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An Analysis of Coordinated Responding

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An Analysis of Coordinated Responding

Brian Katz

Dissertation submitted
to the Eberly College of Arts and Sciences
at West Virginia University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in
Psychology

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Keywords: social behavior, cooperation, coordination, pigeons

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ABSTRACT

An Analysis of Coordinated Responding

Brian Katz

Experimental analyses of coordinated responding (i.e., cooperation) have been derived from a procedure described by Skinner (1962) in which reinforcers were delivered to a pair of subjects (a dyad) if both responded within a short interval, thus satisfying a mutual-reinforcement contingency. Although it has been suggested that this contingency enhances rates of temporally coordinated responding, limitations of past experiments have raised questions concerning this conclusion. The present experiments assessed three of those limitations by holding the schedule of reinforcement (Experiment 1: fixed-ratio 1; Experiment 2: variable-interval 20 s) constant (1) across phases and (2) between dyad members, and (3) varying the number of keys across which responses could be coordinated. Greater percentages of coordinated responding were observed under mutual- than under independent-reinforcement phases in most conditions. The one exception during the one-key condition of Experiment 1 appeared to be a consequence of variability during the independent-reinforcement phase. Furthermore, coordination percentages decreased systematically with increasing response options. The present results thus confirm that mutual-reinforcement contingencies induce higher rates of temporally coordinated responding than independent-reinforcement contingencies. The results further indicate that the effects of mutual-reinforcement contingencies can be influenced by the environmental context in which those contingencies operate.

Keywords: social behavior, cooperation, coordination, pigeons

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An Analysis of Coordinated Responding

As a social species, interactions between individuals are fundamental to human life. In fact, given how ubiquitous group contingencies are in social settings, they may be greater determinants of behavior in such contexts than individual contingencies. Thus, an understanding of the antecedents and consequences that govern social interaction is necessary for a comprehensive experimental analysis of human behavior and an understanding of why people behave as they do (Skinner, 1953).

One such class of social behavior that has been subjected to experimental analysis is *cooperation*. Colloquially, cooperation describes the behavior of two or more organisms responding together to accomplish some task and achieve some goal. Although this is sufficient for everyday discourse, defining behavior in the context of future events is incompatible with a functional analysis of behavior governed by the identification of antecedents and past consequences. To this end, it may prove useful to pursue an experimental analysis of *coordinated responding* rather than cooperation.

Experimental analyses of coordinated responding have been conducted using procedures in which reinforcers are distributed equally to a pair of co-actors, provided that their behavior is synchronized (Hake & Vukelich, 1972, 1973). Three limitations, however, have impeded analyses of the coordinated behavior produced under these procedures. Changes in multiple variables across phases of the experiments, differences in the schedule functionally in place between pairs of cooperating subjects, and the absence of requirements for spatial coordination all have raised questions regarding whether functional control of coordinated responding has been demonstrated conclusively. Furthermore, coordinated responding predominantly has been studied under ratio schedules of reinforcement, with comparatively little attention given to

interval schedules. Demonstrating functional control of coordinated responding under a wider range of conditions would attest to its generality. The following literature review considers these limitations of previous procedures in turn and then is followed by two experiments designed to address the documented procedural limitations and explore coordinated responding under different schedules of reinforcement.

Literature Review

From Cooperation to Coordination

Experimental analyses of cooperation have involved procedures in which, “(1) ...the reinforcers of both individuals are at least in part dependent on the responses of the other individual, and (2) ...the procedure allows such responses, designated as cooperative responses, to result in an equitable division of responses and reinforcers” (Hake & Vukelich, 1972, p. 333). Hake and Vukelich (1972) further stated that individual instances of cooperation need not be *quid pro quo* or *reciprocal* (i.e., include a comparable allocation of responses and reinforcers). Instead, it is only over an extended time frame in which several opportunities to cooperate occur that the distribution of responses and reinforcers must be equitable across cooperating co-actors. Therefore, *cooperation* may be defined as responses from two or more co-actors that together produce reinforcers, with the stipulation that these responses and reinforcers are distributed equitably over an undefined but extended time frame.

Although this definition provides a useful starting point for an experimental analysis of cooperation, it suffers from two shortcomings. First, as outlined by Hake and Vukelich (1972), to constitute cooperation the responses made and reinforcers earned by two or more organisms eventually must be equal. This then raises the question of what to call situations in which responses, reinforcers, or both never are equated. According to Hake and Vukelich’s definition,

two organisms that either earned different numbers of reinforcers for the same number of responses or performed different numbers of responses for the same number of reinforcers would not have cooperated. Cooperation can be said to have occurred only once distributions of responses and reinforcers across co-actors have been equated at a later point in time (thereby ensuring reciprocity). The stipulation that cooperation only may occur when responses and reinforcers are distributed perfectly equitably over time is restrictive, and eliminates from consideration situations in which, although reciprocity never is obtained, responses from two organisms still are required for reinforcement.

The second shortcoming stems from the use of the word “cooperation” as the label for this class of joint behavior by two or more organisms. The teleological, lay definition of cooperation given above is laden with intention, and therefore is at odds with a functional analysis of behavior governed by the identification of antecedents and consequences.

It thus may prove fruitful to replace cooperation with a different, not goal-oriented, term. Coordination may serve as an appropriate replacement given that it simply describes what is occurring without asserting a reason. Were coordination to be adopted, attention would be shifted from an experimental analysis of cooperation to one of *inter-organism coordinated responding* (hereafter referred to as *coordinated responding*), which in turn is defined as two or more responses, each from a different organism, that together produce reinforcers for both co-actors.

Early Coordination Research

With a working definition of coordination, it is possible for the class of behavior thus defined to be measured and subjected to empirical study. One of the earliest behavior-analytic assessments of coordinated responding was a demonstration by Skinner (1962). Pairs of pigeons

(hereafter referred to as *dyads*) each were given access to three vertically mounted response keys. Reinforcers were delivered to both dyad members whenever both responded on a correspondingly positioned pair of keys within 100 ms of one another. If responses from dyad members were directed to different pairs of keys or occurred more than 100 ms apart, then reinforcers were not delivered.

Skinner (1962) therefore enacted a *mutual-reinforcement contingency* (Tan & Hackenberg, 2016) with a fixed-ratio (FR) 1 schedule. A mutual-reinforcement contingency specifies that only *temporally coordinated responses* from dyad members can be followed by the delivery of a reinforcer. Temporally coordinated responses are defined as pairs of alternating responses (i.e., one from each dyad member) that occur within a short time of one another. Thus, only pairs of responses that meet the criteria for another active schedule are reinforced. For instance, if a 500-ms mutual-reinforcement contingency were implemented along with a fixed-interval (FI) schedule, a reinforcer would only be delivered if, after the interval elapsed, both subjects responded within 500 ms of each other.

Using variations of this procedure, mutual-reinforcement contingencies have been suggested to establish temporally coordinated responding (e.g., de Carvalho et al., 2018, 2019, 2020; Łopuch & Popik, 2011; Tan & Hackenberg, 2016). For instance, Łopuch and Popik (2011) reinforced pairs of nose pokes by rat dyads that satisfied a 2000-ms mutual-reinforcement contingency (i.e., two responses, one from each dyad member, must occur within 2000 ms of one another) according to an FR 1 schedule. With these two contingencies in effect, coordinated responding was established and maintained across a series of conditions in which either an opaque or mesh barrier was inserted into the chamber to separate the subjects during the coordinated task. *Coordination ratios* (the ratio of pairs of responses that satisfied the mutual-

reinforcement contingency to all other responses during a session) were lowest when the opaque barrier was in place and highest when no barrier separated the dyad members. The authors concluded that social contact potentiated coordinated responding.

