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Rate of Response-Independent Events as Discriminative Stimuli

Andrés García Penagos

Thesis submitted to the Eberly College of Arts and Sciences
at West Virginia University
in partial fulfillment of the requirements for the degree of
Master of Science
in
Psychology

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ABSTRACT

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Andrés García Penagos

The study of stimulus rates is relevant to understanding how discrete events integrated in time come to function as a single molar unit that can be discriminated from other comparable units. Two experiments examined the roles of stimulus rates as discriminative stimuli in a conditional discrimination paradigm. Pigeons responding according to a fixed interval (FI) schedule of reinforcement were presented concurrently with pairs of stimulus rates (response-independent blackouts of the operant boxes), so that access to food was granted if the pigeons pecked a comparison key associated to each stimulus rate. One-blackout versus two-blackouts stimulus rates were used on the first experiment, whereas two- and three-blackouts were used in the second experiment. The results replicate previous findings congruent with a Weber's law interpretation, emphasizing the relative difference in stimulus magnitude as the controlling factor. The concomitant pattern of responding produced by FI schedule requirements is also proposed to influence the accuracy of the discrimination. Finally, some further implications of the results for the analysis of molar variables are discussed.

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Rate of Response-Independent Events as Discriminative Stimuli

That events occur in time is neither a surprising nor debatable assertion. Nevertheless, far from being simple and innocuous, the temporal nature of events affecting the behavior of organisms has been the source of algid debate in psychological science. What makes this apparently simple phenomenon difficult is related to the historical nature of psychological events, whereby events in the past are said to affect behavior in the present. This problem resembles that of action at a distance in physics (Baum, 1997). The longer the gap of time between environmental events and an effect on behavior, the more difficult it is to understand and analyze it by means of experimental methods. Not surprisingly, most experimental research focusing on the temporal properties of events has been conducted in the last decades, probably reinvigorated with the categorization of interval schedules of reinforcement. Despite notorious advances in the study of temporal phenomena, many questions, both methodological and conceptual, remain to be answered.

The concern over temporal properties of stimuli and behavior is still, however, an important area of study, for a number of reasons to be presented in this review. The role of these temporal properties is one of the key issues separating what has been described as two main paradigms on behavior analysis. According to a molecular view, one of the main explanatory principles of the relation between behavior and reinforcement is the law of contiguity: "two events that occurred close together in time (i.e., in temporal contiguity) would tend to recur together" (Baum, 2002, p. 96). For the alternative view, instead, behavior is to be understood as a composite of behavioral patterns, constituting a whole, and "existing not only in space but spanning time" (Baum, 2004, p. 349). This molar view of behavior (e.g., Baum, 1973, 2001, 2002, 2004), then, considers time a fundamental dimension of behavior, necessary to completely understand the factors that control behavioral patterns, particularly those that determine

loss and gain of effectiveness with the passage of time (Baum, 2001). Although a critique of the postulates of this and competing views of behavior (e.g, a molecular view of behavior) is beyond the scope of this thesis, the foundational and differential role that time plays in both views suggests that a closer examination might be indispensable in understanding the principles of reinforcement.

In line with this assertion, Fetterman (1996) has suggested that a better understanding of the time-relevant functions of stimuli is required, and he considered their study as an example of the move of experimental psychology towards the study of more complex forms of stimulation. Two areas of research illustrate this latter development. First, the performance of different organisms under fixed-interval schedules of reinforcement suggested that animals (including human animals) were sensitive, for lack of a better word, to the passage of time, in the sense that responding becomes faster and faster as the reinforcement approaches. The study of these time-based discriminations has produced a large amount of research, and is often referred to as research on timing. A second area, which has received relatively less attention, derived as well from research on schedules of reinforcement (Rilling, 1993). Performance under fixed-ratio schedules suggested, as well, that organisms are sensitive to the number of events (in this case, responses), and the study of these number-based discriminations (often described under the label 'numerosity'), also has generated considerable research (see Boysen & Capaldi, 1993).

Numerosity procedures are useful in investigating the variables controlling the distribution of events in time, as a way to analyze the role that different stimulus events varying in frequency, duration, and presented at different points in time, have on responding. In particular, the use of a numerosity procedure to study the effects of stimulus rate, that is, the distribution of stimulus events in time on responding is the focus of this re-

search. Experiments related to the conceptualization and research on numerosity in nonhuman animals will be reviewed next, to establish its utility in the study of the temporal distribution of stimuli and to develop an alternative method for its study, which will be explained and then examined experimentally.

Literature Review

The Experimental Analysis of Stimulus Rate

Pigeons, rats, chimpanzees and humans, among other species, are sensitive to temporal and spatial relations among events and to their numerosity, as has been showing using several different procedures (cf. Davis & Pérusee, 1988). As mentioned above, research on ratio schedules of reinforcement renewed interest in counting, and thus some of the original work related to numerosity or, as it will be labeled in this document, stimulus rate was initiated rather accidentally. For instance, Seligman and Meyer (1970), studying the effects of response-independent shocks during schedule performance (conditioned suppression) found that when the number of shocks remained constant and appeared in a predictable sequence rats resumed lever pressing promptly after the last shock, "as if" they were counting the number of shocks (p. 206).

An important caveat regarding the study of counting or numerosity is that it is difficult to integrate the results of research conducted in this area, because, although there is a relatively long tradition in its study, there is still no agreement on many definitional and methodological issues (e.g., Capaldi, 1993; Davis & Memmott, 1982; Davis & Pérusse, 1988; Fetterman, 2008). For example, responding to these number-related stimuli has been called by different authors 'number discrimination,' 'numerosity judgments,' 'numerical competence,' 'counting,' and 'counting-like behavior,' among other labels, and some categorizations of this labels imply that different processes are associated with each (e.g., Davis and Perussé, 1988),

but even this categorizations have been criticized (e.g., Thomas & Lorden, 1993). Arguably, the interest for much of the research on numerosity in nonhuman animals (and in preverbal humans, to a certain extent) is due to two different, and not necessarily interdependent, objectives: (a) the search for effective instances of counting, as predecessors to adult human counting (e.g., Pepperberg, 1994; Rumbaugh & Washburn, 1993), and (b) an interest in the stimulus control properties of this events, particularly as related to timing (e.g., Church & Meck, 1984).

Further complications arise from a linguistic problem. In most languages, the word 'number' is used to refer to both quantities of objects and to successive presentations of the same object. This distinction has appeared as well in the experimental literature: two types of numerosity preparations have been traditionally used. In simultaneous numerosity procedures different numbers of stimuli are presented at the same time, and subjects are trained to respond only to specific quantities. In sequential or successive numerosity procedures one or more stimuli are presented at different points in time. Both of the procedures have proven successful, as will be seen, in establishing behavioral control by number-based stimuli.

Although responding under simultaneous and sequential numerosity procedures often are interpreted as instances of the same behavior (i.e., counting), it is possible that responding under this these experimental preparations is controlled by different variables. For instance, simultaneous numerosity procedures seem to use visual stimuli almost exclusively, whereas visual, auditory, kinesthetic, olfactory, and gustatory have been used in sequential procedures. Because of this difference, albeit visual factors such as area or size affect discrimination in simultaneous procedures that does not seem to be the case with sequential procedures (cf. Davis & Pérusse, 1988). The differences between these two procedures will be reviewed next.

Simultaneous Numerosity Procedures

As will be described more specifically below, the sequential presentation of stimuli introduces time-related factors that must be controlled if the role of number is to be isolated. One common alternative is a simultaneous presentation procedure, which allows time intervals between stimulus events to be ruled out as a source of control of the subjects' response, instead of number (e.g., Emmerton, Lohmann & Niehmann, 1997). Early experiments using simultaneous presentation of stimuli were conducted by Marold and Koehler during the late 1930's (cited in Wesley, 1961). These involved training parakeets to discriminate groups of two and three kernels of food, with inconclusive results.

