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ACQUISITION OF A SPATIALLY DEFINED OPERANT WITH DELAYED REINFORCEMENT

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Two experiments investigated the role of an immediate, response-produced auditory stimulus during acquisition, via delayed reinforcement, of a response selected to control for possible unprogrammed, operandum-related sources of response feedback. Experimentally naive rats were exposed to a delayed-food reinforcement condition, specifically a tandem fixed-ratio 1 differential-reinforcement-of-other-behavior 30-s schedule. The response was defined as breaking a photocell beam located near the ceiling at the rear of the operant conditioning chamber. In Experiment 1, rates of photobeam breaking by each rat increased from near zero, regardless of the presence or absence of a tone that immediately followed the response initiating the delay interval. Though not essential, the tone facilitated response acquisition and resulted in more efficient response patterns at stability. Experiment 2 demonstrated that photobeam-breaking response rates under the delayed reinforcement contingency exceeded those in a preceding baseline condition in which no food was delivered. In addition, upon introduction of the delayed reinforcement procedure, correspondence between response patterns and the requirements of the reinforcement schedule increased over baseline levels in the absence of a food contingency. Together with a previous report of Lattal and Gleeson (1990), the present results suggest that response acquisition with delayed reinforcement is a robust phenomenon that may not depend on a mechanically defined response or an immediate external stimulus change to mediate the temporal gap between response and reinforcer.

Key words: acquisition, reinforcement delay, operant behavior, spatial location, rats

Operant responses typically are defined, for laboratory convenience, as the displacement through space of a response lever, key, or similar mechanical operandum. Often such responses are instated by immediately reinforcing successive approximations of the defined response. Once established, responding usually results in both occasional reinforcement and some type of supplementary sensory feedback (e.g., virtually all standard operanda yield a physical change, such as an auditory click of a switch, immediately following the response). Thus, a "typical" operant conditioning experiment might be said to involve (a) a discrete, mechanically defined response; (b) response acquisition via immediate reinforcement; and (c) immediate, response-produced exteroceptive stimuli in addition to the programmed contingencies of reinforcement or punishment.

Deviations from this formula have been reported infrequently, although a few previous experiments have established operant control of rather nonspecific responses using immediate reinforcement. For example, using negative reinforcement procedures, Graf and Bitterman (1963) increased general activity in pigeons and Hoffman and Fleshler (1959) increased the frequency with which pigeons broke a photocell beam with their heads. Using positive reinforcement, Skinner and Morse (1958) established fixed-interval schedule control of wheel running by rats. For measurement purposes, Skinner and Morse arbitrarily defined one response as a half revolution of the running wheel, although the functional unit was time engaged in running (cf. Baum & Rachlin, 1969) and "it is not clear that [a half revolution of wheel turning] is meaningful in describing behavior throughout the [interreinforcer] interval" (Skinner & Morse, 1958, p. 371). Each of these experiments employed operants not defined or measured in terms of the discrete movements of a mechanical operandum. Moreover, the general movement responses were not accompanied by programmed exteroceptive feedback.

Relatively little is known of how reinforcement delay influences the establishment of new

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behavior, regardless of the form of the operant response. In general, reinforcement delay is thought to impede or, at values exceeding a few seconds, prevent acquisition (e.g., Grice, 1948; Munn, 1950). This conclusion is bolstered by the observation that studies purporting to show acquisition under conditions of delayed reinforcement often include some exposure to immediate reinforcers or to other immediate stimulus changes correlated with reinforcement that might mediate the delay to reinforcement. For example, Harker (1956) established responding by placing a food pellet in a slot above a food-deprived rat's response lever; when approaching the pellet the rat thus was likely to first depress the lever, meaning that bar pressing and food consumption were in close temporal proximity on some occasions. In other studies, a stimulus change (such as handling by the experimenter or a brief tone or light) has been correlated with the start of the delay interval (e.g., Lett, 1975; Logan, 1952). Such stimuli may enhance response maintenance through conditioned reinforcing or other mediating effects, precluding interpretations of response acquisition strictly in terms of delayed reinforcement (e.g., Lattal, 1984; Schaal & Branch, 1988; Spence, 1947).

Using delayed reinforcement and no programmed response-produced feedback, Lattal and Gleeson (1990) produced acquisition of responses defined by a variety of mechanical operanda (a standard rat lever, an omnidirectional vertical lever, or a standard pigeon key). Acquisition was defined as an increase in response rates over low but nonzero baselines not resulting from programmed sources of contingent reinforcement (e.g., see Sidman, 1960, pp. 117–119). Experimentally naive rats and pigeons were magazine trained and then exposed to a condition in which responses initiated an unsignaled delay interval that led to food delivery. In several experiments, responses during the delay reset the delay interval, thereby ensuring that responding always was separated temporally from food presentation. Key pecking by pigeons and lever pressing by rats were acquired and then maintained. The effect was robust across several procedural variations, including reinforcement delays as long as 30 s.

It may be important that the responses described by Lattal and Gleeson (1990) were defined by mechanical operanda that required contact by the animal and movement through space. Although Lattal and Gleeson did not program stimulus changes immediately following responses, it still is possible that such changes facilitated response acquisition. For example, key pecks produce the sound of a beak striking plastic, and bar pressing creates the sound of the metal bar moving on its hinges and striking restraints that limit its range of motion. Both types of responses may produce the audible click of a microswitch. Thus, moving the mechanical operandum produced stimulus changes that were directly correlated with reinforcement. Such stimuli were positively correlated with reinforcement in the sense that reinforcers, when they occurred, always followed a response and never followed periods of no responding that were longer than the delay interval.