Functional Control of Coordination

Although it appears that mutual-reinforcement contingencies may induce coordinated responding, functional control of coordinated responding by such contingencies has not been demonstrated unequivocally. Skinner (1962) claimed that the apparatus and contingencies previously described “sufficed to build cooperative behavior without further attention [once dyad members were paired]”, but did not report empirical findings (i.e., coordination ratios) by which to measure the amount of coordination observed. Furthermore, behavior resulting from the described conditions was not compared with that from a control phase under which a mutual-reinforcement contingency was not present. Similarly, Łopuch and Popik (2011) also did not include a control phase in which the mutual-reinforcement contingency was suspended. Thus, both experimenters failed to show that the presence of a mutual-reinforcement contingency was the sole cause of the observed coordinated responding. Instead, it is possible that what appeared to be coordinated responding was, in fact, a consequence of the incidental synchronization of each dyad member’s individual response patterns under the same FR 1 schedule of reinforcement. This phenomenon, termed “byproduct mutualism,” previously has been proposed as an explanation for responding that, at first glance, appears to be coordinated (Chalmeau et al., 1997; Visalberghi et al., 2000).

To determine if mutual-reinforcement contingencies truly induce coordinated responding as opposed to byproduct mutualism, Tan and Hackenberg (2016) investigated coordinated responding in rats in both the presence and absence of a mutual-reinforcement contingency using

an ABACA reversal design. In the A phase, both an FR 1 schedule and a 500-ms mutual-reinforcement contingency were in effect. Thus, only pairs of temporally coordinated responses counted towards satisfying the requirements of the FR 1 schedule. Conversely, in the B and C phases the mutual-reinforcement contingency was removed and reinforcers were delivered simultaneously to both dyad members independently of temporally coordinated responding according to either a variable-time (VT) or variable-interval (VI) schedule, respectively. To ensure that reinforcement rates did not change across phases, the intervals for each VT and VI schedule were yoked to the inter-reinforcer intervals (IRIs) of the preceding A phases.

Comparisons across phases revealed that coordination ratios were significantly larger in the A phase. Furthermore, alternating inter-response times (IRT; IRTs started by one dyad member and ended by another) shorter than 500 ms primarily occurred when the mutual-reinforcement contingency was in effect. Thus, Tan and Hackenberg (2016) concluded that coordinated responding was under the control of the mutual-reinforcement contingency.

Such control also was suggested when temporally coordinated responses were reinforced according to a schedule of intermittent reinforcement (de Carvalho et al., 2018). In a mutual-reinforcement (A) phase, a 500-ms mutual-reinforcement contingency was enacted along with an FR 6 schedule of reinforcement. Conversely, in a yoked control (B) phase, a VI schedule with intervals yoked to the IRIs of the preceding A phase was enacted. As with Tan and Hackenberg (2016), coordination ratios were significantly larger in the A phases when the mutual-reinforcement contingency was in effect. Thus, de Carvalho et al. (2018) concluded that coordinated responding was sensitive to the prevailing contingencies of reinforcement.

Limitations of Prior Designs

Based on the findings of Tan and Hackenberg (2016) and de Carvalho et al. (2018), mutual-reinforcement contingencies may serve as a promising avenue for an experimental analysis of interorganism coordination. Three methodological aspects of their procedures, however, raise questions regarding whether conclusions of functional control are sound. These procedural limitations are examined further in the following sections.

Global Changes Across Phases

As described previously, Tan and Hackenberg (2016) delivered reinforcers according to an FR 1 schedule in their mutual-reinforcement phase, and either a VT or VI schedule in the two yoked control phases. Similarly, de Carvalho et al. (2018) reinforced temporally coordinated responses according to an FR 6 schedule in the mutual-reinforcement phase, and reinforced responses independently of coordination according to a VI schedule during the yoked control phase. The use of either a yoked VT or yoked VI schedule during these control phases equated reinforcement rates to those of the mutual-reinforcement phases, ensuring that changes in coordinated responding could not be attributed to changes in reinforcement rate across phases.

Given that the reinforcement schedule changed across phases however, the differences in coordination ratios cannot be taken as definitive evidence of changes in coordinated responding. Instead, the discrepancies may have been, at least in part, a consequence of the shift in the schedule of reinforcement, as different schedules of reinforcement may engender different levels of coordinated responding. In a subsequent experiment, de Carvalho et al. (2018) established a 500-ms mutual-reinforcement contingency along with different schedules of reinforcement to determine if temporally coordinated responding is “a social behavioral unit under the functional control of contingencies of reinforcement” (p. 122). Across conditions, temporally coordinated responses were reinforced according to FR 1, FR 10, or variable-ratio (VR) 10 schedules of

reinforcement. Coordination ratios were significantly greater under intermittent schedules of reinforcement (i.e., VR 10 and FR 10) compared to continuous schedules of reinforcement (i.e., FR 1), and under VR schedules compared to FR schedules.

Additionally, under the FR 10 schedule temporally coordinated responses followed a break-and-run pattern, whereas under the VR 10 schedule they occurred at a steady, constant rate. These patterns are similar to those observed when individual organisms respond under FR and VR schedules, respectively (Crossman et al., 1987, 1974; Felton & Lyon, 1966; Ferster & Skinner, 1957; Lattal, 1991; Powell, 1968). Thus, de Carvalho et al. (2018) concluded that schedules of reinforcement influence both individual and coordinated responding similarly, and that therefore patterns and rates of coordinated responding may vary across other schedules of reinforcement as well.

Given these differences across schedules, the lower coordination ratios in the control phases of both Tan and Hackenberg (2016) and de Carvalho et al. (2018) may be the result of the shift to a VI schedule of reinforcement. As response rates of individual subjects are substantially lower on VI than VR schedules (Davison & McCarthy, 1988; Ferster & Skinner, 1957) and, as illustrated by de Carvalho et al., schedules of reinforcement influence both individual and coordinated responding similarly, the possibility that levels of coordinated responding are larger under ratio schedules than interval schedules cannot be ignored. Coordination under FR and VI schedules with yoked reinforcement rates was explored directly by de Carvalho et al. (2019), who reported consistently higher rates of coordinated responding under the former than the latter, and unsystematic differences in coordination ratios across the two schedules. Given these differences in coordinated performance, control over coordinated responding has not been established unequivocally. For such control to be demonstrated, both reinforcement rate and the

schedule of reinforcement would need to be held constant across phases while altering only the presence of the mutual reinforcement contingency.

This was accomplished by de Carvalho et al. (2019), who reinforced responding according to the same VI schedule across mutual-reinforcement and independent-reinforcement control phases. Greater coordination ratios occurred during phases in which the mutual-reinforcement contingency was in effect, which the authors argued supported their prior findings by demonstrating functional control of the mutual-reinforcement contingency over coordination. This design, however, like that of de Carvalho et al. (2018), included simultaneous changes in two variables across phases. During independent-reinforcement phases, reinforcers were delivered to both subjects simultaneously only after a response from each satisfied the programmed VI schedule. Although this ensured that, as in the mutual-reinforcement phase, both dyad members received reinforcers at the same rate, it also introduced unsignaled delays to reinforcement for one dyad member – whichever completed the VI schedule first – that varied in duration from trial to trial. Unsignaled delays also were characteristic of the mutual-reinforcement phases, but those delays consistently were at most 0.5 s – the duration of the mutual-reinforcement contingency – which have been shown to increase response rates moderately when following VI schedules (Arbuckle & Lattal, 1988; Lattal & Ziegler, 1982; Richards, 1981; Sizemore & Lattal, 1978). Conversely, in the independent-reinforcement phase, the unsignaled delays could be longer and more variable. Given that delays greater than 0.5 s decrease response rates (Arbuckle & Lattal, 1988; Lattal, 2010; Richards, 1981; Sizemore & Lattal, 1978), it is possible that differences in delays to reinforcement across phases influenced the reported coordination ratios.

Therefore, control over coordinated responding has yet to be established conclusively as no comparisons exclusively between phases with and without a mutual-reinforcement contingency have been conducted. To accomplish this, the schedule of reinforcement, rate of reinforcement, and delay to reinforcement all would need to be held constant as the presence of the mutual-reinforcement contingency was altered.