Relatively recent examples of this procedure include a study by Davis (1984), who trained a raccoon to discriminate a cube with three grapes or toys from other four cubes with less or more than three objects. The four "wrong" cubes were presented progressively and were only available simultaneously at the end of the experiment. By the end of the experiment (but not on the first trials), the raccoon emitted a correct response with a probability of about .80). Thomas, Fowlkes and Vickery (1980), trained squirrel monkeys to discriminate "more" versus "less" circles of different sizes presented on two white cards. The monkeys had to choose the lower number to receive food, and the number of circles on the "less" circles card was progressively increased to the point that it contained only one circle less than the other card. Both monkeys met a criterion of 75% correct choices for all the numerosities presentations, but when new cards, not previously shown, were presented, only one of the monkeys chose correctly the card with the less circles. Furthermore, because the task implied repeated trials until the subject reached a criterion, it was possible that the monkeys were responding to a simple discrimination and not to number per se, that is, that they responded to a particular configuration of circles rather than to their number. Pepperberg (1987) showed that a Grey parrot, trained to vocally

produce English quantity labels for sets of various items presented simultaneously, correctly verbally labeled the sets in at least 77% of the different trials, even when quantity, mass and contour of the stimuli comprising the numerosity identification task were manipulated.

Honig (1993) used a modification of Herrnstein's procedure for studying concept formation, in which pigeons discriminated among different numbers of people in a picture by pecking at a panel on which photographs were projected. Pigeons responded differentially to one and many persons in a picture with a discrimination ratio of .90. In a subsequent experiment, different numbers of dots were projected on the panel, and pigeons were trained to peck to arrays of 2 and 4 small and large dots and to refrain from pecking samples composed of 3 and 5 dots. The pigeons did not respond discriminatively to the arrays, so further studies were conducted. One involved discrimination training involving two ranges of numbers of dots. Pigeons were trained to respond to 5, 6 or 7 dots, and refrain from responding at samples comprised of 2, 3, or 4 dots, a discrimination that the subjects learned, albeit slowly.

A common difficulty with simultaneous presentation procedures is that responding might depend on nonnumerical stimulus attributes such as brightness, or the total area of the samples (Hirai & Jitsumori, 1009; Honig, 1993). To rule out this possibility, Emmerton, Lohmann and Niemann (1997), exposed pigeons to conditional discrimination training in which the discrimination was between stimuli containing "many" items (6 or 7 white dots, circles, squares, or triangles on a dark background) from stimuli containing "few" (1 or 2 items) that were projected on a center key, but these stimuli had varying sizes, so that the total area of the samples was similar regardless of the number of stimuli. The investigators introduced then transfer tests consisting of new stimuli and intervening quantities of items. Generally, discrimination performance was accurate with the new stimulus exemplars,

although discriminability was relatively better for smaller numbers of items. Accuracy was further shown to depend on the difference in number between the two samples, such that an increase in that difference was accompanied by a higher number of correct choices in discrimination and test phases (Emmerton, 1998).

A further extension of the use of simultaneous numerosity procedures has attempted to simulate the human use of arbitrary symbols (Arabic numerals) as discriminative stimuli for particular responses. For example, Xia, Siemann & Delius (2000), trained pigeons to emit different numbers of responses to each of six arbitrary stimuli presented on a key. Accordingly, pigeons emitted a high proportion of correct responses to each of the stimuli, although this required a large number of trials (15,000 on average), and in the discrimination training particular procedures to facilitate acquisition had to be used, such as the production of additional audible feedback sound to key pecks. Other research has investigated the possibility of associating small numerosities with arbitrary numerical symbols. Xia, Emmerton, Siemann and Delius (2000), for example, trained pigeons to choose an arbitrary symbol (e.g., the letter 'A') after pecking at different number of circles. The pigeons discriminated the numerosity stimuli at levels above chance, although the percentage of correct responses was below 70% in most cases and decreased as bigger numerosities were introduced.

In summary, the research reviewed in this section provides evidence of numerical competence in different species. The simultaneous presentation procedure has the advantage of ruling out time as a potentially confounding variable. It is not free of methodological problems, however, as has been suggested here, especially those related to discrimination of brightness and other visual features inherent in any visual task. Additionally, although by eliminating time as a confounding variable the control by the number of stimuli can be precisely isolated, the close relation between number and time (e.g., Church & Meck, 1984; Fet-

terman, 1993, 2008; Roberts, 1997) suggests that important factors can be overlooked when time is not taken into consideration. For instance, Meck and Church (1983) found that the psychophysical functions in number and duration discrimination tasks were indistinguishable by rats when the ratio of the extremes was constant, although both attributes had previously been confounded. In addition, the administration of methamphetamine (1.5 mg/kg), had similar effects on both of the tasks, and transfer from auditory signals to cutaneous signals was similar for both of the discriminations (see also Breukelaar & Dalrymple-Alford, 1998; Broadbent, Church, Meck, & Rakitin, 1993; Roberts & Mitchell, 1994, found comparable results with pigeons). What these studies suggest then, is that timing and counting are related processes, and if as they argue this is so, then the simultaneous presentation procedure is probably not as useful in the study of control by number. Sequential procedures are an alternative that circumvents this problem, and they are reviewed next.

Sequential Numerosity Procedures

These procedures are exemplified in an experiment reported by Fernandes and Church (1982). Rats were trained to press one of two levers following a sequence of two bursts of .2s white noise and the other lever following a sequence of four bursts of .2 s white noise. The rats learned to do so, even when even when the interstimulus interval and the total duration of the stimulus sequences were manipulated, and in test trials, on which novel sequences were presented in the absence of reinforcement.

A variation of this procedure was used by Davis and Albert (1986). Lever-pressing by rats was reinforced according to a fixed interval (FI) 1-min schedule. Once responding was stable, a discrimination training procedure was effected in which reinforcement delivery according to the FI schedule depended on the presentation of three bursts of white noise while the animal worked on each 1-min cycle of the FI schedule; when two or four bursts of white noise were presented, a response to the lever was not rein-

forced. Thus, if the number of white noise bursts was a discriminative stimulus for FI responding, response rates would be higher in the presence of the three-burst sample than in the presence of the other two samples. The mean response rate for the '3' stimulus was significantly higher, statistically, than that for the other two stimuli for two of the three rats used as subjects, even when the total duration of the stimulus presentation was varied so that a discrimination on the base of duration could be ruled out. For the other rat, although the difference in the rates of response for the 3 vs. 4 stimuli was not statistically significant, the rate of responding was higher for the three stimuli. Unfortunately, the authors did not extend the experiments to account for this discrepancy.

Research also has addressed the possibility of a simultaneous discrimination of number and duration. Roberts and Mitchell (1994) trained pigeons to respond differentially to two or eight flashes of an overhead red light. To prevent control by duration, the flashing light sequences could last for either 2s or 8s respectively, so that in some trials the flashes had the overall same duration. In this way, the authors confounded time and number, and after the stimulus presentation pigeons had to peck one of two side keys to obtain reinforcement. Once a criterion of 80% correct responses was reached, the investigators introduced probe tests for timing and counting control: on timing tests, the number of flashes was held constant but the interflash interval was varied, whereas on counting tests, the flash sequence duration was held constant at 4 s but the number of flashes was varied (two, three, four, five, six, seven, or eight flashes). More responding occurred on the operandum correlated with the more numerous stimulus sample as the difference between the two stimuli increased. A similar result obtained when time was increased from 2 s to 8 s, which shows a confounding of the two stimulus dimensions. In an additional experiment, consisting of specific number training, the total sequence eventually gained control over the responses,

although there was an initial tendency to respond on the basis of time. The authors interpreted these results as evidence that both time and number exert simultaneous influence on numerosness judgments.