The present experiments used procedures like those employed by Lattal and Gleeson (1990) to investigate acquisition (as defined above), via delayed reinforcement, of an operant requiring no mechanical operandum. The operant—breaking the beam of a photocell (hereafter called a photobeam-break response)—was of interest because it did not involve contact by the animal with a mechanical device such as a lever and thus was free of the auditory feedback (and perhaps other types as well) an operandum can produce.

EXPERIMENT 1

If immediate, response-produced auditory feedback facilitated response acquisition with delayed reinforcement, as reported by Lattal and Gleeson (1990), then eliminating that feedback should prevent or impede acquisition. In this study, two groups of rats were exposed to contingencies similar to those used by Lattal and Gleeson, with the exception that the response consisted of silently breaking a photobeam rather than pressing a lever. For one group, responses that initiated the delay to reinforcement produced a brief tone, whereas for the other group, responses produced no programmed stimulus change to initiate the delay.

METHOD

Subjects

Twelve experimentally naive Sprague-Dawley female rats, about 120 days old at the start of the experiment, were housed individually and maintained at 70% of their ad libitum body weights during the 20 to 30 days of the experiment (cf. Lattal & Gleeson, 1990). Stable body weights were maintained by supplementing within-session food intake with Purina® Rat Chow at least 1 hr following each session.

Apparatus

Two identical Gerbrands Model G7010 chambers for rats were housed individually in ventilated, sound-attenuating enclosures. Each chamber was 20.5 cm wide by 19.5 cm high by 23.5 cm long, with clear Plexiglas side panels. Photocell assemblies mounted to the side panels detected a horizontal beam 4 cm from the top panels and 8 cm from the back panels of each chamber. Interruption of the photobeam caused a switch in an adjacent room to close, registering a response. For 4 rats, 2 in each group (A8, KA9, KA10, and KA17), the photocell assemblies were Hunter Model 335S, which emitted a beam visible to the human eye. For the remainder of the rats, the units were Lafayette Model 58011, which emitted an infrared beam not visible to the human eye. In principle, any part of the rat's body could break the photocell beam, but observation during sessions suggested that placement of the photocells in the chamber typically required an animal to rear up and break the beam with its head.

The work panel of each chamber contained a rat lever (Gerbrands Model G6312) that required a force of approximately 0.25 N to operate, a feeder dish into which 45-mg standard Noyes pellets could be delivered, and a houselight that remained continuously illuminated during the session. The lever was 8 cm from the floor and was centered on the work panel; lever presses were recorded but had no other programmed effect. The food cup was located to the left of the lever. White noise (about 50 dB) and an electric ventilating fan masked extraneous sounds. Electromechanical equipment in an adjacent room was used to control the experiment.

Procedure

Magazine training was accomplished by first placing each rat into the illuminated chamber with approximately five food pellets in the food cup. When all five pellets had been consumed, a variable-time (VT) 15-s schedule of pellet delivery began. The VT schedule operated until direct observation indicated that 15 consecutive pellets were collected within 2 s of delivery. Immediately following the last pellet delivery, the VT schedule was replaced by one of two conditions.

For rats in the no-tone group, the schedule was changed to a tandem fixed-ratio 1 differential-reinforcement-of-other behavior 30-s (tand FR 1 DRO 30 s) schedule in which a single break of the photocell beam initiated a 30-s interval with no programmed stimulus change. Additional interruptions of the photobeam during the delay reset the interval to 30 s, ensuring an obtained delay equal to 30 s. At the end of the delay interval, a single pellet was delivered into the food cup. The schedule was identical for rats in the tone group, except that the response that met the FR 1 requirement of the tandem schedule also produced a 0.75-s tone. Further responses during the ensuing delay interval did not produce tones. Lever-press responses were recorded but were without consequence.

Each rat was exposed to the contingency of delayed reinforcement for 20 sessions, each lasting 6 hr or until 60 reinforcers were delivered, whichever came first. In early sessions for each rat it was common to reach the 6-hr maximum, but after acquisition, each session typically lasted only 1.5 to 3 hr.

RESULTS

The photobeam-break response was established and maintained in each of the 12 rats. Individual and group data are presented to depict patterns of acquisition and performance at stability. Group means at stability were statistically evaluated using the Mann–Whitney *U* test for nonparametric comparisons of independent groups, except where noted. Patterns of change in behavior across sessions were evaluated using a test of trends described below.

The first column of Table 1 shows the number of response-independent food pellets required by each rat to reach the criterion for collecting food pellets during magazine training. The groups did not differ significantly on this measure, suggesting that the rats in each group received equivalent pretraining.

Figure 1 (top 12 panels) shows response rates (circles) for the rats in each group across

Table 1

Experiment 1: Pellets to criterion in magazine pretraining and time to stability under the contingency of delayed reinforcement. Between-group differences were evaluated using the Mann–Whitney *U* test for nonparametric comparisons of independent groups (bottom row).