Individual Schedule Differences Between Subjects

As mutual-reinforcement contingencies selectively reinforce pairs of temporally coordinated responses, dyad members in the mutual-reinforcement phases of past experiments (e.g., de Carvalho et al., 2018; Tan & Hackenberg, 2016) responded according to the same ratio schedule of reinforcement and earned reinforcers at approximately the exact same time. In the VI control phases however, the mutual reinforcement contingency was removed, and thus temporally coordinated responses were not required for reinforcement. Instead, the first response by either dyad member that satisfied the requirements of the VI schedule produced a reinforcer for both members. Thus, as in the mutual-reinforcement phase, reinforcers were delivered at the same point in time for both subjects, but the dyad members' responses were not controlled by the same schedule of reinforcement.

When arranged in a procedure requiring coordinated responding, dyad members reportedly adopted a *leader-follower* dynamic in which one co-actor (the leader) either responded at a higher rate than the other (e.g., de Carvalho et al., 2018; Tan & Hackenberg, 2016) or initiated coordinated responses (e.g., Hake & Vukelich, 1973; Skinner, 1962; Tan & Hackenberg, 2016). An early account of this disparity between dyad members was reported by Skinner (1962), who observed that:

In general, there was a division of labor with respect to the two tasks [satisfying the mutual-reinforcement contingency]. One pigeon (the “leader”) explored – that is, it struck the three buttons in some order.... The other pigeon (the “follower”) struck the button opposite that being struck by the leader (p. 533).

As the coordinated task was learned over several successive training trials, coordinated responses came to be initiated predominantly by one pigeon in the dyad directing responses to each of the three response keys. Just as this pigeon adopted the role of the “leader,” the other dyad member came into the role of the “follower” by making responses to the same key as the leader and completing coordinated responses.

Similar dynamics among dyad members also were reported by Tan and Hackenberg (2016) and de Carvalho et al. (2018). In both experiments, one dyad member consistently responded at a higher rate than the other across both mutual-reinforcement and control phases. Additionally, Tan and Hackenberg noted that these disparities in response rate were linked to the initiation and completion of temporally coordinated responses, as “high-rate responders tended to initiate, whereas low-rate responders tended to complete the reinforced sequences” (p. 16). As these differences in response rates between dyad members persisted throughout both the mutual-reinforcement and VI control phases, it is possible that in the latter phase only responses from the leader were reinforced according to a VI schedule. Reinforcers were delivered following the first response from either dyad member that met the requirements of the VI schedule, meaning that the leader, with its substantially higher response rate, likely was the member to respond first after the interval elapsed and produce reinforcement according to the VI schedule. Because these reinforcers were delivered at the same time to both subjects, the follower with its lower response rate likely began to receive reinforcers independently of responding according to a VT schedule.

The notion that the programmed VI schedule instead began to function as a VT schedule for the lower-response-rate rat is supported by Tan and Hackenberg's (2016) observations of individual response frequencies for each dyad member. The overall frequency of responding for the follower in each dyad substantially decreased following the transition from the mutual-reinforcement phase to the VI control phase. As coordination requires responding from both subjects, a cessation in responding by one subject will bring about a sharp decline in levels of coordinated responding. Such declines, however, would not reflect a specific decrease in coordination. Therefore, given the overall decrease in responding by one dyad member in the VI control phases, the declines in coordination in such phases cannot be attributed definitively to the removal of the mutual reinforcement contingency. This is the second limitation concerning why control of coordinated responding has not been shown. For control to be demonstrated, coordinated responding would need to decrease during control phases as individual responding by both dyad members persisted.

This pattern of results was found by de Carvalho et al. (2019) who, as described in the previous section, reinforced responding according to the same VI schedule across mutual-reinforcement and independent-reinforcement control phases. Because responses from both dyad members were required for reinforcement during independent-reinforcement phases, individual responding by both dyad members was maintained even as rates of coordinated responding and coordination ratios decreased. Although the requirement of a response from both dyad members during the independent-reinforcement phase dealt with the discrepancy in schedules across dyad members described previously, it also introduced the confound of variable, unsignaled delays to reinforcement for one dyad member as described in the previous section. To demonstrate functional control over coordinated responding, reinforcers produced during independent-

reinforcement phases would need to be delivered immediately and according to the same schedule of reinforcement across dyad members. This could be accomplished by holding the schedule of reinforcement constant across mutual-reinforcement and control phases, as with de Carvalho et al. (2019), but enacting two completely independent schedules of reinforcement during the control phase as opposed to a single schedule for both dyad members. This method of scheduling independent reinforcement is yet to be explored.

Absence of Spatial Coordination

There are at least two ways that two discrete responses may be coordinated. One is for responses to be synchronized based on the passage of time – *temporal coordination*. For two responses to be temporally coordinated, a certain minimum or maximum amount of time must pass between them. Responses also can be synchronized spatially – *spatial coordination*. For two responses to be spatially coordinated, they must each occur at a specific location.

Tan and Hackenberg (2016) and de Carvalho et al. (2018, 2019) enacted a mutual reinforcement contingency in which reinforcement depended on the temporal coordination of two dyad members' responses. The chambers used in these three experiments were designed for programming temporal coordination and thus only included one response lever each.

Consequently, all recorded responses necessarily were spatially coordinated because there were no other operanda on which responses could occur to produce reinforcers. Thus, although Tan and Hackenberg and de Carvalho et al. stated that their experimental goals were to demonstrate control of coordinated responding, it is more precise to say that they attempted to demonstrate control only of temporally coordinated responding.

Spatial coordination is a prominent component of many social interactions that may be considered cooperative. For instance, consider a family that has moved into a new home and now

is rearranging their furniture. Although certain items like lamps, chairs, or end tables are small enough to be moved by one person, others like couches, beds, and dressers are too heavy. These pieces of furniture only can be moved to their new locations if the family members work together to carry them. To move a heavy couch, the individuals who will carry it must (1) position themselves at opposite ends of the couch and then (2) lift at the same time. This synchronization of responding in space and time constitutes spatial and temporal coordination, respectively. If either does not occur then lifting the couch (i.e., cooperation) will be impossible. Given the myriad situations in which reinforcement is dependent on spatial coordination in addition to or in place of temporal coordination, the failure to examine spatial coordination in experimental analyses of coordinated responding reflects a fundamental limitation of the scope of past experiments. Both temporal and spatial coordination must be subjected to experimentation for a comprehensive analysis of coordinated responding.

To assess both temporal and spatial coordination simultaneously, and thus demonstrate coordinated responding, dyad members each would need more than one operandum on which to respond. With its three pairs of response keys, the previously described apparatus designed by Skinner (1962) fits this requirement and thus provides a means of assessing both temporal and spatial coordination concurrently. Using this design in tandem with the control phases proposed by Tan and Hackenberg (2016) and de Carvalho et al. (2018, 2019) – with the adjustments noted in the preceding two sections – would allow for a more comprehensive analysis of the effects of a mutual-reinforcement contingency on coordinated responding.

Statement of the Problem

Despite nearly 60 years of research on coordinated responding, functional control of such has not been demonstrated conclusively. Skinner (1962) trained two pigeons to each peck, “at the

same time” (p. 532), the same pair of response keys from an array of options, and thus claimed to have demonstrated both temporal and spatial coordination. No empirical data were reported, however, nor was a control phase included in which coordination was not required for reinforcement as a means of comparison. Although subsequent experiments (de Carvalho et al., 2018, 2019; Tan & Hackenberg, 2016) addressed these shortcomings of Skinner’s design and purportedly showed functional control of coordinated responding, as the literature reviewed in the preceding sections outlined, at least three procedural limitations of those experiments limit the conclusions that may be drawn.