Pigeons also respond differentially to two different types of elements presented sequentially. In a study by Alsop and Honig (1991), for example, pigeons were exposed to sequences of red and/or blue flashes of light on a center key (e.g., a sequence might contain three red flashes followed by four blue flashes), and reinforcement was available contingent on a peck to one of two side keys, depending on the number of blue vs. red flashes. So, for example, if the sequence contained more blue flashes, a single peck to the left key was reinforced and a peck to the right key was not reinforced. The proportion of correct responses was high for all the subjects, over 75% for three of the four subjects, and above 70% for the other. In addition, the investigators observed a recency effect: the order of presentation of the red or blue flashes biased the pigeons' performance, such that stimuli presented later in the sequence exerted more control than earlier stimuli. The authors concluded in addition that the time elapsed between the presentation of an element and the opportunity to make the choice response can alter the stimulus control exerted by the element: with longer intervals between flashes accuracy decreased.

A variation of the sequential presentation procedures has been used to investigate if the number of responses can function as a discriminative stimulus. This possibility was suggested by the original research on responding under ratio schedules, in which the number of emitted responses were shown to function as a discriminative stimulus (e.g., Pliskoff & Goldiamond, 1966; see also Hobson and Newman, 1981). Other studies have demonstrated that pigeons could learn to eat only a certain number of peas and then walk away (see Rilling, 1993, for a review).

In the study by Rilling and McDiarmid (1965), for example, pigeons were trained to peck according to two fixed ratio sched-

ules. They had then to peck on one of the side keys if the number of previously made center-key pecks corresponded to the smaller of the two FRs, or to the other side key if the larger ratio requirement had been completed. Whereas the longer ratio was always 50 responses, the shorter ratio was gradually increased from 5 to 35. Both pigeons met a criterion of 90% correct responses with FR 35 as the shortest ratio. When the difference between the two ratios was further reduced, the percentage of correct responses decreased although remained above chance level. Further extension of this procedure, including two FI schedules of reinforcement (Rilling, 1967), yielded comparable results. Interestingly, the number of responses made during the interval was a better predictor of discrimination between the two FIs than the duration of a center key light or the duration of the FI itself. Rilling (1967) interpreted these results as evidence of discriminative control by the previous responses.

The fact that the number of responses can serve a discriminative function has been used to investigate whether pigeons discriminate the relative frequencies of two serially occurring events. Keen and Machado (1999), trained pigeons to peck a side key that was illuminated one color a certain number of times, and then to peck on a second side key that was illuminated a different color a different number of times. Then, during a choice phase, both side keys were transilluminated and only a peck to the less frequently pecked key was reinforced. The experimenters manipulated the total number of light presentations, as well as the difference between the frequencies of the two lights. The pigeons emitted high rates of correct responses, and the accuracy was proportional to the absolute value of the difference between stimulus frequencies and inversely proportional to the total number of presentations, although this relation was not completely clear when the most frequent sequence was presented last, in the sense that the effect of total number of presentations was different for different sizes of this last sequence. In addition, the

authors found primacy (i.e., greater control of choice exerted by the first stimulus of a sample than by subsequent stimuli) and recency (i.e., greater control of choice exerted by the last presented stimulus) effects related to the total number of samples: a primacy effect occurred when the total number of samples was small, whereas a strong recency effect occurred with larger numbers of samples.

A modification of the Keen and Machado (1999) procedure was made by Tan, Grace, Holland, and McLean (2007), in which, instead of responding to side keys, pigeons had to peck on a center key the same number of times as stimulus presentations, what the authors called a "numerical reproduction" procedure. The proportion of correct responses by the pigeons was below .5, and decreased as a function of an increase in the number of flashes.

Finally, some recent research has investigated the effects of delays between numerical samples and comparisons in matching to sample tasks. Santi and Hope (2001) and Santi, Lellwitz and Gagne (2006) found that pigeons demonstrate a tendency to choose a comparison associated with the less frequent numerosity (a choose-few effect) as a function of increasing delays.

The interest for most of the research on sequential presentation procedures has been in the search for a common mechanism for both counting and timing (Emmerton, 2001; Fetterman, 1996), and constructs such as a counts accumulator relatively similar and linked to the time accumulator have been proposed by some timing theories (e.g., Roberts, 1997). From a behavior-analytic view (e.g., Nevin, 1988), nevertheless, the interest lies not in the finding of physiological or other mechanisms, but in characterizing and understanding the dimensions and variables of stimulus control that are related to performance in numerosity tasks. In particular, sequential numerosity procedures as reviewed above have demonstrated that stimuli distributed in time can function as a discriminative stimulus for further responding, and are distinguishable from responding controlled solely by temporal cues.

The experiments reported here constitute a further exploration of the utility of these tasks in understanding the control by events aggregated in time.

Statement of the Problem

To a large extent, the literature reviewed has addressed the issue of control by stimulus rate as a demonstration of numerical competence. Accordingly so, most of the studies have focused in demonstrating that counting is an ability present in nonverbal organisms. A behavior analytic approach to this kind of phenomena differs in a number of ways. Not only the idea of numerical competence or ability is considered theoretically and ontologically problematic, but at the same time the focus goes from an organism-centered ability to an environmentally-based approach. Thus, instead of asking how representations of numbers are accumulated, a behavioral approach attempts to understand how contingencies of reinforcement allow for different stimulus rates to function as discriminative stimuli.

Stimulus rates constitute a particular case of stimulation. Different from other stimuli commonly used in experimental procedures, stimulus rates constitute an aggregate of stimulus presentations. As a unit, a stimulus rate is a time-extended event where the individual stimulus presentations are irrelevant by themselves, and thus the stimulus proper is actually the sum of its parts. A similar notion lies at the molar conception of extended activity (Baum 2002, 2004). According to this concept, behavior is best understood in terms of activities, extended patterns that cannot be seen at a moment in time, but that come to be considered a unit as they are observed in time. Every activity, in this view, is at the same time composed of parts, which are less extended activities, and is part of some more extended activity (Baum, 2002).

Reinforcement theorists have also explored related phenomena, as the discriminative effects of different rates of reinforcement. The fact that different rates of reinforcement can

function at the same time as discriminative stimuli for further behavior (e.g., Commons, 1979; Davison & Tustin, 1978; Lattal, 1981) suggests that organisms may respond to molar patterns of stimulation that only can be conceptualized as time-extended events. Relatively less is known in behavior analysis about how organisms respond to compound antecedent events functioning as a stimulus unit. The study of stimulus rates as discriminative stimulus is relevant to understand how discrete events extended in time come to constitute a single molar unit that can be discriminated from other comparable units. This thesis is comprised of two experiments designed to explore this relatively unexplored question. Pigeons were trained in a conditional discrimination task on which two stimulus rates were used as sample stimuli and side keys were used as comparison stimuli. Food was delivered contingently to choice of the comparison stimulus associated to each stimulus rate. Thus, the role of stimulus rates— presented during ongoing discriminated responding— as discriminative stimulus was explored.

Experiment 1

The position in time of two response-independent stimulus presentations was manipulated, as well as the interstimulus intervals so that discriminative control by time could be prevented. To make the stimuli more salient, the stimulus presentations consisted of black-outs of both houselights and keys, occurring concurrently to previously established FI responding. Two stimulus rates were used, one-blackout versus two-blackouts.

Method

Subjects

Three experimentally naïve male White Carneau pigeons were used. The pigeons were maintained at 80% of their free-feeding body weight and were housed in a vivarium under a 12 hr:12 hr light/dark cycle. Pigeons had free access to grit and water in their individual home cages.

Apparatus

Three operant conditioning chambers were used. Each is located in a sound-attenuating enclosure. Each chamber measures 33.5 cm from the response panel to the back wall, 30.5 cm wide and 37.5 cm high. Three translucent response keys, 25 mm in diameter, separated from each other by 9 cm, were aligned horizontally on the aluminum work panel, 26.5 cm from the chamber floor. Each key could be transilluminated white, and the center key could also be transilluminated red and green.

