (2005c). Using a standard delayed matching task with red and green sample stimuli and delays ranging over four values from 0.2 second to 12 seconds, they included conditions in which responding on the center key (lit white) was reinforced at variable intervals averaging 15 seconds, 30 seconds, or none (extinction). The result from their Experiment 2 is shown in Figure 18.6, with exponential functions in the square root of time fitted to the log d measures. As reinforcers for center-key responding in the delay became more frequent, the intercept of the forgetting function decreased to a small extent (2.60, 2.54, and 2.33 for extinction, variable interval 30, and variable interval 15, respectively), and the rate of forgetting increased (0.53, 0.64, and 0.73, respectively). The increase in the rate of forgetting is consistent with the conclusion that as the retention interval lengthens, the extent of interference from the competing task increases with the delayed matching task.

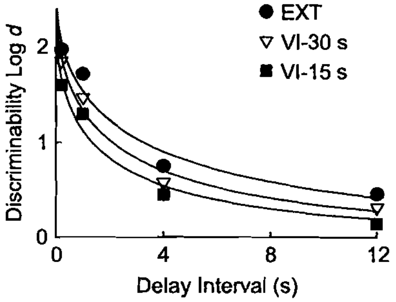

FIGURE 18.6. Discriminability as a function of delay and reinforcement for an extraneous task in the delay. Smooth curves are nonlinear least-squares fits of $y = a \cdot \exp(b \cdot \sqrt{t})$. EXT = extinction; VI = variable interval. Data from Brown and White (2005).

CONDITIONS FOR THE CHOICE RESPONSE

Typically, the comparison stimuli are assumed to be highly discriminable, although their disparity can influence overall matching accuracy (Jones, 2003; White, 1986). Additionally, the reinforcement contingencies are also assumed to be unambiguous, with no reinforcement for errors. Nonetheless, the reinforcement contingency for correct responses has a powerful effect on delayed matching performance. The absolute probability, magnitude, and delay of reinforcement affect matching accuracy. The signaled magnitude effect is the result of signaling two different reinforcer magnitudes (or probabilities) within sessions, with higher accuracy occurring on trials in which the larger reinforcer is signaled. The relative reinforcer probability for correct choices also influences performance. When different reinforcer probabilities, magnitudes, or other qualitative aspects (e.g., food vs. water) follow the different correct choices, the resulting enhancement in accuracy is called the *differential outcomes effect*. When disrupting events are introduced at different stages during the delayed matching trials, discriminability is resistant to change in the same way as the response rate of a single operant. Reinforcement of responses on the previous trial influences choice on the current trial, the local proactive interference effect previously thought to result from the influence of the sample stimulus on the previous trial. These various influences are all associated with the effects of the reinforcement of correct choices in the remembering task.

Absolute Frequency and Magnitude of Reinforcement

Instead of reinforcing each correct response, correct responses can be reinforced with a certain probability. When the probability of reinforcement for each correct choice is reduced from 1.0 to 0.5 or 0.2 across blocks of sessions, overall discriminability decreases (Brown & White, 2009b; White & Wixted, 1999). The same result applies when the magnitude of the reinforcers is reduced (Brown & White, 2009b). When the magnitude of reinforcers for correct choices is varied within an experimental session and the different magnitudes are signaled by different cues on each trial, accuracy or discriminability is greater on trials in which the larger reinforcer is signaled. This effect, the *signaled magnitude effect*, is illustrated in Figure 18.7 from a reanalysis of data reported by McCarthy and Voss (1995). The effect is well documented (Brown & White, 2005a; Jones, White, & Alsop, 1995; Nevin & Grosch, 1990) and reflects a difference in the intercepts of the forgetting functions but not their slopes, as is clear in Figure 18.7. An analogous effect also occurs for signaled probabilities of reinforcement (Brown & White, 2005a).

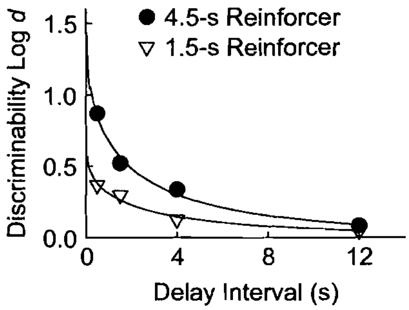

FIGURE 18.7. Discriminability as a function of delay for different reinforcer magnitudes (duration of access to food signaled within sessions). Smooth curves are nonlinear least-squares fits of $y = a \cdot \exp(b \cdot \sqrt{t})$. From "Delayed Matching-to-Sample Performance: Effects of Relative Reinforcer Frequency and of Signaled Versus Unsignaled Reinforcer Magnitudes, by D. McCarthy and P. Voss, 1995, *Journal of the Experimental Analysis of Behavior, 63*, p. 39. Copyright 1995 by the Society for the Experimental Analysis of Behavior, Inc. Adapted with permission.