First, differences in the schedules of reinforcement according to which responses were reinforced across mutual-reinforcement and control phases means that any changes in coordinated responding cannot be attributed definitively to the presence or absence of the mutual-reinforcement contingency. Second, the contingencies enacted during independent-reinforcement control phases differed between dyad members and in some cases only maintained responding by one subject. Thus, the declines in coordinated responding observed when the mutual-reinforcement contingency was removed could not be attributed to decreases in coordination specifically, as they may have been a side effect of extinction of the responding of one dyad member. Even when these two concerns were addressed by holding the schedule of reinforcement constant across phases and between dyad members (i.e., de Carvalho et al., 2019), variable, unsignaled delays to reinforcement during the control phase may have been responsible for the decreases in coordinated responding that occurred. Finally, past assessments of coordination have focused on temporal coordination exclusively at the expense of a systematic assessment of spatial coordination as described by Skinner, leaving unanswered questions regarding coordinated responding across multiple, topographically distinct responses. Empirical

assessments of coordinated responding with multiple response options have not been reported, nor have the potential effects of the number of response options on amounts of coordination been parametrically evaluated.

The purpose of the present experiments, therefore, was threefold. First, by incorporating the control phases proposed by Tan and Hackenberg (2016) and de Carvalho et al. (2018, 2019) – with the modifications outlined above – to Skinner’s (1962) design, the effects of a mutual-reinforcement contingency on coordinated responding according to a schedule of continuous reinforcement was assessed. Second, the limitations of assessments of coordinated responding under VI schedules (i.e., de Carvalho et al., 2019) were addressed to assess the generality of the effects of a mutual-reinforcement contingency on coordinated responding. Third, coordination across topographically distinct responses was investigated as a function of a systematic change in the number of available response options.

Experiment 1

Experiment 1 was designed to (1) further assess whether the mutual reinforcement contingency or byproduct mutualism underlies coordinated responding on an FR 1 schedule by including appropriate control procedures, and (2) empirically evaluate the effects of the number of response options on levels of coordinated responding.

Method

Subjects

Six mature male White Carneau pigeons were maintained at 80% of their free-feeding weight. Each was housed in a separate cage in a vivarium under a 12:12-hr light/dark cycle and had continuous access to water and health grit in their home cages.

Apparatus

A single operant chamber enclosed in a 113-cm by 61-cm sound-attenuating, ventilated enclosure was used (see Figure 1). A transparent plastic partition (A) running lengthwise through the center of the chamber separated it into two equal-sized left and right compartments. Positioned at the front of each compartment was an aluminum work panel. A bend in that panel at a 55-degree angle created an approximately 14-cm-wide portion (the *response panel*) perpendicular with the central divider, and an approximately 30.5-cm portion (the *feeder panel*) angled away from the center of the chamber. Three 2.5-cm response keys (B) were mounted vertically on the response panel and were visible from both compartments. A fourth key (C), unused in this experiment and therefore not described further, was mounted on the feeder panel. Each key required a force of approximately 0.15 N to operate and could be transilluminated red, yellow, or green. The top pair of keys was transilluminated red, the middle pair yellow, and the bottom pair green.

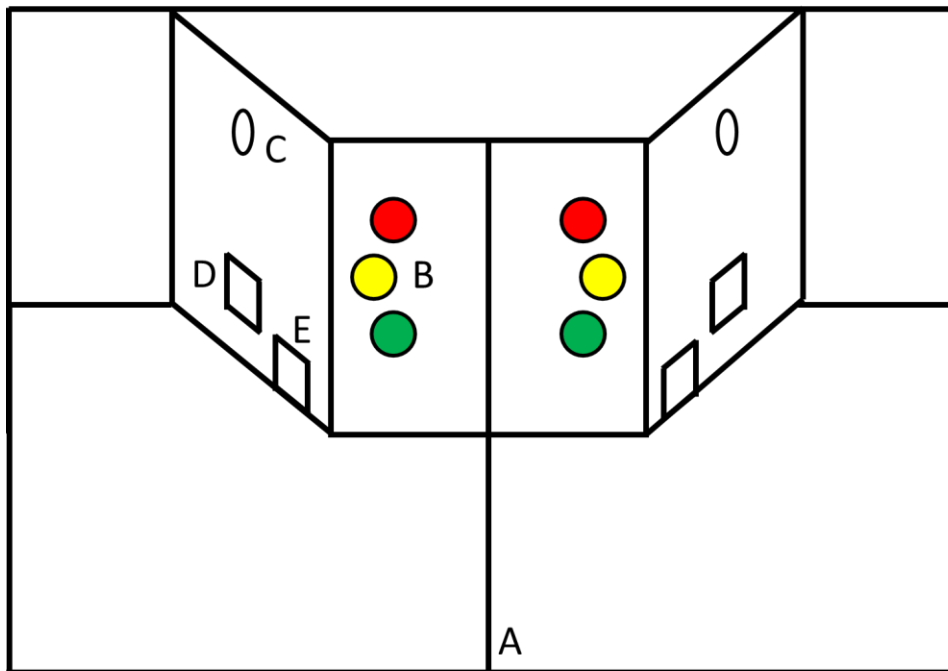
Reinforcement was 3-s access to Purina Nutri-Blend™ pellets delivered from a standard food hopper (D) accessible through an approximately 5-cm by 5-cm aperture located on the feeder panel. Each compartment in the chamber had its own feeder and aperture for food access. Two houselights (E), one in each compartment, were on throughout each session except during food presentations when the hopper was illuminated instead. Contingencies were programmed, and data recorded, using a desktop computer operating with Med-PC® software and interface equipment located in a room adjacent to the one housing the chamber.

Procedure

The six pigeons were paired to form three dyads for the duration of the experiment. Each member of a dyad was assigned to one of the two compartments in the chamber (left or right) and completed all sessions in that compartment. Sessions occurred seven days a week at

Figure 1

A diagram of the operant chamber that will be used for these experiments.



Note. The above figure is not to scale. The chamber was divided into two equally sized compartments by a central transparent barrier (A). A work panel in each compartment was bent to create a response panel perpendicular to the central divider and a feeder panel that met the response panel at a 55-degree angle. Three choice keys (B) were located on each response panel and were visible from both compartments. A fourth, unused, key (C) was located on the feeder panel. An aperture through which reinforcers were delivered (D) and houselight (E) also were located on each feeder panel.

approximately the same time each day and were preceded by a 3-min blackout in the chamber to minimize the effects of handling on responding. After the blackout, the start of each session was signaled by the onset of the houselight and choice keys. All sessions ended after 30 reinforcer deliveries to each dyad member.

Training. Both members of a dyad were placed in their respective compartments simultaneously and individually exposed to an FR 1 schedule of reinforcement. During each trial (comprised of the time between two reinforcer presentations) of these sessions the FR 1 schedule was in effect on only one of the three keys in each compartment. The key with the schedule in effect varied semirandomly across trials so that an equal number of reinforcers was delivered for responses to each key. The FR 1 schedule was in effect for at least 10 sessions, and until (1) there were no increasing or decreasing trends in response rate over the last three sessions and (2) none of the final five sessions contained either the minimum or maximum response rate observed during these sessions (cf. Tan & Hackenberg, 2016).

Assessment of Independent Variables. Dyads were exposed to a series of four *conditions* with differing numbers of transilluminated choice keys, each with reversals between independent- (A) and mutual- (B) reinforcement *phases* (described below). Across conditions, a different number of pairs of choice keys (one, two, or three) were transilluminated during sessions. The order of these conditions, the arrangement of independent- and mutual- reinforcement phases within each reversal design, and the number of sessions comprising each manipulation for each dyad are shown in the top half of Table 1. Transitions between phases occurred when (1) at least 10 sessions had been conducted and (2), across the final four sessions, the average coordination percentages (see the Data Analysis section below) of the first and last two sessions were within 5% of the grand mean of these four sessions (cf. Sidman, 1960). There

Table 1

Number of keys and order of phases for each of the reversal designs in Experiments 1 and 2