A houselight was located at the center of the work panel above the response keys at about 2.5 cm from the top of the panel, and a grain hopper was located on the panel behind a 65 mm x 55 mm aperture centered horizontally on the response panel midway between the base of the center response key and the chamber floor. When operated, a light was turned on above the feeder, illuminating the aperture. Reinforcement consisted of 3-s access to mixed grain for Pigeon 1903, and 2.5-s for Pigeons 6891 and 12098.

A ventilation fan circulated air and masked extraneous noise throughout the experimental sessions. All experimental events were controlled by a personal computer, located in an adjacent room, running MED-PC software.

Procedure

Preliminary training. The pigeons were trained to eat from the illuminated food hopper with an autoshaping procedure (Brown & Jenkins, 1968). Then, they were trained to peck at each of the three lit responses keys, by means of a multiple schedule on which they received reinforcement for every response to a transilluminated key (MULT FR1 FR1 FR1). During this phase, each key was transilluminated in a semi-random order for 3-s, and a peck to a lit key resulted in access to the raised food hopper. Sessions concluded when the pigeon earned 20 reinforcements for each key. This phase of preliminary training expanded for four consecutive sessions. Throughout all the preliminary training the houselight remained lit for the duration of the session.

After this training, each pigeon was exposed to a number of sessions of conditional discrimination training. For every trial the center key was transilluminated red until pecked, at which point one of the two side keys was transilluminated white. The position of the transilluminated side key was randomized and counterbalanced so that each side key would be lit no more than two consecutive times, and for a total of 30 times for each session. A peck to the illuminated side key was reinforced.

The number of pecks on the center key necessary for one side key to be illuminated was gradually increased, so that 1, 2, 5, 10, 15 and 20 pecks on that key were subsequently required for a side key to be transilluminated. A single peck to the transilluminated side key was reinforced. Thus, by the end of this phase a heterogeneous chained FR 20 FR 1 schedule was in effect, with the first component on the center key and the second one on either of the side keys.

Once responding under this chained schedule was stable, the requirement on the center key was changed to an FI 3-s. Thereafter the FI value was increased progressively to 12 s. As in the preliminary training, the houselight remained lit for the duration of the session.

Finally, an observing response was required to initiate a trial. The center key was transilluminated green at the end of the ITI blackout and a single peck changed the color of the key to red and the FI began. This observing response requirement was introduced to increase the probability that the pigeon would attend to the onset of the FI interval.

Conditional discrimination training. Stability was calculated from the mean response rates of the last six sessions on the FI link, by first obtaining the difference between the means of the three first sessions and the three last sessions, and then dividing this difference by the overall mean of the six sessions. Responding was considered stable if the result was inferior to 5. When the criterion was reached, a conditional discrimination procedure was introduced. The procedure is diagrammed in Figure 1. After an observing response (one peck to the white center key), the FI 12-s sample component was initiated. During the sample component, one or two extraneous events, consisting of a 1-s blackout of the houselight and keys occurred at different points. After 12-s in the sample component, the next key peck turned off the center red key and transilluminated the side keys white.

The blackouts in the sample component (hereafter, in-task blackouts) had no effect on the FI requirement, but the correct choice key in the choice component (that is, the one granting access to reinforcement) was determined by the number of blackouts during the FI sample component. During trials on which only one in-task blackout occurred, a response to the right choice key was reinforced. During trials on which two in-task blackouts occurred, a response to the left key was reinforced. An incorrect response, that is, a response to the left key after one blackout,

Figure 1. Schematic representation of the experimental task.

or a response to the right key after one blackout, was not be reinforced, but rather re-started the intertrial interval, after which the same trial was presented over and over again until a "correct" response was emitted (correction procedure).

During the intertrial interval (ITI) the keys were darkened, but the houselight remained illuminated. The ITI had a mean duration of 60-s, and ranged randomly from 15-s to 105-s. Different temporal cues could have been the source of control of the pigeons responding. Particularly, pigeons could respond to the total duration of the intervals between blackouts, to the duration of the interval between the last blackout and the end of the FI interval, or to the duration of the interval previous to the first blackout. On the grounds of keeping the FI interval constant, the total duration of the intervals was not modified, even though in practical terms it means that the houselight and center key remained on one less second in those trials on which there were two blackouts (cf. Davis & Albert, 1986). To rule out confounding stimulus control by the other two temporal factors, the blackouts were presented at quasi-randomized times during the FI interval. Specifically, three temporal factors were varied: (a) the interval between the onset of the center key and the first blackout, (b) the inter-blackouts interval, and (c) the interval between the last blackout and the end of the FI time.

Accordingly so, three different sequences of temporal distribution of the blackouts were presented for each number of blackouts. These sequences were set up in such a way that the duration of different intervals was constant regardless of the number of stimuli. These distributions are presented in Figure 2. Sessions ended after 60 reinforcers had been earned, so one blackout was presented for half of the trials, and two blackouts were presented for the remaining thirty trials. Each possible sequence was thus presented randomly a total of 10 times for each session. If stimulus rate was exerting discriminative control over responding, whether it was the interval between the last blackout and the end

Figure 2. Distribution of the in-task blackouts in the two conditions for the two types of trials during the 12-s FI schedule component. The numbers refer to the number of seconds during which the houselights and keylights were illuminated, and the striped areas represent 1-s blackouts.

of the FI interval or the duration of the interval previous to the first blackout that was kept constant across the two trial types, should not matter. If instead the proportion of correct responses would vary as a function of which interval was kept constant, it would mean that it is not number that controls performance but temporal factors. As a consequence, two pigeons were exposed to a set of sequences on which the last interval was kept constant, and the third pigeon was exposed to a different set on which it was the first interval that was kept constant.

As shown in Figure 2, for Pigeons 1903 and 6891 there were three possible blackout temporal configurations for each of the two types of trials, distributed in such a way that the interval between the last (or only) blackout and the onset of the comparisons was the same for each of the two types of trials (2-s, 4-s or 6-s). These trials will be described hereafter as constant tail

trials. For Pigeon 12098 (lower part of Figure 2), three different configurations were presented, but in this case what remained constant for the two types of trials was the interval between the onset of the center key and the onset of the first (or only) blackout (2-s, 4-s, or 6-s); I will refer to these trials as constant head trials.

For both of the conditions, the presentation of each of the three types of configurations was counterbalanced so that no more than three trials with the same sample configuration were presented consecutively. Sessions were conducted seven days a week at approximately the same time each day. Each session concluded when sixty reinforcers had been earned, thirty on each of the side keys. Fifty sessions were conducted, and results from the last ten sessions were analyzed.

Results

Figure 3 shows the percentage of correct responses for non-correction trials during the last ten sessions of the conditional discrimination training for the three pigeons. The percentages were calculated by dividing the number of noncorrection trials (that is, trials during which a correct response occurred the first time the blackout configuration was presented) by the maximum possible number of correct responses per session, that is, by 60. The

Table 1

Proportion of Correct Responses on Noncorrection Trials for Both Numerosities

Pigeon	1 Blackout			2 Blackouts		
	Mean	Range	SD	Mean	Range	SD
1903	0.81	0.63 – 0.93	0.09	0.89	0.73 – 1.00	0.07
6891	0.79	0.70 – 0.90	0.05	0.76	0.67 – 0.87	0.07
12098	0.83	0.77 – 0.90	0.04	0.77	0.70 – 0.87	0.05

proportion of correct responses exceeded that predicted by chance (50%) for each pigeon.

Table 1 shows the individual proportions of correct responses for each of the pigeons for the last ten sessions. In each of the cases the mean proportion of correct responses was above a criterion of 75%, which was selected because of its conventional use in the experimental literature. Pigeon 1903 performed slightly better when the sample consisted of two blackouts. The mean proportion of correct responses was always above 75%, with the exception of Session 7, during which the proportion in 1-blackout trials was 0.63, but the 2-blackouts trials proportion was 1.00, the highest during all sessions. The proportion for the final three sessions was about 90% for both types of trials. Pigeon 6891, instead, performed slightly better in 1-blackout trials, but in general there was no major difference in responding to one or the other stimulus rate, and the mean proportion was above 75%. Proportions of correct responses in noncorrection trials were similar for Pigeon 12098, which was exposed to a different sequence of one and two blackouts. This subject responded more accurately during 1-blackout presentations for all but one of the sessions. Even in this case, however, responding was above 75% for all but one of the sessions.