Delay of Reinforcement

Interest in the effects of delaying the delivery of the reinforcer for correct matching responses was sparked by the possibility that the forgetting function confounds the delay of the choice with a delay of the reinforcer for a correct choice, with both delays measured from the sample. That is, the forgetting function reflects the influence of the reinforcer delay (Weavers, Foster, & Temple, 1998), a possibility that has been shown to be incorrect. In studies reporting a systematic reduction in discriminability with increasing reinforcer delay measured from the time of choice (McCarthy & Davison, 1986, 1991), reinforcer delays were varied only for a 0-second retention interval (see Sargisson & White, 2003, Figure 1). Sargisson and White (2003) varied retention interval within sessions and reinforcer delays across conditions and observed a substantial and systematic reduction in the intercepts of the forgetting functions with increasing reinforcer delay. Their analysis (Sargisson & White, 2003, Figure 4) demonstrated that varying the retention interval with the delay between sample and reinforcer held constant did not result in a constant level of discriminability. That is, the reduction in discriminability with increasing retention interval duration is not caused by an increase in the temporal distance between the sample and reinforcer.

Differential Outcomes

The signaled magnitude effect and the signaled probability effect both involve the same magnitude or probability of reinforcement for correct choices on a given trial type, but with two different trial types signaled by different cues within the experimental session. An alternative arrangement involves different outcomes for the two correct choices within a session. For example, correct choices of red result in one outcome, and correct choices of green result in another. The two outcomes may differ in quality (food vs. no food, food vs. water) or quantity (magnitude or probability). Compared with separate sessions in which outcomes of correct responses are the same, overall accuracy is higher when outcomes are different. This is known as the *differential outcomes effect,* and it has been extensively investigated in a range of species, including rats (Savage & Parsons, 1997; Trapold, 1970), dogs (Overmier, Bull, & Trapold, 1971), horses (Miyashita, Nakajima, & Imada, 2000), pigeons (Nevin, Ward, Jimenez-Gomez, Odum, & Shahan, 2009), and humans (Estévez, Overmier, & Fuentes, 2003; Legge & Spetch, 2009).

The differential outcomes effect has influenced the direction of theories of discrimination and their account of the role of the stimulus–reinforcer relation (Urcuioli, 2005). Jones and White (1994) reported a within-session differential outcomes effect in pigeons, in a procedure in which trials with different outcomes and trials with same outcomes were differentially signaled. Using the within-sessions procedure, Jones et al. (1995) showed that the differential outcomes effect was very different from the signaled magnitude effect. Whereas the signaled magnitude effect is manifest as a difference in the intercepts of the forgetting functions but not their slopes, the differential outcomes effect is best described as a difference in slopes, whereby the rate of forgetting for trials with different outcomes is less than that for trials with same outcomes. Figure 18.8 illustrates the difference in rates of forgetting for different- and same-outcome trials, for data taken from the within-sessions procedure of Jones and White (1994).

Jones and White (1994) also reported a study in which pigeons acquired the discrimination without any prior experience and with training that included four delays ranging from 0.01 second to 8 seconds from the outset of training. For the first 10 sessions, performance was at chance at all delays and on both types of trials. By Session 30, a differential outcomes effect emerged, and by Sessions 60 through 80, it was strongly established. Figure 18.9 shows the result for Bird C5 in Jones and White's study, plotted as percentage correct over six successive blocks of 10 sessions and a final block of 20 sessions. The main change in the course of the development of the differential outcomes effect was a progressive reduction in the rate of forgetting on different-outcomes trials (Figure 18.9, filled circles).

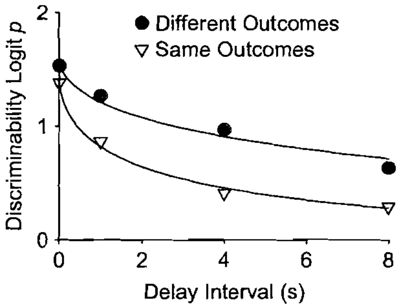

FIGURE 18.8. Discriminability as a function of delay and trials with different and same outcomes, replotted from data reported by Jones and White (1994). Smooth curves are nonlinear least-squares fits of $y = a \cdot \exp(b \cdot \sqrt{t})$.

Resistance to Change

The resistance to change of an operant response to extinction or other disruptors depends directly on rate of reinforcement and not on response rate (Nevin & Grace, 2000). Odum, Shahan, and Nevin (2005) applied resistance to change analysis to accuracy in delayed matching to sample by using a novel multiple schedule (or successive discrimination) procedure (also see Nevin, Milo, Odum, & Shahan, 2003). In the presence of two colors (red and green) presented in succession on a center key, responses produced delayed matching trials at variable intervals. The delayed matching trials, with retention intervals that varied in duration, used blue and yellow sample and comparison stimuli. Reinforcers for correct matching responses in red and green components were obtained with different probabilities. Both the responses to red and green stimuli and accuracy in the delayed matching trials were resistant to various disruptors (prefeeding, food in the