Experiment	Dyad	1st Condition			2nd Condition			3rd Condition			4th Condition			5th Condition		
		Number of Keys	Phase Sequence	Number of Sessions	Number of Keys	Phase Sequence	Number of Sessions	Number of Keys	Phase Sequence	Number of Sessions	Number of Keys	Phase Sequence	Number of Sessions	Number of Keys	Phase Sequence	Number of Sessions
1	824/2215	3	ABA	15, 10, 16	1	ABA	21, 10, 27	2	ABA	10, 11, 15	3	ABA	10, 12, 13	-	-	-
	8964/19841	3	AB	12, 10	1	ABA	23, 16, 23	2	ABA	12, 10, 19	3	ABA	10, 10, 11	-	-	-
	4079/7472	3	AB	12, 7	1	ABA	26, 11, 13	2	A	11	-	-	-	-	-	-
2	19222/19957	1	BAB	15, 15, 10	2	ABA	10, 11, 10	3	ABA	10, 10, 11	2	ABA	14, 10, 11	-	-	-
	18057/11829	1	BAB	10, 15, 10	2	ABA	16, 10, 11	3	ABA	13, 10, 11	2	ABA	10, 12, 11	-	-	-
	18390/21055	1	BAB	15, 16, 11	2	ABA	10, 10, 11	3	ABA	11, 10, 11	3	ABA	10, 13, 11	3	ABA	11, 10, 11

were four exceptions to the stability criteria and sequence of phases outlined above. During the mutual-reinforcement phase of the three-key condition for Dyad 4079-7427, only seven sessions were conducted before behavior extinguished and the phase was terminated. For that same dyad, the full sequence of phases at the two-key condition was not completed due to the death of one pigeon. Finally, neither Dyad 8964-19841 nor 4079-7472 finished the full sequences of phases at the three-key condition due to an absence of changes across phases.

Sessions consisted of 30 trials (each defined as the time between two reinforcer presentations). Reinforcers were delivered on an FR 1 schedule only for pecks on a preselected pair of keys (hereafter labeled the *active pair*). The active pair was selected semirandomly at the beginning of each trial so that each of the three pairs of keys served as an active pair on one third of the trials in a session. Depending on the condition, none, one, or both (corresponding to the one-, two-, and three-key conditions, respectively) of the other pairs of keys were transilluminated concurrently with the active pair. Regardless of condition, responses to the other two pairs of keys, transilluminated or not, had no programmed consequences.

Independent-Reinforcement Phase (A). Key-peck-produced reinforcers arranged according to the FR 1 schedules in effect on each key within the active pair were delivered independently of the other dyad member's key pecks. That is, coordinated responses were not required for reinforcement. On each trial a reinforcer was delivered to a dyad member following the first response directed to a choice key within the active pair, independent of the other member's responding.

Mutual-Reinforcement Phase (B). On each trial the first pair of responses (i.e., one from each member of a dyad) to the active keys that occurred within 500 ms of each other (de Carvalho et al. 2018, 2019; Tan & Hackenberg, 2016) procured the reinforcer. Thus, once

reinforcers were arranged by the FR 1 schedule on a given trial, they were delivered to both dyad members only after they each responded on their respective active key within 500 ms of one another. Once a trial began, the reinforcer remained available until this requirement was fulfilled.

Data Analysis. Total responses made and reinforcers earned by each dyad member were divided by the total session time to yield each member's response and reinforcement rates for a given session. Furthermore, a *coordination percentage* (cf., coordination ratio; de Carvalho et al., 2018) representing the relative frequency of coordination was calculated for each session by dividing the total number of coordinated responses (pairs of alternating responses from each dyad member that occurred within 500 ms of one another) by the total number of responses throughout the session that *could have been coordinated* and multiplying by 100.

The number of responses that *could have been coordinated* were required to calculate coordination percentages because the FR 1 schedules for dyad members in the independent-reinforcement phase were independent of one another. As a result, it was possible for one dyad member to respond on a given key while that same key was not transilluminated in the other dyad member's compartment. During all three key conditions, this could occur if one dyad member responded while the other was consuming a reinforcer or already had finished the session. Additionally, during the one- and two-key conditions, this was a possibility if dyad members were on different trials with different arrangements of transilluminated keys (during the three-key condition all three keys were transilluminated on every trial). So as not to artificially deflate the coordinated percentage by including in the calculation these responses that could not possibly have been coordinated, they were subtracted from the total number of responses to yield the total number of responses that could have been coordinated. The total number of coordinated

responses then was divided by this number and multiplied by 100 to yield the coordination percentage.

Results and Discussion

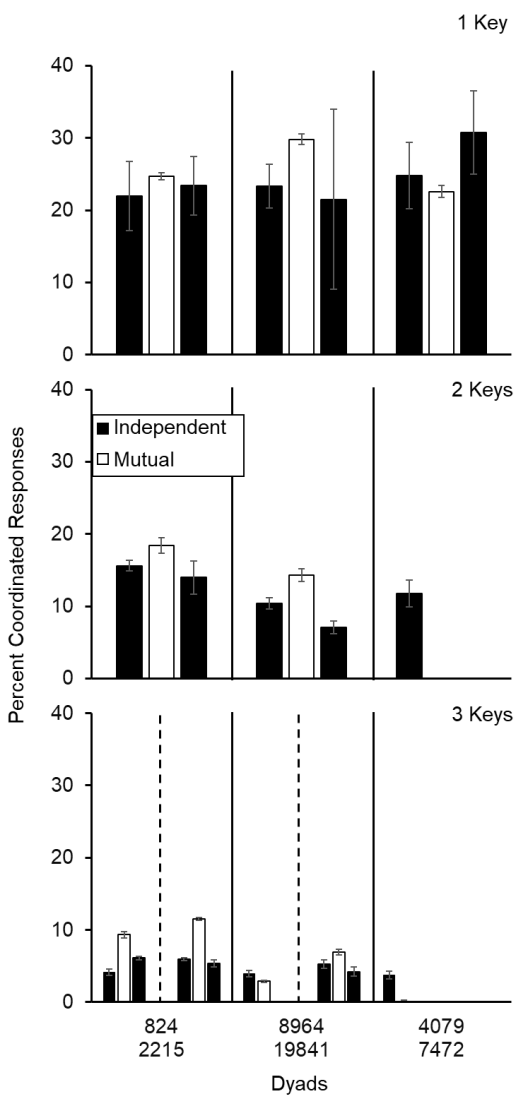
Results from Experiment 1 are shown in Figures 2 through 7. For all but Figure 5, bars represent the mean of a given dependent measure from the final four sessions of a given phase (Figures 2, 3, and 4) or condition (Figures 6 and 7). In all figures, error bars – when present – represent ± 1 standard error of the mean for those same four sessions. Details regarding Figure 5 are outlined below.

Effects of the Mutual-Reinforcement Contingency

Changes in Coordination Percentages. Figure 2 shows changes in coordination percentages for all three dyads as a function of the presence or absence of the mutual-reinforcement contingency. During the one-key condition (top panel), two different relations between mean coordination percentages across mutual-reinforcement (white bars) and independent-reinforcement phases (black bars) occurred. For two dyads (824-2215 and 8964-19841), mean coordination percentages during mutual-reinforcement phases (24.7-29.8%) were larger than those during corresponding independent-reinforcement phases (21.5-23.4%). Conversely, for the third dyad (4079-7472), coordination percentages were lower during the single mutual-reinforcement phase (22.6%) than during either the preceding or following independent-reinforcement phase (24.8% and 30.8%, respectively). For all three dyads, however, variability in coordination percentages (expressed as ± 1 standard error of the mean) during independent-reinforcement phases completely encompassed that of the mutual-reinforcement phase. Thus, it cannot be stated conclusively that coordination percentages during the

Figure 2

Coordination percentages for each dyad in Experiment 1 as a function of the presence or absence of the mutual-reinforcement contingency.



Note. Bars represent mean coordination percentages from the final four sessions of a phase, and error bars represent ± 1 standard error of the mean for those same sessions. Data from the one-, two-, and three-key conditions are shown in the top, middle, and bottom panels of the figure, respectively. Solid vertical lines separate data from different dyads, whereas dashed vertical lines, when present, separate initial and secondary replications of the conditions.

mutual-reinforcement phase were greater than – or, in the case of the third dyad, less than – those during the independent-reinforcement phase.