	Pellets to criterion in magazine training	Sessions to stability	Time to stability (min)
Tone group			
A2	79	13	1,572
A7	168	11	2,172
A9	95	9	1,642
A12	88	16	2,593
KA9	50	12	2,100
KA17	100	12	2,446
M	96.7	12.2	2,088
No-tone group			
A4	116	20	5,258
A1	75	17	3,748
C18	115	18	4,295
KA14	89	17	2,695
KA10	75	12	1,688
A8	75	16	3,665
M	90.8	16.7	3,555
Mann–Whitney *U* test	$p = .749$	$p = .019$	$p = .025$

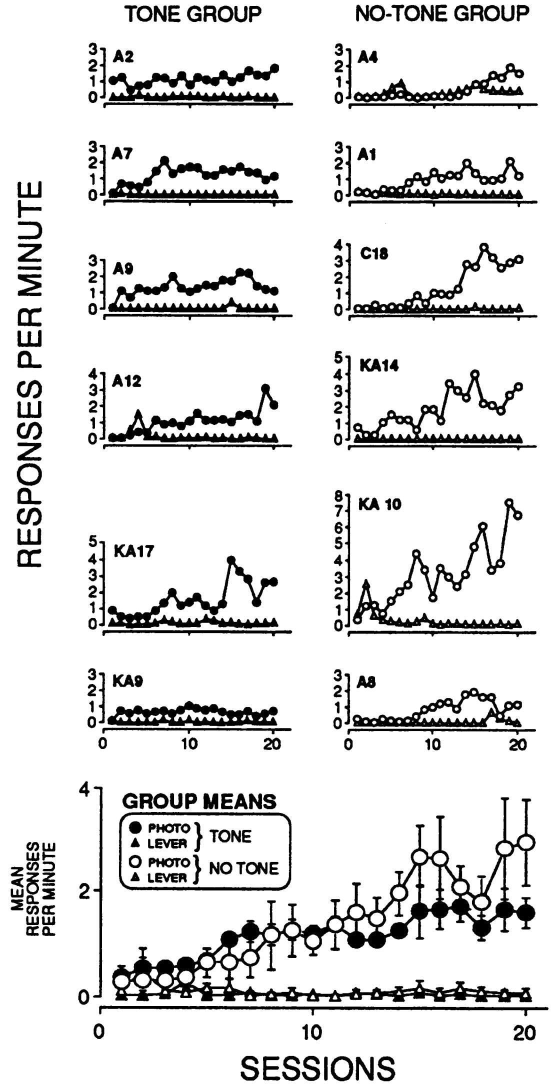

Fig. 1. Experiment 1: Response rates for rats in the tone and no-tone groups. The reinforcement contingency operated on photobeam-break responses. Lever-press responses were ineffective. In mean functions at bottom, vertical bars show ±1 standard error; where bars do not appear, data points are larger than the area covered by the standard error.

the 20 successive sessions of the study. All rats emitted the photobeam-break response and showed rate increases across sessions, indicating that the response was selectively increased for each subject. By contrast, lever-press rates (triangles) tended not to increase systematically across sessions. To facilitate comparisons, the bottom panel of Figure 1 shows the mean rates of responding on successive sessions. Mean rates of photobeam-break and lever-press responding initially were comparable in each group. As indicated in the individual functions, however, only photobeam-break response rates increased across the 20 sessions of observation. The pattern of rate changes was similar for the two groups, although in later sessions rats in the no-tone group (open circles) tended to break the photobeam more frequently than the rats in the tone group (filled circles).

Figure 2 (top 12 panels) shows the reinforcement rate for each rat during successive sessions. Reinforcement rates increased above those in the first session and for most rats appeared to reach asymptote within the 20 sessions of the experiment (the results of formal stability assessments are described below). The bottom panel shows mean rates of reinforcement on successive sessions. Reinforcement rates appeared initially to increase more quickly for the tone group, but by the 20th session rates were comparable for the two groups.

To describe group-specific patterns of behavior change better, response and reinforcement rate functions were compared for the two groups using a test of curvilinear trends amenable to the analysis of nonindependent repeated measures (e.g., Cox & Cory-Slechta, 1987; see Appendix A). Third-order orthogonal polynomial fits were determined for each individual subject's data. The resulting functions provided four descriptors of performance for each dependent variable: a constant (intercept), which is the midpoint of each individual series of observations, and linear, quadratic, and cubic coefficients. These descriptors (Appendix B) were then subjected to group comparison using the Mann–Whitney test.

Possible group differences in the shape of photobeam-break response rate functions, as suggested in Figure 1 (bottom panel), were not corroborated by the test for trends, which showed no statistically significant group differences for any of the coefficients (although the difference based on linear coefficients approached statistical significance, $p = .055$). The same was true for lever-press response rates. To explore the contrast between photobeam-break and lever-press response rates evident in Figure 1, data from the two groups were combined and photobeam-break and lever-press response rate functions were compared using the Wilcoxon signed-rank test for nonindependent scores. The visually apparent difference across response types was statistically significant ($p = .0001$) for all coefficients, providing support for the notion that rates of photobeam breaking, but not lever pressing, changed across sessions (such an outcome is hardly surprising; the polynomial test describes patterns of change, and there was essentially no variance to account for in the lever-press data). Finally, group comparison of reinforcement rate functions yielded statistically significant differences for the constant ($p = .025$) and cubic ($p = .016$) components of the acquisition functions; linear and quadratic components were not statistically different for the two groups.

As additional descriptors of acquisition, the final two columns of Table 1 show the time required by each rat to reach a stable response pattern. Because the DRO component of the tandem schedule could restrict response rates, and food delivery depended as much on the temporal distribution of responding as on response rate, stability was calculated in terms of reinforcement rate. Specifically, responding was considered stable if (a) the difference in mean reinforcement rate across adjacent three-session blocks constituted no more than 10% of the mean reinforcement rate for the 6-day mean, and (b) visual inspection indicated no