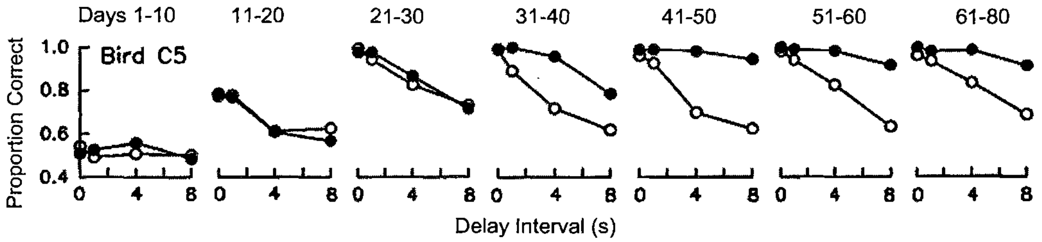

FIGURE 18.9. The development of the differential outcomes effect over 80 sessions with one pigeon from the study reported by Jones and White (1994). Proportion correct on different outcomes trials is shown as filled circles and on same outcomes trials as unfilled circles. From "An Investigation of the Differential-Outcomes Effect Within Sessions" by B. M. Jones and K. G. White, 1994, *Journal of the Experimental Analysis of Behavior, 61,* p. 399. Copyright 1994 by the Society for the Experimental Analysis of Behavior, Inc. Adapted with permission.

intercomponent interval, extinction) in the same way. Thus, accuracy in delayed matching to sample depends on reinforcement rate in the same way as does the rate of a single operant response. Brown and White (2009b) also reached this conclusion by using different measures of the strength of delayed matching performance when reinforcement probability and magnitude were varied, as did Nevin, Shahan, and Odum (2008), who demonstrated behavioral contrast for both response rate and discriminability in delayed matching.

Nevin et al. (2009) used the multiple-schedule procedure to study the resistance to change of the differential outcomes effect (see preceding section). Responses in successive red and green components of the multiple schedule led to delayed matching trials with different or same outcomes, respectively. The different outcomes were two probabilities of reinforcers for correct yellow and blue choices. On same-outcome trials, reinforcer probabilities were the same for correct yellow and blue choices. Across three experiments, Nevin et al. observed a consistent differential outcomes effect. Resistance to disruption in the same-outcomes component was greater than in the different-outcomes component only when total reinforcement rate in the same-outcomes component was greater than that in the different-outcomes component. In other words, resistance to change of delayed matching accuracy was not affected by whether accuracy was enhanced by differential outcomes. Nevin et al. also showed a positive relation between the magnitude of the differential outcomes effect and total reinforcers on different-outcome trials as a ratio of total reinforcers on same-outcome trials.

Local Proactive Interference

Choice accuracy in delayed matching to sample is lower when the sample on the current trial differs from the sample on the preceding trial than when samples are the same across consecutive trials (Grant, 1975, 2000; Hogan, Edwards, & Zentall, 1981; Roberts, 1980). This intertrial agreement effect is a form of proactive interference because performance on the current trial is influenced by events on the previous trial (A. A. Wright, Urcuioli, & Sands, 1986). I include it here as a condition of the choice response because reinforcers for choice responses on the prior trial influence the choice on the current trial. Edhouse and White (1988) termed it *local proactive interference* to distinguish it from general proactive interference, in which accuracy is lower with shorter intertrial intervals (see the section Intertrial Interval Conditions later in this chapter). Local proactive interference is manifest as a steeper rate of forgetting (slope) on trials in which consecutive samples differ compared with when they are the same. It is nicely illustrated by the results reported by Williams, Johnston, and Saunders (2006), replotted in Figure 18.10. Williams et al. studied adults with mental retardation in a delayed matching-to-sample task with either two samples in each session or unique samples throughout each session (cf. A. A. Wright, 2007). The exponential functions in the square root of time fitted to the data replotted in Figure 18.10 differ in slope but not intercept and account for 96% of the variance.

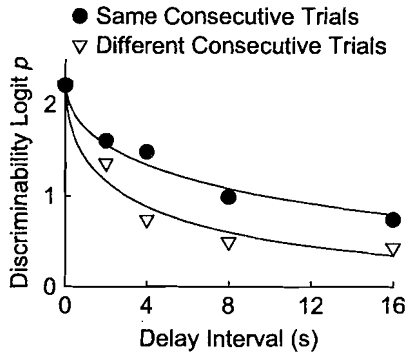

FIGURE 18.10. Discriminability as a function of delay for consecutive trials with same or different samples. Smooth curves are nonlinear least-squares fits of $y = a \cdot \exp(b \cdot \sqrt{t})$. From "Intertrial Sources of Stimulus Control and Delayed Matching-to-Sample Performance in Humans," by D. C. Williams, M. D. Johnston, and K. J. Saunders, 2006, *Journal of the Experimental Analysis of Behavior, 86*, p. 256. Copyright 2006 by the Society for the Experimental Analysis of Behavior, Inc. Adapted with permission.