During the two-key condition (middle panel), larger coordination percentages occurred during mutual-reinforcement phases than during corresponding independent-reinforcement phases for both dyads that completed this condition. Across the dyads 14.3-18.4% of responses were coordinated during the mutual-reinforcement phases, and only 7.1-15.6% of responses were during the independent-reinforcement phases.

The same general pattern of results obtained during the two-key condition was replicated during the three-key condition (bottom panel). For three of the five sequences, greater coordination percentages occurred during mutual-reinforcement phases (6.9-11.5%) than during corresponding independent-reinforcement phases (4.1-6.1%). For the first exposure for Dyad 8964-19841, however, the coordination percentage from the independent-reinforcement phases (3.9%) exceeded that from the mutual-reinforcement phase (2.9%). On replication of the sequence for this dyad, the coordination percentage from the mutual-reinforcement phase (6.9%) was, as with other dyads, greater than those from the immediately preceding and following independent-reinforcement phases (5.2% and 4.2%, respectively). For Dyad 4079-7472, coordination percentage from the independent-reinforcement phases (3.8%) exceeded that from the mutual-reinforcement phase (0.15%). This was because coordinated responding completely extinguished after only seven mutual-reinforcement phase sessions because Pigeon 7472 ceased responding.

Comparison to Previous Findings. Results from the one-key condition failed to replicate those previously reported by Tan and Hackenberg (2016) and de Carvalho et al. (2018) as coordination percentages during the mutual-reinforcement phase were not substantially greater

than those from the independent-reinforcement phase. For two of the three dyads (824-2215 and 8964-19841) this was due to the substantial variability in coordination percentages observed during independent-reinforcement phases. The implications of this variability, which appears to be a consequence of pairing independent FR 1 schedules with the one-key condition, on conclusions and measurement of coordinated responding will be explored further in the General Discussion.

During the two- and three-key conditions, overall a greater percentage of coordinated responses occurred during mutual- than independent-reinforcement phases. This was true of both dyads that completed the two-key condition and for three of the five replications at the three-key condition. Given that, in contrast to previous experiments, delays to reinforcement were eliminated from the independent-reinforcement phase and the schedule of reinforcement was held constant across phases, differences in coordinated responding cannot be attributed to changes in these two variables. The present results, therefore, support the assertion that coordinated responding during mutual-reinforcement phases was not a consequence of byproduct mutualism, and that coordinated responding is sensitive to the mutual reinforcement contingency. Furthermore, the replication of this finding at both the two- and three-key conditions both extends upon the findings from Tan and Hackenberg (2016) and de Carvalho et al. (2018, 2019) and supports the observations reported by Skinner (1962) by illustrating how mutual-reinforcement contingencies can be used to reinforce spatial coordination in addition to temporal coordination.

Reinforcement- and Response-Rate Considerations. Reinforcement rates across phases were not equated because, in order to address the first two limitations noted in the introduction, the schedule of reinforcement was held constant across phases and delays to

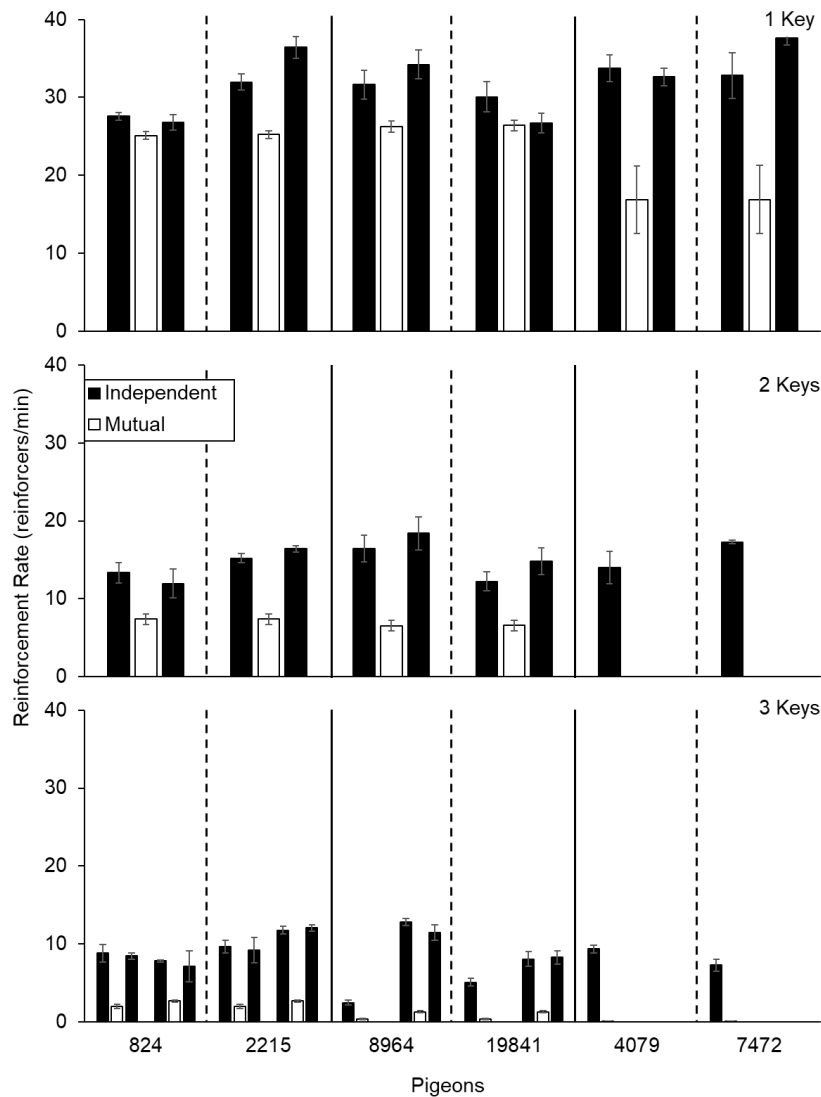
reinforcement during independent-reinforcement phases were eliminated. Changes in reinforcement rates across phases for all six pigeons at all three key conditions are shown in Figure 3. Reinforcement rates during mutual-reinforcement phases consistently were lower than those from immediately preceding and following independent-reinforcement phases. Therefore, the previously described increases in coordination percentages during mutual-reinforcement phases at the two- and three-key conditions cannot be attributed to increases in reinforcement rates, which in turn supports the conclusion that mutual-reinforcement contingencies lead to greater levels of coordinated responding.

Broadly, these declines in reinforcement rates cannot be attributed to declines in responding by either one or both dyad members during mutual-reinforcement phases. In Figure 4 response rates are plotted as a function of the presence or absence of the mutual-reinforcement contingency under all key conditions for all six pigeons. For 18 of the 20 sequences with at least one independent- and mutual-reinforcement phase, response rates during mutual-reinforcement phases were comparable to those during corresponding independent-reinforcement phases. The only exceptions to this pattern were Pigeons 4079 and 7472 at the three-key condition, both of which responded at lower rates during mutual- than independent-reinforcement phases. This was because no coordinated responses occurred during mutual-reinforcement phases for this dyad, and thus key pecking extinguished for Pigeon 7472.