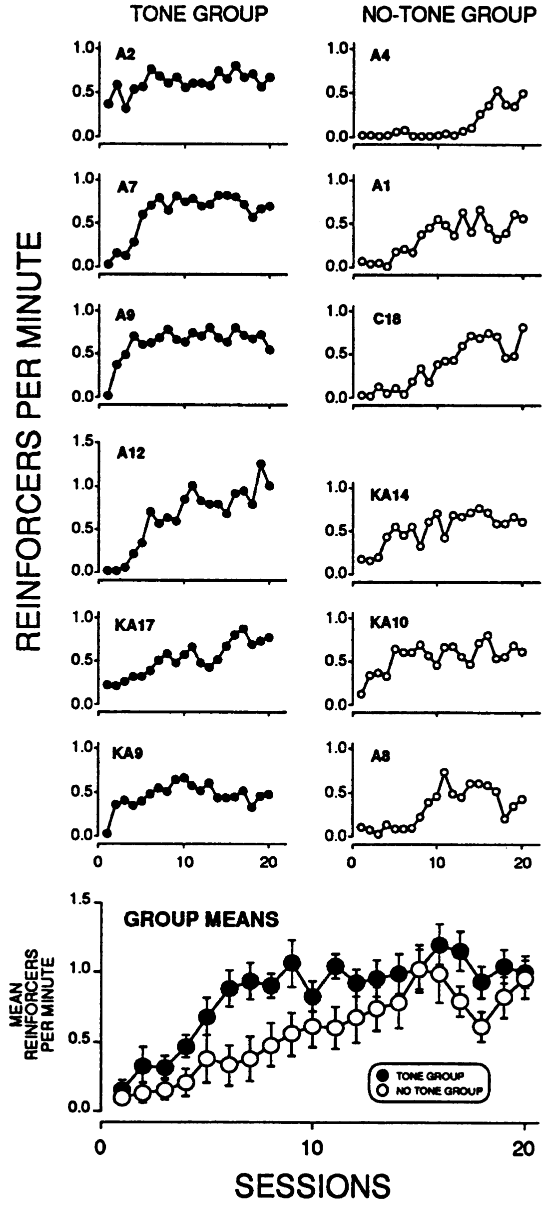

Fig. 2. Experiment 1: Reinforcement rates for rats in the tone and no-tone groups. In mean functions at bottom, vertical bars show ±1 standard error; where bars do not appear, data points are larger than the area covered by the standard error.

Table 2

Experiment 1: Descriptive measures of performance and of response efficiency and schedule control at stability, for rats in the tone and no-tone groups. Data are means of the six sessions on which stability calculations were based. Response rates are for the photobeam-break response on which reinforcement was contingent. Between-group differences were evaluated using the Mann–Whitney *U* test for nonparametric comparisons of independent groups (bottom row).

	Descriptive measures of performance at stability		Measures of response efficiency and schedule control			
	Reinforcers per minute	Responses per minute	Responses per minute out of delay	Responses per minute in delay	Ratio of rates in/out of delay	Responses emitted per reinforcer
Tone group						
A2	0.61	1.06	0.92	1.68	0.55	1.49
A7	0.75	1.63	1.33	2.02	0.66	2.21
A9	0.68	1.33	1.16	1.54	0.75	1.91
A12	0.83	1.26	1.51	1.01	1.50	1.50
KA9	0.58	0.81	0.84	0.80	1.05	1.14
KA17	0.55	1.45	0.83	2.73	0.30	2.65
M	0.67	1.26	1.10	1.63	0.80	1.82
No-tone group						
A4	0.49	1.30	0.49	3.91	0.24	3.35
A1	0.47	1.28	0.66	3.64	0.18	3.16
C18	0.66	2.68	1.08	5.15	0.23	4.17
KA14	0.57	2.87	1.21	5.09	0.24	4.11
KA10	0.62	3.08	1.00	6.47	0.15	4.95
A8	0.58	1.46	0.78	3.02	0.26	2.68
M	0.55	2.11	0.87	4.55	0.22	3.74
Mann–Whitney *U* test	$p = .128$	$p = .109$	$p = .200$	$p = .004$	$p = .004$	$p = .004$

evidence of increasing trend. All subjects, except Rat A4 in the no-tone group, achieved stability by this criterion within the 20 sessions of the experiment. For the purposes of the table and statistical analyses, Rat A4's performance was considered to be stable on Session 20.

Table 1 (second column) shows the number of sessions required for each rat's performance to stabilize. Individual differences were evident but, as suggested in Figure 2, rats in the tone group required fewer sessions, on average, for reinforcement rate to stabilize. Because session duration could vary, the third column of Table 1 shows actual time of exposure to the schedules required by each rat for performance to stabilize. The effect mirrored that for sessions to stability, and the between-group difference in speed of acquisition was statistically significant for both measures.

Thus, a response-produced auditory stimulus influenced the course of acquisition for the photobeam-break response. Consequently, additional comparisons were conducted to examine possible effects of the tone on performance at stability. Table 2 provides measures of performance, response efficiency, and schedule control for each rat at stability. The first two columns show stable reinforcement and photobeam-break response rates, respectively, of each rat. At stability, reinforcement rates for the rats in the tone group tended to be higher, and response rates lower, than those of the no-tone rats, but not statistically so. Thus, on a global level, performance at stability was similar for the two groups.

The remaining columns of Table 2 examine stable response patterns in greater detail, specifically in the context of the tandem FR 1 DRO 30-s schedule. In the tandem schedule, reinforcement rate could be maximized with a single response following quickly after each reinforcer. Long latencies following a reinforcer, or responses during the delay, reduced reinforcement rates from their maximum value. Latency to the first postreinforcement response was not directly recorded, but the response rate outside the delay interval provides an analogous measure (i.e., given that only a single response was required to initiate the delay, higher rates indicate short latencies). Mean response rate outside the delay interval was higher for rats in the tone group than for rats in the no-tone group, but the difference was not statistically significant. The fourth column of Table 2 shows that during the delay, when responding postponed reinforcement, response rates were significantly lower for the tone group. The fifth column provides the ratio of nondelay to delay response rates. The larger the ratio, the more precisely response patterns corresponded to requirements of the tandem schedule. Values generally were higher for the rats in the tone group. Another measure of response efficiency, the mean number of responses per reinforcer (sixth column), also favored the tone group. Group differences for the last two columns were statistically significant.