Figure 4 depicts mean individual performance for each type of trial during the last ten sessions of the experiment for the three pigeons. No particular trends were observed on the performance as a function of the distribution of the blackouts during the FI time. The mean proportion of correct trials at the first attempt for Pigeon 1903 was above 75% for all the types of trials. Choice accuracy was slightly better for those trials on which two blackouts were the sample. Also, when the sample consisted of two blackouts, choice accuracy among the three different types of trials was more consistent, as can be seen in Figure 4.

Figure 3. Proportion of correct responses on initial (noncorrection) trials for each of the last ten sessions of the first experiment for the three pigeons. Filled circles represent two-blackouts trials, and open circles represent one-blackout trials.

Figure 4. Mean proportion of correct responses on noncorrection trials for each distribution of the one vs. two-blackouts for the last ten sessions of the first experiment for the three pigeons. The number sequences below each bar refer to the different configurations of blackouts for each type of trial. Open bars represent two-blackouts trials, and filled bars represent one-blackout trials. The error bars indicate the ranges of the mean proportions.

For Pigeon 6891 choice accuracy was more variable, and relatively lower as compared to Pigeon 1903, which was exposed to the same trial configurations. Although the differences in choice accuracy among the six types of trials were more marked than for Pigeon 1903, no real trend can be observed. Similar results were obtained for Pigeon 12098 (constant 'head' condition), although in this case, choice accuracy was slightly higher for the 1-blackout trials. In addition, a decreasing pattern in choice accuracy can be seen in the one-blackout trials, so that the longer the pre-blackout interval (that is, the 'head'), the less accurate choice was. This result, however, does not seem to be of major importance, first because even though slightly different, the distribution of correct responses overlapped across the three types of trials, and second, because if this factor was fundamental, a similar pattern should be found in the two-blackout trials, as they had a similar pre-blackout interval. Nevertheless, as shown in Figure 5, that does not seem to be the case.

Discussion

Different methodological problems are common in sequential numerosity procedures. Whereas more attention has been devoted to an even distribution of stimulus and gap durations, less attention has been devoted to possible confounding variables. For example, in the study by Santi, Lellwitz and Gagne (2006), the pigeons had to peck one of two side keys contingent on the number of light flashes of the food hopper. The samples consisted of either two flashes (with duration of 400 ms or 800 ms) in an interval of 4 s, or four flashes (with duration of 200 ms or 400 ms) in the same interval of 4 s. Nevertheless, no contingency was established during the sample presentation, which was brief to start with, and accordingly so, the possibility that the pigeons were oriented away from the hopper was not taken into account. Furthermore, no latencies data were presented, so that no information regarding how much time occurred between the onset of the samples and the pecks on the side keys, and consequently the pos-

sibility that pigeons were not actually contacting the samples was not considered.

Part of the rationale for the present experiment was to eliminate these confounding variables. Of course, with the procedure employed in the present experiment it is not possible to rule out completely the possibility of the pigeons closing their eyes during the sample presentation or other behavior preventing contact with the samples, but the use of blackouts as stimuli was demonstrated to be a salient, effective discriminative stimulus. In addition, the blackouts occurred during response-initiated intervals, and during ongoing discriminated FI responding.

These results do not provide support for the idea that the temporal properties of the distribution of response-independent blackouts was the controlling variable for choice in this experimental situation. The levels of choice accuracy were high and constant across all three pigeons, regardless of the temporal distribution of blackouts, and no systematic differences were found among pigeons.

Experiment 2

Discrimination of 1- and 2-blackouts was established in all three pigeons. Fetterman (1993) has indicated that proportion of responses between two numerosities, as used in experiments as the present ones, are consistent with Weber's law which states that the amount a stimulus must be changed before the change is detectable (i.e., the 'just noticeable difference') is proportional to the size or magnitude of the stimulus. Accordingly so, in the case of numerosity, the discriminability of different stimulus rates should be a function of the proportionality between the two different rates. In the first experiment of the present study, the relative difference between the two stimulus rates is of 50%. If the parallel with the Weber's law is accurate, animals can discriminate between quantities differing by about 25% or more (cf. Hobson & Newman, 1981), and accordingly so, the numerosities presented in this experiment were relatively easy. The question remains, then, as to the utility of the procedure with a lower relative difference between stimulus rates.

Figure 5. Distribution of the 1 s in-task blackouts in the second experiment during the 15-s FI schedule component. The numbers refer to the number of seconds during which the houselights and keylights were illuminated.

The pigeons in the first experiment responded accurately when the samples consisted of 1 and 2 blackouts. A possible variation involves presenting two stimulus rates with the same absolute difference in blackouts as in Experiment 1, as well as differing in the relative difference: if 2 blackouts vs. 3 blackouts are used as samples, the absolute difference between them, 1, is the same as that between the two previously used stimulus rates, whereas the relative difference will be of 33.3%.

Method

Subjects and Apparatus

The same pigeons used in Experiment 1 were used as subjects, and the same conditioning chambers were used.

Procedure

The procedure was similar to that in Experiment 1. That is, pigeons pecked a center key according to an FI schedule of reinforcement, and 1 s response-independent blackouts were presented during the FI interval. Upon completion of the FI component, two side keys were illuminated and reinforcement was obtained on pecking one of them depending on the number of blackouts during the FI interval. For purposes of fitting more blackouts during the interval, two possibilities were considered, first, reducing the duration of the blackouts, or second increasing slightly the FI interval. The second alternative was chosen for practical purposes, and thus, the pigeons responded according to an FI 15-s, rather than on an FI 12-s as in the previous experiment.

During the FI interval (sample component), two or three 1-s blackouts were presented at different points in time. Because no differences were found in the previous experiment regarding whether the initial or final intervals remained constant, it was decided that all three pigeons would be exposed to the same temporal configurations. For each of the 2-blackouts and 3-blackouts trials, three possible configurations were possible, which are depicted in Figure 5. As can be seen in the Figure, the interval

Figure 6. Proportion of correct responses on initial (noncorrection) trials for each of the last ten sessions of the second experiment for the three pigeons. Filled circles represent two-blackouts trials, and open circles represent three-blackout trials.

Figure 7. Mean proportion of correct responses on noncorrection trials for each distribution of the two vs. three-blackouts for the last ten sessions of the first experiment for the three pigeons. The number sequences below each bar refer to the different configurations of blackouts for each type of trial. Open bars represent two-blackouts trials, and filled bars represent three-blackout trials. The error bars indicate the ranges of the mean proportions.

between the last blackout and the end of the FI interval was kept constant.

During trials where two in-task blackouts occurred, a response to the left choice key was reinforced. During trials where three in-task blackouts occurred, a response to the right key was reinforced. Incorrect responses were not be reinforced, but rather started the correction procedure as described in Experiment 1, that is, the same trial was presented after ITI until a correct response occurred. As in the previous experiment, during the intertrial interval (ITI) the keys were darkened, but the houselight remained illuminated, and it had a mean duration of 60-s, ranging randomly from 15-s to 105-s. The probability of presentation of the two samples (one or two in-task blackouts) after the ITI was the same for each trial ($p = .5$).

As in Experiment 1, each configuration of blackouts was presented for a minimum 10 trials, and the session ended when pigeons earned 60 reinforcers. Sessions were conducted seven days a week. As in Experiment 1, fifty sessions were conducted and results from the last ten sessions were analyzed.