As described in the introduction, in past experiments, the use of a single VI schedule during the independent-reinforcement phase for both dyad members may have contributed to declines in coordinated responding during this phase. In the present experiment, two distinct VI schedules were used to address this limitation. Because the two schedules were independent of one another, dyad members continued to earn reinforcers immediately upon satisfying the

Figure 3

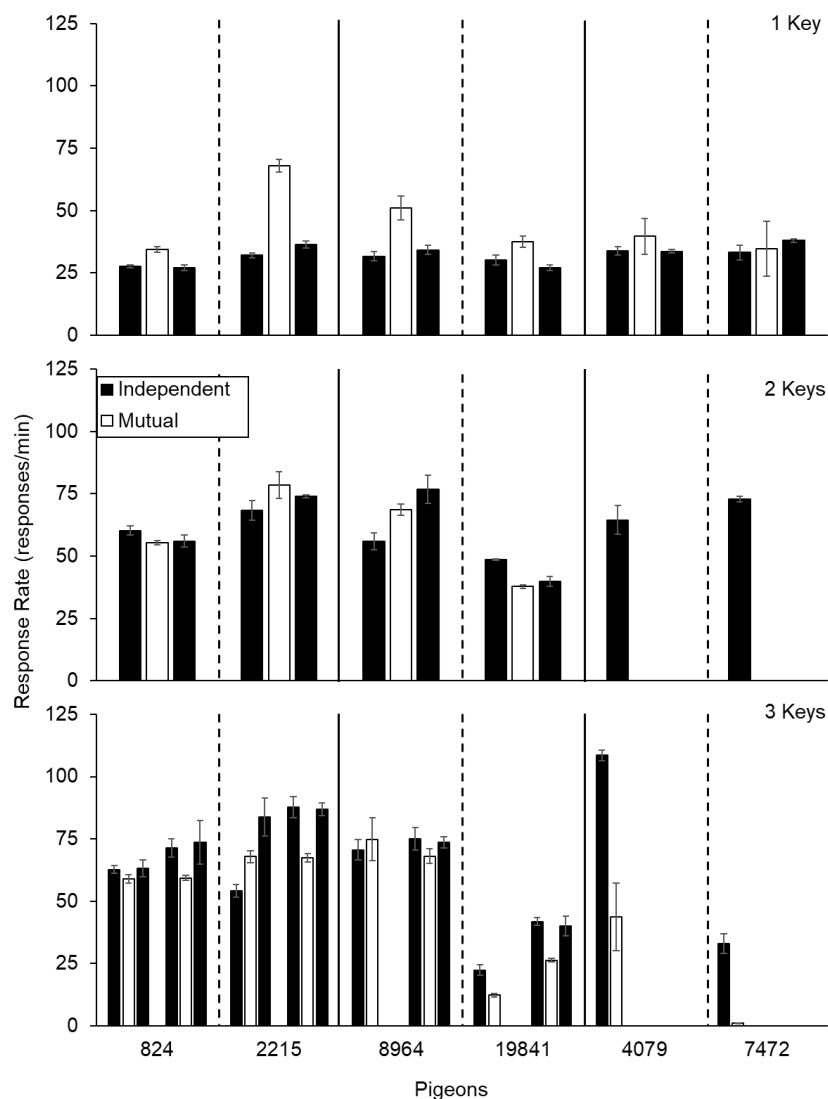
Reinforcement rates for each pigeon in Experiment 1 as a function of the presence or absence of the mutual-reinforcement contingency.



Note. Bars represent mean reinforcement rates from the final four sessions of a phase, and error bars represent ± 1 standard error of the mean for those same sessions. Data from the one-, two-, and three-key conditions are shown in the top, middle, and bottom panels of the figure, respectively. Solid vertical lines separate data from different dyads and dashed vertical lines separate data from different pigeons within the same dyad.

Figure 4

Response rates for each pigeon in Experiment 1 as a function of the presence or absence of the mutual-reinforcement contingency.



Note. Bars represent mean response rates from the final four sessions of a phase, and error bars represent ± 1 standard error of the mean for those same sessions. Data from the one-, two-, and three-key conditions are shown in the top, middle, and bottom panels of the figure, respectively. Solid vertical lines separate data from different dyads and dashed vertical lines separate data from different pigeons within the same dyad.

programmed schedule requirements as in the mutual-reinforcement phase. Thus, no unsignaled delays to reinforcement occurred during independent-reinforcement phase sessions. Furthermore, during the two- and three-key conditions in the present experiment, lower coordination percentages (Figure 2) and similar response rates for both dyad members (Figure 4) occurred during independent-reinforcement phases compared to mutual-reinforcement phases. Thus, declines in coordinated responding during independent-reinforcement phases cannot be attributed to the prevention of coordination when one dyad member stops responding, but to a decrease in coordinated responding specifically as a consequence of the absence of a mutual-reinforcement contingency.

Coordination Magnitude. Coordination percentages from mutual-reinforcement phases during the one-key condition (25.7% on average across all dyads) were slightly larger than those obtained during the mutual-reinforcement phases previously reported by Tan and Hackenberg (2016; 18.6% on average) and de Carvalho et al. (2018, 2019; 20.3% and 20.6%, respectively). Conversely, coordination percentages from the individual-reinforcement phase of the present one-key condition were 24.3% on average across all dyads – substantially greater than the 2.9% (Tan & Hackenberg, 2016), 5.5% (de Carvalho et al., 2018), or 10.6% (de Carvalho et al., 2019) reported by those investigators. The implications of this disparity in independent-reinforcement phase coordination percentages across experiments will be addressed further in Experiment 2.

Effects of Keylight Consistency Across Trials. As stated in the Method section, the active pair of keys on each trial was determined semirandomly to ensure that, during each session, an equal number of reinforcers were earned for responses to each key. The order in which keys served as members of the active pair – and thus were transilluminated during the one- and two-key conditions – however, was not held constant across sessions. Therefore, during

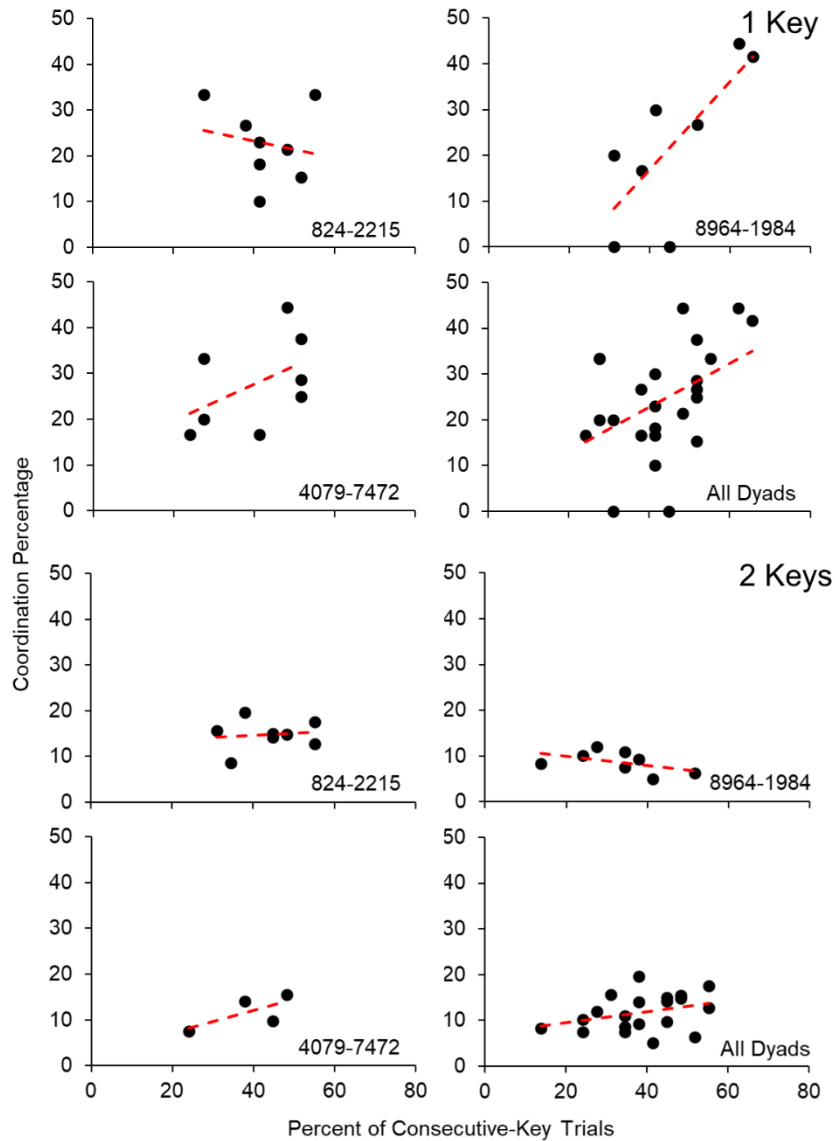
some sessions the same key(s) remained transilluminated for several trials in a row as the active pair did not change, whereas during others the transilluminated keylights frequently shifted as the active pair moved from key to key. Given how (1) each individual response from a dyad member only had the potential to be coordinated if that same key was transilluminated in the other dyad member's compartment and (2) the dyad members could progress through trials in the independent-reinforcement phase asynchronously, coordination percentages from a given session may have been influenced by the frequency with which the active pair changed keys.