EXPERIMENT 2

Changes in photobeam-break response and reinforcement rates across sessions in Experiment 1 were consistent with an interpretation based on acquisition due to contingent delayed reinforcement, but other variables may have entered into the effect. Given the absence of an observation period in which food delivery did not occur, it was not possible to determine with certainty for individual subjects whether the increased response rates resulted from operant conditioning or from some other variable, such as adaptation to the experimental chamber over time. In Experiment 2, the introduction of a delayed reinforcement contingency for each subject was preceded by a baseline condition in which photobeam-break responses were recorded and those initiating sham delay intervals produced a tone. In a subsequent condition the tone was followed, after the appropriate delay, by food delivery, replicating the contingency used in Experiment 1.

Experiment 2 also was designed to characterize further the function of the tone used in Experiment 1. At stability, rats in the tone group of Experiment 1 tended to cease responding after the photobeam-break response that produced the tone. Although based on this pattern the tone might be presumed to serve as a discriminative stimulus, it also could have controlled responding in other ways (e.g., by eliciting responses, such as a startle, that were incompatible with the photobeam-break response; Nissen, 1946). In Experiment 2, a discriminative function of the tone could be expected to be manifested as reduced delay-interval response rates during the food-contingency condition. By contrast, if the tone elicited competing responses, delay-interval response rates would also be relatively low during the no-food baseline condition.

METHOD

Subjects and Apparatus

Three experimentally naive Sprague-Dawley female rats, about 120 days old at the start of the experiment, were maintained at 70% of their ad libitum body weights. The apparatus was the same as in Experiment 1. The photocell units used for each rat were Lafayette Model 58011.

Procedure

The pretraining procedure was the same as in Experiment 1. At the completion of pretraining, each rat remained in the chamber for the first session of a no-food condition, during which the experimental arrangement replicated that of the tone group in Experiment 1, except that the food dispenser was disconnected. Photobeam-break and lever-press responses were recorded, with the latter ineffective and the former producing an immediate 0.75-s tone and simultaneously starting a 30-s timer (a sham delay interval). The timer reset with each additional response during its operation, although no further tones were produced during the timer operation. When the timer timed out, no food pellet or other stimulus change occurred, but a pulse was recorded and a new cycle began. This programming arrangement allowed the baseline assessment of correspondence between response patterns and the requirements of the tandem schedule. That is, response rates in and out of the "delay" interval could be computed, as well as the rate at which food reinforcers, if available, would have been produced.

In the subsequent food condition, the pellet dispenser was connected, allowing the pulse at the end of the delay both to deliver a pellet and to be counted. Thus, the schedule was tandem FR 1 DRO 30 s. The no-food and food conditions each lasted 20 sessions.

RESULTS

Figure 3 shows photobeam-break (circles) and lever-press (triangles) response rates of

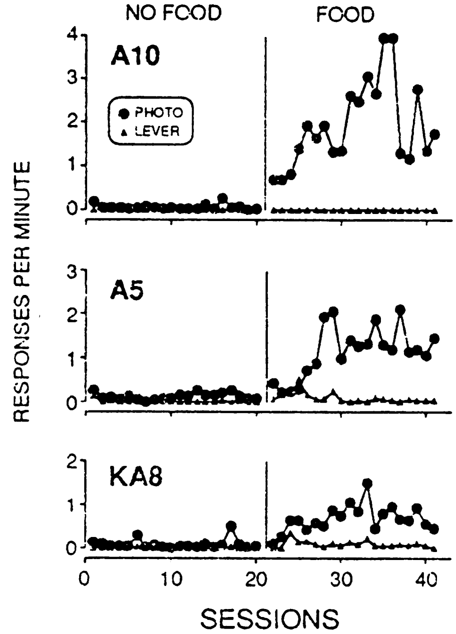

Fig. 3. Experiment 2: Response rates in the no-food and food conditions. The reinforcement contingency operated on photobeam-break responses. Lever-press responses were ineffective.

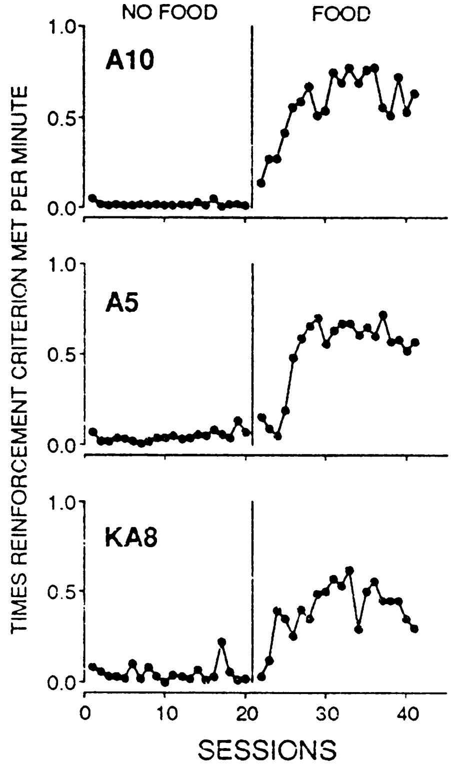

Fig. 4. Experiment 2: Rates at which photobeam-break response patterns met the criterion for reinforcement of the tandem FR 1 DRO 30-s schedule in the no-food and food conditions. The pellet dispenser was disconnected in the no-food condition, and thus no reinforcers were actually delivered.

each rat during each session of the experiment. When photobeam-break responses produced a tone but no food, response rates were near zero for all 3 rats. Photobeam-break response rates increased with introduction of the delayed reinforcement contingency (food condition). Lever pressing increased slightly in 2 rats and not at all in the 3rd.