Earlier theories of short-term memory in nonhuman animals suggested that proactive interference results from competition between conflicting traces of sample stimuli established on successive trials (Grant, 1975; Roberts & Grant, 1976) or from failure to discriminate the most recently seen sample (D'Amato, 1973). When accuracy levels are high, however, the sample on the previous trial is confounded with the choice. Therefore, what may appear to be an influence of the sample on the prior trial is actually an effect of the prior choice, as demonstrated by Roberts (1980) and Edhouse and White (1988). In these studies, accuracy on the current trial was higher when samples on consecutive trials were the same than when they differed, but only when the choice on the previous trial was correct (and thus reinforced). White, Parkinson, Brown, and Wixted (2004) arranged a reinforcer probability of .75, thus allowing for correct choices that went unreinforced on the previous trial. Accuracy was lower on consecutive trials with different samples than on trials with same samples, but only when the previous correct choice was reinforced. That is, local proactive interference results from reinforcers for correct choices on the previous trial influencing choices on the current trial.

Relative Reinforcer Probability

According to the generalized matching law (Baum, 1974), the log ratio of responses on two choice alternatives is a linear function of the log ratio of reinforcers for the choice responses. The slope of the function estimates the sensitivity of the response ratio to changes in the reinforcer ratios. The intercept provides a measure of bias to one or the other choice alternative. By varying the probability of reinforcement for correct matching separately for choices following each of the two sample stimuli, a pair of matching law functions can be plotted for choices at each retention interval. Consistent with the intuitively plausible view that at long retention intervals, the samples are less effective and choice is predominantly governed by the reinforcers, Hartl and Fantino (1996), Jones and White (1992), White and Wixted (1999), and Sargisson and White (2007a) showed that the matching law functions were steeper at long retention intervals than at short intervals. That is, across retention interval durations, there was an inverse relation between discriminability and sensitivity to reinforcement, consistent with the more general relation in conditional discriminations (Nevin, Cate, & Alsop, 1993; White, 1986).

Other studies reporting a direct relation between discriminability and sensitivity to reinforcement (McCarthy & Davison, 1991; McCarthy & Voss, 1995) used a specific procedure to control relative reinforcer probabilities. The controlled reinforcement procedure is designed to maintain equivalence between obtained and arranged reinforcer ratios. When a reinforcer for a correct choice becomes available, it is held until that correct choice occurs, whereas correct choices of the alternate comparison go unreinforced. This procedure, however, reduces the number of reinforcers obtained at long delays for which there is low discriminability and many errors and generates a left–right bias that constrains the sensitivity of the choice between comparison stimuli (e.g., red vs. green) to variation in the relative probability of reinforcers for choices (Jones & White, 1992). When the controlled reinforcement procedure is used, low or near-zero sensitivity to reinforcement at long retention intervals results from a bias to choose one key (e.g., left) when (color-correlated) comparison stimuli alternate, thus generating indifference between comparisons independently of the reinforcer ratio arranged for choices. In the extreme, when discriminability in delayed matching is zero, choice between comparisons is expected to follow the usual matching law pattern, as it does when reinforcer probabilities are independent for the two choices.

Sargisson and White (2007a) varied both relative reinforcer probability and reinforcer delay in delayed matching to sample. An increase in the delay of reinforcers from the choice reduces discriminability (see the section Delay of Reinforcement earlier in this chapter). Sargisson and White asked whether this reduction was a result of weakened contingency discriminability (knowing "what reinforcer goes with what response"; Davison & Nevin, 1999, p. 445) or impaired conditional discrimination owing to weakened association between sample and choice (White, 2002). They observed increasing sensitivity to the biasing effects of reinforcement as both retention interval and reinforcer delay increased, consistent with the general principle that factors that weaken the discrimination by weakening the association between sample and choice will also increase the biasing effect of reinforcers on choice.

INTERTRIAL INTERVAL CONDITIONS

In studies of human memory, accurate performance is facilitated by spaced learning (Baddeley, 1997). Similarly, longer intervals between trials in nonhuman delayed matching to sample result in higher matching accuracy (Edhouse & White, 1988; Kraemer & Roberts, 1984; Nelson & Wasserman, 1978; Roberts, 1980; Roberts & Kraemer, 1982; White, 1985). This effect was thought to be the result of decreasing interference from events on the previous trial, either through diminishing influence of competing traces (Grant, 1975; Roberts & Grant, 1976) or enhanced temporal discrimination of the most recently experienced sample (D'Amato, 1973). Edhouse and White (1988) varied both intertrial interval duration and intertrial agreement and argued that the two effects were independent. Whereas the intertrial agreement effect, or local proactive interference, is manifest as a difference in the slope of forgetting functions, the intertrial spacing effect, or general proactive interference, influences only the intercept of forgetting functions. This conclusion was confirmed by White's (1985) fitting of simple exponential functions to data from the study by Roberts and Kraemer (1982). For intertrial intervals of 4, 8, 16, and 32 seconds, intercepts increased systematically, whereas slopes did not change.