Results

The proportion of correct responses for noncorrection trials during the last ten sessions of the conditional discrimination training for all the pigeons is depicted in Figure 6. As in Experiment 1, the proportions were calculated by dividing the number of noncorrection trials by the maximum possible number of correct responses per session, (i.e., 60). Results of this experiment are largely negative, in that the proportion of correct responses rarely exceeded that predicted by chance (50%) for all the pigeons.

The proportion of correct responses by Pigeon 1903 for the first four sessions considered, during which a higher proportion for 2-blackouts was accompanied by a decrease in the proportion

of correct responses in the 3-blackouts, suggests a slight bias to the left key. Although that does not seem to be the case for the remaining sessions, and although the proportion of correct responses increased for Sessions 8 and 9, performance was always lower than the criterion of 75% correct responding. As can be seen in Figure 7, which depicts the mean proportion of choices as a function of the trial type for the last ten sessions, no major differences were found across the different trial types.

Similar results, shown in the middle panel of Figure 6, were obtained with Pigeon 6891. Again, high proportions of correct response occurred when the sample consisted of 2-blackouts, with accompanying decreases in correct responding when the sample consisted of 3-blackouts, which suggests a bias to the left key. Although the proportions were more similar for the last four sessions, the proportions were close to 50%, which indicates that the pigeon was responding randomly to each of the keys. The bias to the left key appeared to be related to the type of trial for this pigeon, as shown in Figure 7. Both the major proportion of correct responses to the left key and the lowest proportion of correct responding to the right key occurred when the last blackout occurred 2s before the end of the FI interval, and the distribution of responding became more even as this interval between the last blackout and the end of the FI interval increased.

Nevertheless, this pattern did not occur with Pigeon 1903 or with Pigeon 12098. In the responding of Pigeon 12098 the bias to the left key seen in the other two subjects was not evident, and as shown in the lower panel of Figure 6 responding was more stable, but close to chance level (50%) for all the sessions. This pigeon responded slightly better to the 3-blackouts during the last five sessions. Similar to Pigeon 6891, correct responding to the 3-blackouts increased proportionally to the increase of duration of the interval between the last blackout and the end of the FI interval, but no corresponding increase was shown when the sample consisted of 2-blackouts.

Discussion

The results of Experiment 2 clearly did not replicate those of Experiment 1. In Experiment 2, the effect of increasing the magnitude of one of the stimulus rates, so that the absolute difference between the two stimulus rates would be kept constant, whereas the relative difference between the two was varied, was addressed. By comparing 3 versus 2 response-independent stimulus presentations, the absolute difference between the rates was kept constant at 1, but the ratio between the two was reduced from 2.0 to 1.5. None of the pigeons in Experiment 2 chose the appropriate comparison stimuli at above chance level, and some evidence was presented that position biases were developed, although no systematic pattern of choice was found across the subjects.

This failure to replicate the results of Experiment 1 indicates that a difference of 2 vs. 3 stimuli is less discriminable than that of 1 vs. 2 stimuli. This fact suggests that responding accuracy may be related to the relative proportion of the stimulus rates rather than to their absolute difference, which was kept constant in both of the experiments. This provides some support for an interpretation of these results in terms of the Weber's law, although the decrease in accuracy was far larger than expected.

General Discussion

In the present experiments, pigeons accurately discriminated between one and two response-independent events, but discriminative performance was less accurate when the discrimination was between two and three such events. This negative result, however, is not without precedent in the literature. Actually, it corresponds to what Roberts (2010) has called a 'magnitude or Weber's law effect': just as it seems to be easier to discriminate between two numerosities proportionally to the distance between the numbers, the difficulty of discriminating between two numbers an equal distance apart (such as the one used here) increases as the size of the numbers increases. That is, he argued, it seems to be easier to discriminate a 2:1 difference than an 8:7 difference. This magnitude effect has been reported in some experiments (e.g., Cantlon & Brannon, 2006), but generally in the context of simultaneous numerosity tasks on which the distance between numerosities is varied parametrically within each session. In particular, experiments reporting this effect involve the presentation of two numerosities on each trial, one after the other, and subjects are supposed to choose a key associated to each numerosity. Thus, a different sequence of numerosities is presented on each trial, and subjects are trained to choose either the largest or the shortest one.

The results of most of these studies suggest that discrimination accuracy declines as a function of the smaller/larger ratio (e.g., Beran, 2007; Cantlon & Brannon, 2006), so that, as reported here, discrimination is slightly better for a 2:1 ratio than for a 3:2 ratio. In particular, Roberts (2010) studied similar ratios to those in the present study. Pigeons' choices of a side key associated with the more frequent of two sequences of flashes on a center key were reinforced (a "choose-the-larger" task). Thus, different from other studies (e.g., Cantlon & Brannon, 2006; Olthof, Iden & Roberts, 1997), he used a sequential presentation rather than a simultaneous procedure. He found, as expected, that

discrimination accuracy improved as a function of the difference between the two sequences, and also that accuracy decreased with size when the difference was kept constant. In particular, in his second experiment Roberts presented 2:1, 3:2, and 4:2 numerosities (i.e., stimulus rates) during each session and found accuracy levels in a manner relatively similar to those found in the present two experiments: when the ratio was 2:1 overall accuracy for all pigeons was about 72%, decreased to about 65% when the ratio was 3:2, and increased to about 74% when the ratio was 4:2.

The present experiments thus have replicated Roberts's (2010) findings, although the methodological differences between the studies must be taken into account. First, pigeons in the Roberts (2010) study were exposed to all the different ratios during each session, whereas pigeons in the present two experiments were trained to respond explicitly to only two stimulus rates simultaneously (1 vs. 2, or 2 vs. 3). Second, pigeons in the Roberts (2010) experiments had to choose the larger of two numerosities, so it might be claimed that training was relational in nature in his study. As a consequence, pigeons were exposed to both numerosities during each trial, whereas pigeons in the present study were exposed to only one numerosity on each trial. Finally, two methodological variables might have confounded Roberts's results. First, there was no response requirement during the sample component, and this sample consisted of brief flashes (.66 s in duration, separated by .33 s gaps) of the center key. Because of this, it was not possible to assess whether the pigeon was in physical contact with the samples (that is, if the pigeon was looking at the center key at the moment of the stimulus presentation). Second, as discussed by Roberts, because the two stimulus rates were presented successively on each trial, recency effects appear and constitute a confounding variable, that is, pigeons tended to respond to the most recently presented stimulus rate regardless of its magnitude.

Roberts (2010) proposed some plausible interpretations of this effect involving what he called an "increased confusion" between larger magnitudes accumulated in an internal clock or noisy neuronal activation. Whether the 'problem' lies in that those internal quantities are confused or in that neurons tuned to particular numbers are accidentally aroused, according to Roberts (2010) the conclusion is that the more similar two magnitudes are the more likely it is that confusion will be generated. He proposed a variation of a mathematical model to account for the results of his experiments, emphasizing the notion of sensitivity to the difference between two numerical representations (a Weber fraction). To account for the strong recency effects obtained in his experiments, Roberts (2010) proposed that such sensitivity is modulated by memory decay, and is representational in nature. The model accounts for a large proportion of the variance of the data, although it was less useful when the total duration of the stimulus rates was equaled. A similar decay model is not well-suited to the present results because the time between the samples onset and comparisons onset was the same for the two stimulus rates that served as discriminative stimuli in each experiment. Regardless of the necessity of a decay parameter in the model, the fact that sensitivity is after all a quantitative index of the absolute difference between stimulus rates provides some support for a similar interpretation of the results obtained with comparable magnitudes found in the experiments reported here.