Figure 4 shows acquisition in terms of the correspondence of photobeam-break response patterns to requirements of the tandem FR 1 DRO 30-s schedule. For each rat, the left panel shows the rate at which the observed response patterns would have produced reinforcers had food been available in the no-food condition (recall that this was assessed by programming the apparatus as if food were to be delivered, with the exception that the pellet dispenser was disconnected; thus, technically speaking, Figure 4 shows pulses per minute sent to the pellet dispenser). The right panel shows actual reinforcement rates in the food condition. Correspondence between photobeam-break response patterns and the schedule requirements was low in the no-food condition and increased markedly in the food condition.

Table 3 illustrates the improvement in correspondence in greater detail. The data in the first column summarize Figure 4, showing that mean rates of correspondence with the reinforcement schedule were low in the no-food baseline and higher in the food condition. The data in the remaining columns show that, relative to the no-food baseline, overall response rates and response rates out of the delay increased, whereas response rates in the delay decreased. That is, when the delayed reinforcement schedule operated, the rats responded after a shorter pause following a reinforcer and were less likely to emit multiple responses once the first postreinforcer response occurred. This effect runs contrary to what would be expected if the tone merely elicited freezing or other responses incompatible with the photobeam-break response.

DISCUSSION

Operant classes are distinguished according to their effects on the environment. The functional nature of this definition renders details of response topography unimportant in most circumstances as long as the relevant consequences are produced (e.g., Skinner, 1935; but see Pliskoff & Gollub, 1974). Accordingly, a response defined spatially for laboratory purposes is likely to share many critical features with one defined in terms of the discrete movements of an operandum, such as bar pressing. For example, both types of responses occur more frequently following reinforcement, become topographically stereotyped under some kinds of contingencies, and occur less frequently under extinction (e.g., Hefferline, Keenan, & Harford, 1959; Notterman & Mintz, 1965; Schwartz, 1980). The present results demonstrate another shared feature in that a spatially defined operant was acquired and maintained with delayed reinforcement in a manner much like that demonstrated previously with operandum-defined responses (Lattal & Gleeson, 1990).

Despite the many similarities, however, spatially defined responses differ structurally from operandum-defined responses in ways that may be experimentally useful. At least two important differences derive from the physical nature of operanda. First, operanda define at what point the organism must contact the environment. As distinctive features of an otherwise sterile experimental environment, response levers or illuminated keys may attract "exploratory" or other presumably nonoperant behavior (depending on the species) that ultimately increases the organism's interaction with programmed contingencies. Moreover, in some species manipulation of the operandum may produce odor cues that attract future behavior not exclusively under operant control (Hughes, 1991). Such effects might be unwanted in careful studies of response acquisition, especially because the prevalence and persistence over time of the presumably nonoperant behavior remain to be fully explored (e.g., Poucet, Durup, & Thinus, 1988). Second, operanda may produce immediate stimulus changes contingent on a response (e.g., movement of the operandum or the click of a microswitch) in the interval separating response and reinforcer. Such stimuli can mediate the effects of programmed contingencies (e.g., Schaal & Branch, 1988) or provide independent sources of immediate reinforcement (e.g., "sensory reinforcement"; Barnes & Baron, 1961)—effects of potential concern when the interest is in direct relations between behavior and delayed reinforcement.

Table 3

Experiment 2: Comparison of performances in the no-food and food conditions. Data are means from the final six sessions per condition. Response rates are for the photobeam-break response on which reinforcement was contingent. The first column shows the mean times per minute each rat met the criterion for reinforcement specified by the tandem FR 1 DRO 30-s schedule (note that the schedule did not operate in the no-food condition).

	"Reinforcers" per minute	Responses per minute	Responses per minute out of delay	Responses per minute in delay
A5				
No food	0.06	0.19	0.06	3.88
Food	0.59	1.36	0.90	2.08
A10				
No food	0.02	0.07	0.02	4.47
Food	0.62	2.03	0.97	3.84
KA8				
No food	0.06	0.13	0.06	1.73
Food	0.43	0.69	0.57	1.12

Spatially defined responses may minimize nuisance variables inherent in mechanical operanda, thus improving the prospects for studying behavior in the absence of such variables (and for manipulating these variables directly, as in our Experiment 1). In the present experiments, a photobeam-break response requiring no operandum was acquired and maintained with delayed reinforcement even in the absence of a response-produced tone (no-tone group of Experiment 1). By virtue of increased control over operandum-related stimuli, this outcome adds confidence to the conclusion from a previous study that delayed reinforcement can produce operant acquisition (Lattal & Gleeson, 1990).

Of course, eliminating an operandum does not eliminate all potential sources of immediate stimulus change. Proprioceptive and visual stimulus changes may still accompany the response (these would be difficult to control completely even through surgical alteration of the subject), and conceivably may contribute to response demarcation and differentiation (e.g., Spence, 1947). Nevertheless, our findings are noteworthy in the extent to which they prompt skepticism toward traditional assumptions (a) that substantial reinforcement delay prevents response acquisition (e.g., Grice, 1948; Munn, 1950) and (b) that gross, exteroceptive response-produced stimulus changes are integral to reinforcement effects. In the latter case, for example, Bolles (1988) proposed that removal of the microswitch from an operandum "so that it yields no immediate response feedback" causes "the abundant bar pressing that we are apt to take for granted [to] totally collapse" (p. 449). The present results suggest otherwise.