When a normally dark intertrial interval is illuminated, the trial-spacing effect is eliminated (Santi, 1984), but the intertrial agreement effect persists (Edhouse & White, 1988, Experiment 2). Grant (2000) demonstrated persistence of the intertrial agreement effect over intertrial intervals of as long as 60 seconds. His claim that the effect was underestimated at short intertrial intervals is difficult to evaluate, however, owing to the mixing of different intertrial intervals within sessions, a procedure that tends to result in the averaging of intervals (Roberts & Kraemer, 1982). What is needed is a study in which the intertrial agreement effect is examined over very long intertrial intervals.

APPLICATIONS: DRUG EFFECTS

A main area in which the quantitative analysis of forgetting has been applied concerns the effects of various drugs on behavior (see also Chapter 23, this volume). Much of the work has been published in neuroscience journals. By fitting a mathematical function such as the exponential function to accuracy or discriminability measures, the forgetting function can be summarized in terms of its intercept (initial discriminability) and slope (rate of forgetting). Many drugs influence the neurotransmitter mechanisms presumed to be associated with remembering. A good example is the cholinergic antagonist, scopolamine, which reduces initial discriminability without affecting rate of forgetting in many drug studies of the cholinergic hypothesis for Alzheimer's disease (White & Ruske, 2002). The reduction in initial discriminability caused by administration of scopolamine can be reversed by administration of agonists (Harper, 2000; Ruske, Fisher, & White, 1997). Glucose administration can also reverse scopolamine-induced deficits as well as the reduction in initial discriminability that results from reducing the sample-response ratio requirement from five to one (Parkes & White, 2000).

A second area of interest concerns recreational drugs. For example, Harper, Wisnewski, Hunt, and Schenk (2005) studied the effects of amphetamine, cocaine, and 3,4-methylenedioxymethamphetamine (ecstasy) on delayed matching performance in rats. In all cases, initial discriminability decreased with increasing dose, without affecting rate of forgetting. Lane et al. (2005) reported the first quantitative analysis of the effects of marijuana on forgetting functions in human delayed matching to sample. It is noteworthy that this carefully conducted study is one of the few to have shown an effect of drug administration on rate of forgetting but not initial discriminability, an effect that Lane et al. attributed to disruption of cannabinoid receptor function in the hippocampus.

A third area of interest concerns drugs used in clinical settings. Here, too, there are instances of change in rate of forgetting as well as in initial discriminability. Examples are the effects of the antipsychotic chlorpromazine (Watson & Blampied, 1989) and the barbiturate phenobarbital (Watson & White, 1994). Increasing doses of the dopamine agonist methylphenidate, widely used to treat attention deficit disorder, reduces initial discriminability without affecting rate of forgetting (F. K. Wright & White, 2003).

BEHAVIORAL THEORIES OF REMEMBERING

Cognitive theories of short-term remembering in nonhumans are not considered here. They rely on mechanisms such as trace decay and rehearsal and temporal distinctiveness, which remain in vogue in current theorizing about human short-term memory (Jonides et al., 2008; Suprenant & Neath, 2009) but which have proven less fruitful in studies with nonhumans. Unlike cognitive theories, behavioral theories of remembering and forgetting are characterized by inclusion of reinforcement as a major determinant of performance. Accordingly, they can account for reinforcer influences on the forgetting function, including the signaled magnitude effect, the differential outcomes effect, and the effects of absolute reinforcer probability. The three behavioral theories I briefly summarize in this section were all published in the *Journal of the Experimental Analysis of Behavior*. All incorporate well-established principles of reinforcer control—specifically delay reduction, behavioral momentum, and the matching law—and all are able to predict forgetting functions, that is, a reduction in discriminability with increasing retention interval. The mechanisms proposed by the different models to predict the forgetting functions differ, however, and might ultimately provide the main basis for comparisons between the models. These mechanisms are delay reduction (Wixted, 1989), diffusion (White, 2002; White & Wixted, 1999), and disruption of attention to the stimulus as coded during the retention interval (Nevin, Davison, Odum, & Shahan, 2007).

Wixted (1989)

Fantino (1977) proposed that the discriminative strength of a stimulus is given by the extent to which its onset reduces the delay to primary reinforcement. Wixted (1989) recognized that the sample stimuli in delayed matching to sample signal the presentation of the comparison stimuli that are intermittently associated with reinforcement. That is, in relation to the overall delay between one reinforcement and the next, onset of the sample reduces the delay by an amount that approximates the delay interval t. Following the delay-reduction formulation, Wixted represented the discriminative strength of the sample as $(d_r + \gamma)/(t + \alpha)$. The term d_r is the delay reduction quantity and equals the total time T between reinforcements minus the average delay d from onset of the sample to the choice, and d_r happens to equal the intertrial interval. The constants γ and α allow for differential effectiveness of the intertrial interval and delay. A third parameter accounts for the discriminative strength of all other stimuli. Wixted calculated the strength of a sample relative to all other stimuli and predicted the proportion of correct choices by weighting reinforcer proportions for correct matching responses by the discriminative strength of the sample. The model predicts that as discriminative control by the sample decreases, control by the reinforcement proportion increases (cf. Jones & White, 1992). Fits of the model to a wide range of data accounted for high proportions of the variance in the data. In most cases, the major independent variable was delay interval duration, and the model did an excellent job of predicting the forgetting functions. One prediction of interest was the linear relation between proportion correct and the ratio of the intertrial interval to the delay interval. This relation was reported by Roberts and Kraemer (1982) from a comprehensive manipulation of both parameters and was predicted by Wixted's model with high accuracy. The relation seems to fall out naturally from the delay reduction approach because the delay reduction quantity ($T - d$) is in most cases equivalent to the intertrial interval.