Other possible interpretations of these results involve a timing approach. As discussed in the literature review, the relation between counting and timing makes it difficult to distinguish whether temporal factors or stimulus rates (or both) are controlling performance. In the present experiments, time variables were controlled, although not completely. Although the blackouts appeared quasi-randomly during the sample component, the fact that they were superimposed on an FI schedule of reinforcement meant that on each session the trials with the smaller stimulus rate

Figure 8. Mean proportion of responses emitted during each of the inter-blackout intervals for all of the pigeons in the first experiment (upper panel), and second experiment (lower panel). The mean proportion was calculated from the last ten sessions of each experimental condition.

always had one second more of light than was the case during the trials with the more numerous stimuli. The traditional solution to this kind of problems in the literature would have involved either reducing the duration of each blackout or increasing the interval. The problem, however, is that whichever is done, additional confounding variables are put into play. Reducing the duration of the blackouts would have implied a similar reduction on at least some of the trials involving the smaller stimulus rate, with the unavoidable increase in the "illuminated" time duration, which would have required additional modifications. If

the duration of the FI interval were modified, then regardless of the arrangement the FI contingency would have been modified with potentially confounding results. Thus, a timing interpretation cannot be completely rejected. Nevertheless, in the light of the comparable performance observed with the different temporal configurations (see Figures 4 and 7), it is doubtful that time exerted a consistent effect on responding.

Another variable that might be related to the current data is related to an "interference" effect from the FI responding. Different to previous studies, the present procedure involved stimulus rates appearing concurrently with previously established discriminated responding. As expected from such a behavioral history, pigeons pecked more towards the end of the FI component. What this meant in terms of the blackout onset is that generally pigeons only pecked after the first blackout was presented. Indeed, blackouts seemed to briefly interrupt pecking. It might have been the case that rather than the rate of blackouts functioning as discriminative stimuli, the effective stimulus could have been the number of interruptions until the end of the FI component. It might be the case, then, that rather than responding only to stimulus rates, pigeons responded to their own responses. Such a strategy would have been most beneficial with the 2:1 stimulus rates. If pigeons only started pecking after the first blackout, it would mean that in the one-blackout trials they would not be interrupted until the end of the FI component, whereas they would be interrupted once in two-blackout trials. Such a response cue might have been less reliable when the stimulus rates were 3 vs. 2 in the second experiment, because rather than an interruption/no-interruption comparison, pigeons would have had to compare one-interruption versus two interruptions.

Some preliminary support for this possibility can be obtained by analyzing the patterns of the responses emitted by the pigeons during the fixed interval component. Figure 8 depicts the mean proportion of responses to the center key emitted during each

inter-blackout interval for the three pigeons during the last ten sessions of Experiment 1 (upper panel) and 2 (lower panel), respectively. For all pigeons in both experiments, the majority of responses were allocated to the final interval, which is to be expected as the pigeons pecked according to a fixed interval schedule. Interestingly, as can be seen, the proportions of responding in the *initial* interval were generally higher than those on the intermediate intervals. This suggests that the pigeons were indeed using their own rates of responding as discriminative stimuli, as proposed above.

More precise evidence of the role of this variable will require, of course, further experimental evidence. This might be explored experimentally in a variety of ways, although some methodological issues need to be resolved in advance. For example, one possibility would be a study involving a no-response contingency during the stimulus rate presentation, but such an experiment would have the difficulty of preventing any type of response cue which might be implausible. A further direction involves the study of higher stimulus rates with comparable absolute differences in magnitude, such that response cues are more and more difficult.

The rate of antecedent stimuli can function as a discriminative stimulus for responding, as shown in the present experiments. An interpretation of these results from a molecular view that analyzes behavior in terms of discrete units is particularly complicated. For example, how is a stimulus rate to be interpreted in molecular terms? Is it a chain of discriminative stimuli? Stimulus rates appear to function as a unit even though they are composed of discrete events occurring at different times. As Fetterman (1992) has claimed, at issue here is whether stimulus rates should be viewed as "one stimulus, or as a collection of stimulus elements" (p. 7).

Fetterman (1996) has argued that a molecular or elementarist view on the type of stimuli here studied favors interpretations

in cognitive terms, and thus often must include hypothetical constructs such as memory mechanisms (cf. Roberts, 2010). Gibson (1960) traced this molecular view of stimulation to the notion that a stimulus can only be something momentary. He argued that the notion is unfounded, and actually a temporal sequence of events may be perceived as a single stimulus. In his view (Gibson, 1966), the idea of stimuli as momentary is related to a notion of the world as "frozen" rather than continuously changing. In this static world notion, then, a stimulus in the past can only be responded to as a memory. Gibson proposed instead that if stimuli such as presented in the experiment here reported are considered holistically as a unit, the problem of memory becomes irrelevant: "We have the feeling that perception is confined to the present, whereas memory refers to the past... the idea that form or space is perceived, whereas sequence or time is remembered, lurks vaguely at the back of our psychological thinking; but it is surely mistaken" (Gibson, 1966, p. 142).

As shown here, indeed, a mediational account of responding under the control of stimulus rates is not necessary, and responding in such tasks can be interpreted as a function of differences in stimulation, as well as in terms of the inseparability between stimulus counting and response counting. Of course, the present experiments neither support nor contradict a molar approach to responding under the control of stimulus rates. Nevertheless, these studies suggest that the study of molar variables should also include those corresponding to antecedent stimulation, rather than only those related to the correlation between responses and consequences in time.

References

- Alsop, B., & Honig, W. K. (1991). Sequential stimuli and relative numerosity discriminations in pigeons. *Journal of Experimental Psychology: Animal Behavior Processes*, 17 (4), 386-395.
- Baum, W. M. (1973). The correlation based law of effect. *Journal of the Experimental Analysis of Behavior*, 20, 137-153.
- Baum, W. M. (1997). The trouble with time. In L. J. Hayes & P. M. Ghezzi (Eds.), *Investigations in behavioral epistemology* (pp. 47-59). Reno, NV: Context.
- Baum, W. M. (2001). Molar versus molecular as a paradigm clash. *Journal of the Experimental Analysis of Behavior*, 75, 338-341.
- Baum, W. M. (2002). From molecular to molar: A paradigm shift in behavior analysis. *Journal of the Experimental Analysis of Behavior*, 78, 95-116.
- Baum, W. M. (2004). Molar and molecular views of choice. *Behavioural Processes*, 66, 349-359.
- Beran, M. J. (2007). Rhesus monkeys (*Macaca mulatta*) enumerate large and small sequentially presented sets of items using analog numerical representations. *Journal of Experimental Psychology: Animal Behavior Processes*, 33 (1), 42-54.
- Boysen, S. T., & Capaldi, E. J. (1993). *The development of numerical competence: Animal and human models*. Hillsdale, NJ: Lawrence Erlbaum.
- Breukelaar, J. W. C., & Dalrymple-Alford, J. C. (1998). Timing ability and numerical competence in rats. *Journal of Experimental Psychology: Animal Behavior Processes*, 24 (1), 84-97.
- Broadbent, H. A., Church, R. M., Meck, W. H., & Rakitin, B. C. (1993). Quantitative relationships between timing and counting. In S. T. Boysen & E. J. Capaldi (Eds.), *The development of numerical competence: Animal and human models* (pp. 171-187). Hillsdale, NJ: Lawrence Erlbaum.