Our results also join those of many others in showing that response-produced stimuli can have functional significance. In Experiment 1, rats acquired a spatially defined operant more quickly in the presence of a response-produced tone than in its absence, as indicated by two measures of the speed of response development (Table 2) and by a trend analysis that confirmed group differences in the shape of acquisition curves based on reinforcement rates. In addition, after extended exposure to the reinforcement contingency, rats tended to emit the photobeam-break response more efficiently when it produced a tone (Table 2). That is, at stability rats in the tone group responded less frequently during the resetting delay period of the schedule and, as a result, emitted fewer responses per reinforcer. Direct observation suggested a tendency among rats in the tone group to move toward and remain near the food cup after emitting the response that initiated the delay, whereas the movement of rats in the no-tone group during the delay was more variable. These patterns indicate that response-produced stimuli can facilitate both acquisition and maintenance (for analogous demonstrations in other contexts see Schaal & Branch, 1988; Williams, 1991). However, acquisition of the photobeam-break response by all 6 rats in the no-tone group reminds us that exteroceptive, response-produced stimulus change may not be essential to the establishment of new behavior.

Increases in response rate observed in the present research can be labeled with confidence as acquisition due to delayed reinforcement only after nonoperant effects have been ruled out. For example, it is possible (but in our view unlikely) that food delivery per se elicited increases in general activity that could account for increased photobeam breaking. In a study of lever pressing, Lattal and Gleeson (1990, Experiment 4) found that a delayed reinforcement contingency produced acquisition, but an equivalent rate of food presentation arranged independently of responding did not. In the present experiments, photobeam breaking increased markedly and systematically after a food contingency was introduced, but lever pressing, which served as a control response by virtue of its lack of correlation with food delivery, changed only marginally across sessions. There is no obvious reason to expect that food-elicited increases in general activity would differentially affect lever pressing and photobeam breaking, although future research could investigate such a possibility through a control condition involving response-independent food delivery.

Another interpretation of the results of Experiment 1 is that increases in photobeam breaking resulted from adaptation to the chamber (i.e., increased time in the chamber was correlated with increased exploration, one result of which was increased tripping of the photobeam). This possibility is inconsistent with three effects: a generally observed positive correlation between stimulus novelty and rat exploratory behavior (Dember, 1956; Montgomery, 1953); the failure in Experiments 1 and 2 of an alternative measure of activity level (lever pressing) to increase systematically in conjunction with the photobeam-break response; and the failure of photobeam-break responding in Experiment 2 to change systematically, across 20 sessions of baseline, until the delayed reinforcement contingency was effected. The last observation, in particular, directly precludes an interpretation of the present studies in terms of adaptation to the chamber.

The procedure involving a brief auditory stimulus at the onset of the delay interval (tone group) is similar to a procedure for pigeons described by Schaal and Branch (1988). Following exposure to variable-interval schedules of immediate reinforcement, a nonresetting delay was effected prior to each food presentation. The reinforced response initiated a delay interval and a concurrent 1-s change in the stimulus transilluminating the response key.

After 1 s, the visual stimuli reverted to those present in the nondelay portion of the procedure. Response rates were considerably higher under the briefly signaled delay procedure than during an unsignaled delay procedure. These findings with long-maintained responding may be similar to those seen for acquisition in the present experiments.

With several qualifications, Schaal and Branch (1988) suggested that the brief immediate stimulus at delay onset in their experiment might function to control responding in a manner similar to a conditional stimulus in an autoshaping paradigm (Brown & Jenkins, 1968). It is conceivable that other stimuli, such as the click of a microswitch, might function analogously to maintain responding in a procedure like that described by Lattal and Gleeson (1990). The present experiments render such an account of response acquisition with delayed reinforcement implausible because an operandum-free response was established in the absence of a correlated stimulus in the no-tone group of Experiment 1. Moreover, rats were used as subjects, and rats demonstrate autoshaping only under some rather unique conditions. Whether rats' responding can be autoshaped when a 30-s trace interval is in effect, as in the present experiments, has not been investigated. Given the results of Experiment 1, our data and those of Lattal and Gleeson (1990) seem more reasonably accounted for in terms of response–reinforcer dependency that establishes a weak (because of the long delay duration) positive correlation between photobeam-breaking activity of the rat and the reinforcer.

The present results are also analogous to those of Pear and Legris (1987), who continuously tracked head movements of pigeons and immediately reinforced successive approximations of movement to an arbitrarily defined target location. The procedure involved titrating the target area so that it expanded whenever the animal was out of the area for a specified time period and contracted when the animal was in the target area. Frequency of contact with the target location increased when contact was differentially reinforced. The present procedures differ from those of Pear and Legris (1987) in that contact with a target location was neither shaped nor immediately reinforced. Although movement of our rats was not systematically recorded (beyond frequency of photobeam breaks), the animals were observed to move about the chamber alternating between raising up on their hind legs and moving on all four legs to a new location, where they again raised up with their heads above the level of the photobeam. The Pear and Legris procedure seems useful in measuring and tracking response differentiation in ways far beyond the modest informal observations obtained in the present experiments (see also Kernan, Mullenix, & Hopper, 1989). However, the present results suggest that a titrating contingency of immediate reinforcement and precise shaping of the response are not necessary for the differentiation of a response defined in terms of its spatial location.