White and Wixted (1999)

In a blend of signal detection theory and matching law, White and Wixted (1999) proposed a model that does not include the decision criterion of signal detection theory and applies the matching law to discrete trial-by-trial choices based on reinforcer distributions. They assumed that on each trial, the choice between comparison stimuli matches the proportion of reinforcers obtained in the past by those choices given a particular value of stimulus effect. The stimulus effect dimension varies from trial to trial, the probability of which is given by a pair of normal distributions, one for each sample. The reinforcer distributions that predict the choice responses are derived by multiplying the stimulus effect distributions by the arranged reinforcer probabilities. The model can be implemented in a spreadsheet by using normal distribution functions (also see Wixted & Gaitan, 2002). With only two free parameters (the distance between the stimulus effect distributions and their variance), the model predicts the inverse relation between discriminability and sensitivity of the ratio of choice responses to variation in the reinforcer ratio reported by Jones and White (1992) and Sargisson and White (2007a). The model also predicts the proactive interference effects of reinforcing the choice on the previous trial (White et al., 2004) and the asymmetrical effects of retention intervals in signal detection versus recognition procedures (White & Wixted, 2010).

To predict a reduction in discriminability with increasing delay, that is, the forgetting function, White and Wixted (1999) assumed that the variance of the distributions increased with increasing delay. White (2002) addressed the model's shortcoming in not specifying the precise relation between variance and delay. He showed that the mathematical form of the forgetting function could be predicted by a specific diffusion function describing the increase over time of the variances of the stimulus effect distributions. The resulting model retains only two parameters. The distance between distribution means predicts the intercept of the forgetting function, and the rate of diffusion of the variances of the distributions predicts the slope of the forgetting function. Empirical evidence for the diffusion function has not yet been reported, however.

Another shortcoming of the White and Wixted (1999) model is that because choices are based on ratios of reinforcers, the model cannot predict the increase in discriminability when the absolute probability or magnitude of reinforcement is increased. Brown and White (2009b) addressed this problem by including a parameter for extraneous reinforcement. The model's overall strength is that it is based solely on distributions of reinforcer probabilities as well as extraneous reinforcement. The model's potential weakness is its inability to predict the forgetting function without making an additional assumption about a diffusion process.

Nevin et al. (2007)

Behavioral momentum theory (Nevin & Grace, 2000) suggests that response rate relative to a baseline is inversely related to the ratio of the reinforcer rate r_s correlated with the stimulus situation in which responding is measured and to the overall average reinforcer rate r_a. The reinforcer ratio is raised to an exponent b, which measures resistance to change to the reinforcer ratio. Nevin et al. (2007) proposed that attending to samples, $p(A_s)$, and to comparison stimuli, $p(A_c)$, is given by the following equations in which x and z are general background disruptors and qt and vt are disruptors specific to the retention interval t: $p(A_s) = \exp[(-x \cdot qt)/(r_s/r_a)^b]$ and $p(A_c) = \exp[(-z \cdot vt)/(r_c/r_s)^b]$.

With variation in a parameter for sample–stimulus discriminability d_s and different levels of background disruptors, x and z, the model predicts forgetting functions that differ in intercept and that are generally exponential in form. With d_s held constant, and variation in the retention interval disruptors, q and v, the model predicts forgetting functions that vary in slope. Varying the parameters to reflect disruption of attention to different components of the task allows the successful prediction of the effects of relative and absolute reinforcer probability. The model has difficulty in providing accurate quantitative predictions for the signaled magnitude effect (McCarthy & Voss, 1995) and the differential outcomes effect (Nevin et al., 2009), but over a wide range of other data, the model makes impressively accurate predictions by assuming different levels of attention to samples, coded representations of the samples in the retention interval, and the comparisons.

The Nevin et al. (2007) model has several features in common with Wixted's (1989) model. One similarity is in the effects of the sensitivity parameters γ and α in Wixted's model and the effects of x and z in Nevin et al.'s model. Another is the partitioning of the probability of attending versus not attending. A difference, however, is that Wixted's model is based on reinforcer proportions and does not predict the change in discriminability that occurs when absolute reinforcer rate is varied (Brown & White, 2009b), whereas the Nevin et al. model is able to satisfactorily predict the reduction in discriminability with reduced overall reinforcer probability (Brown & White, 2005a).