- Brown, P. L., & Jenkins, H. M. (1968). Auto-shaping of the pigeon's keypeck. *Journal of the Experimental Analysis of Behavior*, 11, 1-8.
- Cantlon, J. F., & Brannon, E. M. (2006). Shared system for ordering small and large numbers in monkeys and humans. *Psychological Science*, 17, 401-406.
- Capaldi, E. J. (1993). Animal number abilities: Implications for hierarchical approach to instrumental learning. In S. T. Boysen & E. J. Capaldi (Eds.), *The development of numerical competence: Animal and human models* (pp. 191-207). Hillsdale, NJ: Lawrence Erlbaum.
- Church, R. M., & Meck, W. H. (1984). The numerical attribute of stimuli. In H. L. Roitblat, T. G. Bever, & H. S. Terrace (Eds.), *Animal cognition* (pp. 445-464). Hillsdale, NJ: Lawrence Erlbaum.
- Commons, M. L. (1979). Decision rules and signal detectability in a reinforcement-density discrimination. *Journal of the Experimental Analysis of Behavior*, 32 (1), 101-120.
- Davis, H. (1984). Discrimination of the number three by a raccoon (*Procyon lotor*). *Animal Learning & Behavior*, 12 (1), 409-413.
- Davis, H., & Albert, M. (1986). Numerical discrimination by rats using sequential auditory stimuli. *Animal Learning & Behavior*, 14 (1), 57-59.
- Davis, H., & Memmott, J. (1982). Counting behavior in animals: A critical evaluation. *Psychological Bulletin*, 92 (3), 547-571.
- Davis, H., & Pérusee, R. (1988). Numerical competence in animals: Definitional issues, current evidence, and a new research agenda. *Behavioral and Brain Sciences*, 11, 561-615.
- Davison, M. C., & Tustin, R. D. (1978). The relation between the generalized matching law and signal-detection theory. *Journal of the Experimental Analysis of Behavior*, 29 (2), 331-336.

- Emmerton, J. (1998). Numerosity differences and effects of stimulus density on pigeons' discrimination performance. *Animal Learning & Behavior*, 26 (3), 243-256.
- Emmerton, J., Lohmann, A., & Niemann, J. (1997). Pigeons' serial ordering of numerosity with visual arrays. *Animal Learning & Behavior*, 25 (2), 234-244.
- Fernandes, D. M., & Church, R. M. (1982). Discrimination of the number of sequential events by rats. *Animal Learning & Behavior*, 10 (2), 171-176.
- Fetterman, J. G. (1993). Numerosity discrimination: Both time and number matter. *Journal of Experimental Psychology: Animal Behavior Processes*, 19 (2), 149-164.
- Fetterman, J. G. (1996). Dimensions of stimulus complexity. *Journal of Experimental Psychology: Animal Behavior Processes*, 22 (1), 3-18.
- Fetterman, J. G. (2008). Time and number: Learning, psychophysics, stimulus control, and retention. In E. A. Wasserman & T. R. Zentall (Eds.), *Comparative cognition: Experimental explorations of animal intelligence* (pp. 285-304). NY: Oxford.
- Gibson, J. J. (1960). The concept of the stimulus in psychology. *American Psychologist*, 15, 694-703.
- Gibson J. J. (1966). The problem of temporal order in stimulation and perception. *Journal of Psychology*, 62, 141-149.
- Hirai, S., & Jitsumori, M. (2009). Counting absolute numbers of items, from 1 to 8, in pigeons. *Learning & Behavior*, 37 (4), 365-379.
- Hobson, S. L., & Newman, F. (1981). Fixed-ratio-counting schedules: Response and time measures considered. In M. L. Commons & J. A. Nevin (Eds.), *Quantitative analyses of behavior, Vol. 1: Discriminative properties of reinforcement schedules* (pp. 193-224). Cambridge, MA: Ballinger.
- Honig, W. K. (1993). Numerosity as a dimension of stimulus control. In S. T. Boysen & E. J. Capaldi (Eds.), *The develop-*

- ment of numerical competence: Animal and human models (pp. 61-86). Hillsdale, NJ: Lawrence Erlbaum.
- Keen, R., & Machado, A. (1999). How pigeons discriminate the relative frequency of events. *Journal of the Experimental Analysis of Behavior*, 72 (2), 151-175.
- Lattal, K. A. (1981). Reinforcement contingencies as discriminative stimuli: Implications for schedule performance. In M. L. Commons & J. A. Nevin (Eds.), *Quantitative analyses of behavior: Vol. 1. Discriminative properties of reinforcement schedules* (pp. 113-133). Cambridge, MA: Ballinger.
- Lattal, K. A. (1995). Contingency and behavior analysis. *The Behavior Analyst*, 18 (2), 209-224.
- Nevin, J. A. (1988). Reinforcement schedules and "numerical competence." *Behavioral and Brain Sciences*, 11, 594-595.
- Olthof, A., Iden, C. M., & Roberts, W. A. (1997). Judgments of ordinality and summation of number symbols by squirrel monkeys (*Saimiri sciureus*). *Journal of Experimental Psychology: Animal Behavior Processes*, 23, 325-339.
- Pepperberg, I. M. (1994). Numerical competence in an African gray parrot (*Psittacus erithacus*). *Journal of Comparative Psychology*, 108 (1), 36-44.
- Pliskoff, S. S., & Goldiamond, I. (1966). Some discriminative properties of fixed ratio performance in the pigeon. *Journal of the Experimental Analysis of Behavior*, 9 (1), 1-9.
- Rilling, M. (1967). Number of responses as a stimulus in fixed interval and fixed ratio schedules. *Journal of Comparative and Physiological Psychology*, 63 (1), 60-65.
- Rilling, M. (1993). Invisible counting animals: A history of contributions from comparative psychology, ethology, and learning theory. In S. T. Boysen & E. J. Capaldi (Eds.), *The development of numerical competence: Animal and human models* (pp. 3-37). Hillsdale, NJ: Lawrence Erlbaum.
- Rilling, M., & McDiarmid, C. (1965). Signal detection in fixed ratio schedules. *Science*, 148, 526-527.

- Roberts, W. A. (1997). Does a common mechanism account for timing and counting phenomena in the pigeon? In C. M. Bradshaw & E. Szabadi (Eds.), *Time and behaviour: Psychological and neurobehavioural analyses* (pp. 185-215). Amsterdam: Elsevier.
- Roberts, W. A., & Mitchell, S. (1994). Can a pigeon simultaneously process temporal and numerical information? *Journal of Experimental Psychology: Animal Behavior Processes*, 20 (1), 66-78.
- Roberts, W. A. (2010). Distance and magnitude effects in sequential number discrimination by pigeons. *Journal of Experimental Psychology: Animal Behavior Processes*, 36 (2), 206-216.
- Rumbaugh, D. M., & Washburn, D. A. (1993). Counting by chimpanzees and ordinality judgments by macaques in video-formatted tasks. In S. T. Boysen & E. J. Capaldi (Eds.), *The development of numerical competence: Animal and human models* (pp. 87-106). Hillsdale, NJ: Lawrence Erlbaum.
- Santi, A., & Hope, C. (2001). Errors in pigeons' memory for number of events. *Animal Learning & Behavior*, 29 (3), 208-220.
- Santi, A., Lellwitz, J., & Gagne, S. (2006). Pigeons' memory for sequences of light flashes: Reliance on temporal properties and evidence for delay interval/gap confusion. *Behavioural Processes*, 72, 128-138.
- Seligman, M. E. P., & Meyer, B. (1970). Chronic fear and ulceration in rats as a function of unpredictability of safety. *Journal of Comparative and Physiological Psychology*, 73 (2), 202-207.
- Tan, L., Grace, R. C., Holland, S., & McLean, A. P. (2007). Numerical reproduction in pigeons. *Journal of Experimental Psychology: Animal Behavior Processes*, 33 (4), 409-427.
- Thomas, R.K., Fowlkes, D., & Vickery, J. D. (1980). Conceptual numerosness judgments by squirrel monkeys. *American Journal of Psychology*, 93, 247-257.
- Thomas, R.K., & Lorden, R.B. (1993). Numerical competence in animals: A conservative view. In S. T. Boysen & E. J. Capaldi

- (Eds.), *The development of numerical competence: Animal and human models* (pp. 127-147). Hillsdale, NJ: Lawrence Erlbaum.
- Wesley, F. (1961). The number concept: A phylogenetic review. *Psychological Bulletin*, 58 (5), 420-428.
- Xia, L., & Emmerton, J. (2001). Pigeons (*Columba livia*) learn to link numerosities with symbols. *Journal of Comparative Psychology*, 115 (1), 83-91.
- Xia, L., Siemann, M., & Delius, J. D. (2000). Matching of numerical symbols with number of responses by pigeons. *Animal Cognition*, 3, 35-43.