Responses in natural settings often produce consequences after unsignaled delays of considerable duration. For example, Lovell (1958) described an instance of baiting by a green heron. The bird was observed capturing fish attracted to small pieces of bread that the bird earlier had picked up and dropped onto the water. Despite obvious differences between the heron's behavior and that of our rats, it is possible that both might arise through a similar process. In the case of the rat, movements likely to break a photocell beam are part of the general, undifferentiated activity pattern of the species. A tone produced by such movements initially has no special relation to food presentation, and as a result does not control behavior (e.g., the no-food baseline of Experiment 2). However, two complementary effects occur when the response produces both tone and delayed food. First, delayed reinforcement begins to select the response from the animal's general activity pattern (no-tone group of Experiment 1); second, the tone, via its correlation with reinforcement, exerts supplementary control that may enhance the primary reinforcement process (tone group). Similarly, picking up objects and dropping them is part of the general activity pattern of many species, including herons. Behavior of this sort produces immediate stimulus changes (including, in the present example, the sight of bread on the water) that initially can have no special relation to the subsequent appearance of fish near the surface. When, after a delay, fish do appear, however, the behavior of dropping bread onto water may be strengthened and thus selected from the bird's general activity. As the behavior is repeated, response-produced stimuli (including possibly proprioceptive ones) could quickly acquire properties that would enhance the primary reinforcement process. The analogy is speculative but plausible. Thus, in addition to shedding light on the theoretical issues discussed in the preceding paragraphs, the present study may be useful in suggesting how seemingly complicated behavior in natural settings (such as that of the green heron) could be established by ontogenic contingencies of reinforcement.

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APPENDIX A

Pedhazur (1982) describes computations for calculating orthogonal third-order polynomial fits to individual subjects, as used in Experiment 1. Other polynomial fits may be considered, but Cox and Cory-Slechta (1987) report that in a number of experiments, third-order polynomials have been proven to account for most of the variance in individual subject functions. For group comparison, the individual coefficients in Experiment 1 were subjected to the Mann–Whitney test for nonparametric comparisons of independent groups. Data sets with special properties may require different statistical techniques (see Cox & Cory-Slechta, 1987; Edgington, 1980). Here, a statistically significant outcome for one of the coefficients indicates a between-group difference in the shape (as described by the specific coefficient) of acquisition functions. This method of characterizing patterns across within-subject repeated observations is preferable to time series analysis because it focuses on the existence of long-term trends rather than short-term fluctuations, and is also preferable to repeated measures analyses of variance because it makes no assumptions about the theoretical properties of underlying distributions (Cox & Cory-Slechta, 1987). Moreover, the orthogonal coefficients can be tested independently, and each provides an indication of a specific characteristic on which functions may differ.

APPENDIX B

Coefficients from orthogonal third-order polynomial fits to individual functions for rates of two responses and of reinforcement contingent on the photobeam-break response.

	Photobeam-break response rate					Lever-press response rate		
Subject	Constant	Linear	Quadratic	Cubic	VAC	Constant	Linear	Quadratic
Tone group								
A2	1.149	.035	.003000	.0000927	.47	.026	−.00200	−.0002434
KA9	0.671	.003	−.004000	.0004119	.45	.034	.00100	.0000381
KA17	1.579	.126	.001000	−.0010000	.56	.127	.00300	−.0010000
A9	1.333	.049	−.007000	−.0002792	.54	.023	.00300	−.0003320
A7	1.221	.040	−.011000	.0004112	.69	.001	−.00038	.0000666
A12	1.065	.099	.000445	.0010000	.75	.128	−.01800	.0010000
No-tone group								
KA14	3.179	.280	.007000	.0020000	.76	.305	−.05300	.0070000
A4	1.355	.197	.006000	−.0020000	.89	.010	.00100	−.0000387
A1	0.931	.075	−.005000	.0002586	.68	.050	−.00800	.0010000
C18	0.464	.085	.009000	.0002757	.92	.319	.01900	−.0010000
KA10	0.821	.079	−.005000	−.0020000	.80	.056	.01200	.0010000
A8	1.826	.139	−.005000	−.0010000	.64	.000[a]	.00000[a]	.0000000[a]
Mann–Whitney *U* test	$p = .873$	$p = .055$	$p = .333$	$p = .296$		$p = .631$	$p = .810$	$p = .374$

Note. VAC = Variance accounted for by the orthogonal third-order polynomial equation in a multiple regression analysis of each individual function.

[a] No trend analysis was possible because Subject A8 made no lever-press responses during the study; values of zero have been assigned in lieu of actual coefficients.

APPENDIX B *(Continued)*

Lever-press response rate		Reinforcement rate				
Cubic	VAC	Constant	Linear	Quadratic	Cubic	VAC
.0000333	.11	.618	.011	−.001	.0000931	.46
−.0000124	.01	.462	.008	−.003	.0003220	.75
−.0000391	.21	.528	.030	−.001	.0000617	.82
−.0001780	.13	.634	.016	−.004	.0003281	.78
−.0000073	.23	.611	.028	−.005	.0002965	.89
.0004195	.14	.653	.052	−.003	.0003332	.87
−.0010000	.49	.530	.024	−.003	−.0000092	.75
−.0000292	.12	.143	.025	−.003	.0000035	.85
−.0001916	.70	.348	.028	−.002	−.0000606	.74
.0000750	.18	.376	.041	−.001	−.0003908	.87
−.0001162	.27	.554	.017	−.002	.0003032	.66
.0000000[a]	.00[a]	.336	.025	−.003	−.0010000	.76
$p = .336$		$p = .025$	$p = .688$	$p = .503$	$p = .016$	