REMEMBERING AS DISCRIMINATION

White (1985, 2001, 2002) has argued that remembering is a discrimination specific to the retention interval at which it occurs. In effect, the discrimination involves a compound consisting of the sample and comparison stimuli and also the delay that forms part of the context for remembering. That is, remembering is specific to the delay. Remembering at one delay may be independent of remembering the same event at a much longer, or shorter, delay.

To study delay-specific discrimination, White and Cooney (1996) trained pigeons in delayed matching tasks with 0.1-second and 4-second delays mixed randomly within sessions. In one set of conditions, choices of red and green comparison stimuli at the short delay were reinforced with different probabilities, creating a strong bias to choose the comparison associated with the higher reinforcer probability. Choices at the long delay were nondifferentially reinforced, and the bias at the short delay did not generalize to choices at the long delay. In another set of conditions, strong reinforcer biases at the long delay did not generalize to the nondifferentially reinforced choices at the short delay. In other words, performance at one delay was independent of factors influencing remembering at another.

Temporal Independence

The conclusion that the discrimination made at one time may be independent of the discrimination made at another, that is, temporal independence, was supported by the result of another delayed matching task in which reinforcers at a particular delay were omitted (White, 2001). The result was a reduction in discriminability at the delay without reinforcers. This result was not surprising. What was surprising, however, was the increase in discriminability at longer delays. Compared with functions for which reinforcers were included at all delays, the result demonstrated that performance at one delay was independent of whether discriminability was higher or lower at a preceding delay. Temporal independence was also reported by Nakagawa, Etheridge, Foster, Sumpter, and Temple (2004). In one condition, they reinforced correct choices at an intermediate delay, and choices at both shorter and longer delays went unreinforced. The result was a nonmonotonic forgetting function, with highest discriminability at the intermediate delay.

Discriminations made at one retention interval may be independent of discriminations made at another retention interval, just as two discriminations about the spatial aspects of stimuli may be independent. Fetterman (1996) discussed the advantages of treating remembering in the same terms as discriminations between proximal stimuli. Temporal distance is a dimension of the stimulus complex that influences behavior along with other physical aspects of the event to be remembered and the stimulus context. To illustrate, Sargisson and White (2007b) made the discrimination of delay intervals an explicit requirement in a delayed matching task in which sample stimuli were a cross and a square and comparison stimuli were red and green. Following the cross, choices of red were reinforced at 1-second delays and choices of green were reinforced at 4-second delays. Following the square, choices of green were reinforced at 1-second delays and choices of red were reinforced at 4-second delays. After extensive training in this procedure, probe tests were conducted at 10 delays between 1 second and 4 seconds. The results from a replication in a later study (White & Sargisson, 2011) in which probe tests were included in a maintained test, averaged over four pigeons, are shown in Figure 18.11. The functions demonstrate conjoint control of comparison-stimulus choice by both the sample and the delay duration.

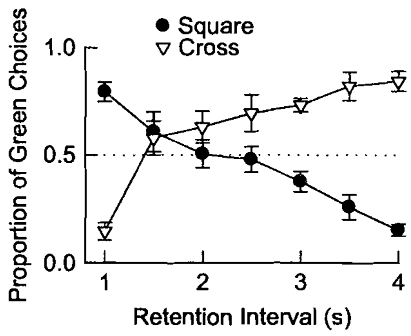

FIGURE 18.11. Proportion of choices of green given square and cross samples as a function of delay interval during maintained testing in which, given square, choices of green were reinforced at 1-second delay and choices of red were reinforced at 4-second delay, and given cross, choices of red were reinforced at 1-second delay and choices of green were reinforced at 4-second delay. Smooth curves are nonlinear least-squares fits of $y = a \cdot \exp(b \cdot \sqrt{t})$. From "Maintained Generalization of Delay-Specific Remembering," by K. G. White and R. J. Sargisson, 2011, *Behavioural Processes, 87*, p. 312. Copyright 2011 by Elsevier. Reprinted with permission.

Delay-Specific Remembering

Evidence for delay-specific matching comes from two studies in which training in delayed matching tasks included two delays and two different cues during the sample and delay interval, one correlated with the short delay and the other with the long delay (MacDonald & Grant, 1987; Wasserman et al., 1982). When the relation between the delays and the cues was switched in probe tests, accuracy at the long delay when it was cued by the short cue was higher than when it was cued by the long cue. More interesting, in the miscue condition of the probe tests, accuracy at the long delay was actually higher than at the short delay. Accuracy does not depend on how much time has passed but on the combination of the delay duration and stimulus conditions at the time of remembering. As Wixted (1989) noted,

> This interesting finding suggests that the strength of a discriminative stimulus may be delay specific only when one retention interval is employed. That is, a generalization gradient of discriminative strength may be conditioned around a particular delay such that it is strongest at the baseline delay and weaker at other delays (longer or shorter). (p. 416)

Wixted's (1989) suggestion was later confirmed by Sargisson and White (2001). They trained inexperienced pigeons in delayed matching to sample with just one delay from the outset of training: 0, 2, 4, or 6 seconds for different groups. Once a discrimination criterion had been attained, a single session was conducted with reinforced training trials and unreinforced probe trials with different delays between 0 second and 10 seconds, including the training delay.

The results are shown in Figure 18.12. The delay-interval functions tend to peak at the training delay, reminiscent of generalization gradients along spatial dimensions (Honig & Urcuioli, 1981). They also flatten as the training delay becomes longer, the likely result of the scalar property of time, where two intervals

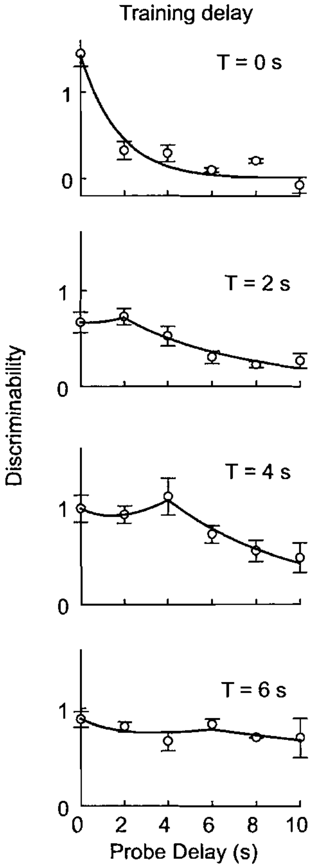

FIGURE 18.12. Discriminability, log *d*, as a function of delay in probe trials with different delays, after exclusive training with just one delay (T). Curves are predictions from an equation with temporal distance and generalization components (White, 2001). From "Generalization of Delayed Matching-to-Sample Performance Following Training at Different Delays," by R. J. Sargisson and K. G. White, 2001, *Journal of the Experimental Analysis of Behavior, 75,* p. 12. Copyright 2001 by the Society for the Experimental Analysis of Behavior, Inc. Reprinted with permission.

at long delays are less discriminable than otherwise equally spaced intervals at short delays. The curve described by White (2001) fitted to the data is a combination of a negative exponential function, which describes the effect of temporal distance, and a generalization component, which follows Shepard's (1987) exponential law of generalization. The resulting double exponential function, similar to the mathematical forgetting function suggested by Wicklegren (1969), closely fits data that follow the exponential to $\sqrt{t}$ and perfectly fits data that follow negative exponential functions when the training delay T = 0. The composite function retains the characteristics of independent variation in intercept and slope of forgetting functions. Both parameters are influenced by temporal distance and generalization components. The reasonable fit of the equation reinforces the notion that remembering is a delay-specific discrimination with generalization along the temporal dimension.

Direct Remembering

Considerable interest in the question of memory has been sparked by the theoretical question of how to bridge the temporal gap between events and subsequent behavior and also by the practical problems (neurological, legal, aging, everyday) that arise when memory goes wrong. An important task of psychology is to address the practical issues. Perhaps, however, new insights for dealing with the practical problems will follow from an approach that the temporal gap does not have to bridged. Watkins (1990) complained that mediationist theories of memory that rely on a representation of an event embodied in a memory trace to bridge the temporal gap are flawed. He argued in favor of bringing out the role of the stimulus environment in determining memory. In the study of perception, two very general approaches have been taken. In one, perception involves active construction and the processing of information by the brain. In the other, perception is direct, as advocated by James J. Gibson (1979). The notion that remembering, too, might be direct is consistent with an emphasis on environmental causes of remembering and forgetting (Hackenberg, 1993). Briefly, in a theory of direct remembering, the individual system is tuned to resonate to information available at the time of retrieval through prior learning and evolution (White, 1991). If remembering is direct, the forgetting function reflects increasing temporal distance in the same way that errors of depth perception reflect increasing spatial distance. Similarly, errors of memory follow the same principles as errors of perception such as geometrical illusions, for which, as Gibson explained, the information creating the error is actually in the environment. Gibson, a self-confessed behaviorist, made a significant contribution to psychology of perception, and the extension of his views to memory has the potential to bring new light to many unresolved questions about remembering.

CONCLUSION

The experimental analysis of remembering has succeeded in its description of the effects of a range of variables on the function defining the relation between accuracy and temporal distance. Different parameters of the sample stimulus, such as its duration, repetition, and complexity, influence the intercept of the forgetting function. Conditions during the retention interval and at the time of remembering influence the slope of the forgetting function. Reinforcement parameters can influence both intercept and slope. Reinforcement variables have similar effects on both accuracy of remembering and the strength of a single response. Together, these findings support a general view that the complex making up the sample, the delay interval, and the choice is an integrated behavioral unit. Thus, remembering is a discrimination at the time of the choice response and follows the same principles that govern discrimination and generalization of other behavior. In general, the effect of the delay between the sample and the comparison stimuli is to make the discrimination more difficult (by analogy with the effect of spatial distance). By treating remembering as an integrated unit of behavior, seeking processes that bridge the temporal gap becomes unnecessary. The temporal gap is a component of the compound discriminative stimulus and is the most relevant aspect of the individual's environment when it comes to remembering.

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