Figure 5 shows coordination percentages as a function of the percentage of trial-to-trial transitions during which the transilluminated key(s) did not change. Data in the top four panels are from the one-key condition, and data from the bottom four panels are from the two-key condition. For both conditions, the bottom-right panel shows data for all three dyads together, whereas the remaining three panels show data for each of the three dyads individually. Data from the three-key condition are not shown because the transilluminated keylights did not change from trial to trial.

During the one-key condition coordination percentages decreased slightly with increases in the frequency of consecutive-key trials for Dyad 824-2215, but a simple linear regression did not reveal a significant relation between the two variables ($p = 0.64$). For Dyads 8964-19841 and 4079-7472, coordination percentages increased with increases in the percentage of consecutive-key trials. However, simple linear regressions showed that only for Dyad 8964-19841 was there a significant relation between the two variables ($p < 0.05$). For Dyad 4079-7472 no significant relation was found ($p = 0.23$). When the data from all three dyads were compiled together, a simple linear regression revealed a significant relation between the two variables ($p < 0.05$).

Figure 5

Coordination percentages for each dyad in Experiment 1 as a function of the percentage of trial-to-trial transitions that the active pair remained constant.



Note. The top and bottom four panels show data from the one- and two-key conditions, respectively. Within each condition, the first three panels show data from individual dyads, and the bottom-right panel shows data from all three dyads. Dashed lines show linear regressions calculated to fit the data.

During the two-key condition, coordination percentages increased slightly with increases in the frequency of consecutive-key trials for Dyads 824-2215 and 4079-7472. Simple linear regressions, however, did not show a significant relation between the two variables for either dyad ($p = 0.77$ and $p = 0.29$, respectively). The same was true of Dyad 8964-19841 ($p = 0.21$), for which coordination percentages decreased slightly with increases in the frequency of consecutive-key trials. When the data from all three dyads were compiled together coordination percentages slightly increased with increases in the frequency of consecutive-key trials, but a simple linear regression did not reveal a significant relation between the two variables ($p = 0.15$). The implications of this analysis will be explored in the General Discussion section.

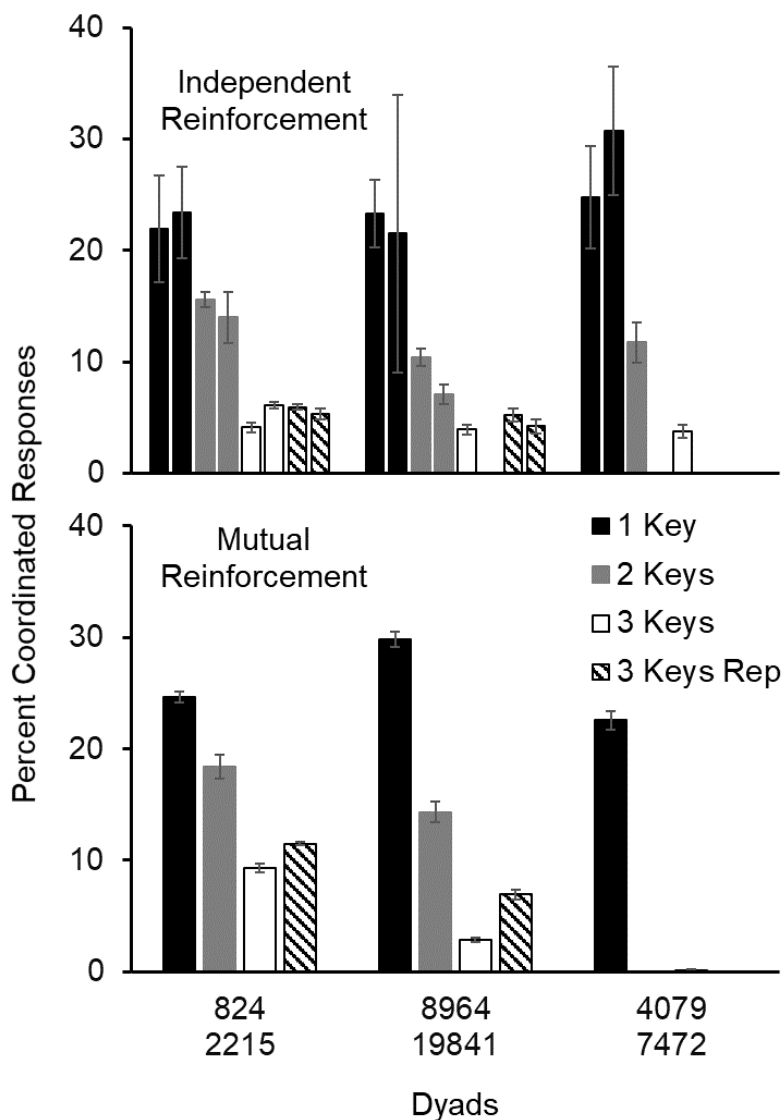
Effects of the Number of Keys

Changes in Coordination Percentages. Mean coordination percentages from the final four sessions of each phase for all three dyads – the same data depicted in Figure 2 – are shown in Figure 6 as a function of the number of keys across which responses could be distributed. During the independent-reinforcement phase (top panel) lower coordination percentages occurred when additional pairs of keys were transilluminated along with the active pair. Across dyads, 21.5-30.8% of responses were coordinated with a single key, 7.1-15.6% with two keys, and 3.8-6.1% with all three keys. This same decrease in coordination percentages with additional keys occurred during the mutual-reinforcement phase (bottom panel). Across dyads, 22.6-29.8% of responses were coordinated with a single key, 14.3-18.4% with two keys, and 0.14-11.5% when all three keys were transilluminated (note that the ranges for the three-key conditions include data from both the initial exposure and replication).

Comparison to Previous Findings. The analysis of the two- and three-key conditions in the present experiment extends previous findings by (1) providing empirical support for greater

Figure 6

Coordination percentages for each pigeon in Experiment 1 as a function of the number of transilluminated keys.



Note. Bars represent mean coordination percentage from the final four sessions of a condition, and error bars represent ± 1 standard error of the mean for those same sessions. Data from the independent- and mutual-reinforcement phases are shown in the top and bottom panels of the figure, respectively.

coordination percentages during mutual- than independent-reinforcement phases with multiple response options and (2) demonstrating the degradation of coordinated responding with the inclusion of pairs of keys other than the active pair. The fact that substantially lower coordination percentages were observed during independent- and mutual-reinforcement phase sessions in both two- and three- compared to one-key condition demonstrates the importance of the environmental context in determining how a mutual-reinforcement contingency influences coordinated responding.

Furthermore, assessments of the magnitude of the change in coordination percentages as a function of the number of keys revealed an additional effect of multiple response options on coordination. The data in the top panel of Figure 6 show a negative, roughly logarithmic change in coordination percentages throughout the independent-reinforcement phase as the number of pairs of keys increases (comparisons during the mutual-reinforcement condition were not conducted because the full sequence of phases at the two- and three-key conditions were not completed for all dyads). When averaged across dyads, 24.3%, 11.7%, and 4.5% of responses were coordinated during the one-, two-, and three-key conditions, respectively. Thus, mean coordination percentages decreased by 12.6 percentage points across the one- and two-key conditions, but only by 7.2 percentage points with the addition of a third pair of keys. This suggests that most of the decrease in coordinated responding with additional response options occurs with the inclusion of just one other operandum, and that further response options produce smaller effects. This is an implication that invites further analysis through additional experimentation.

Interaction Between the Mutual-Reinforcement Contingency and the Number of Keys

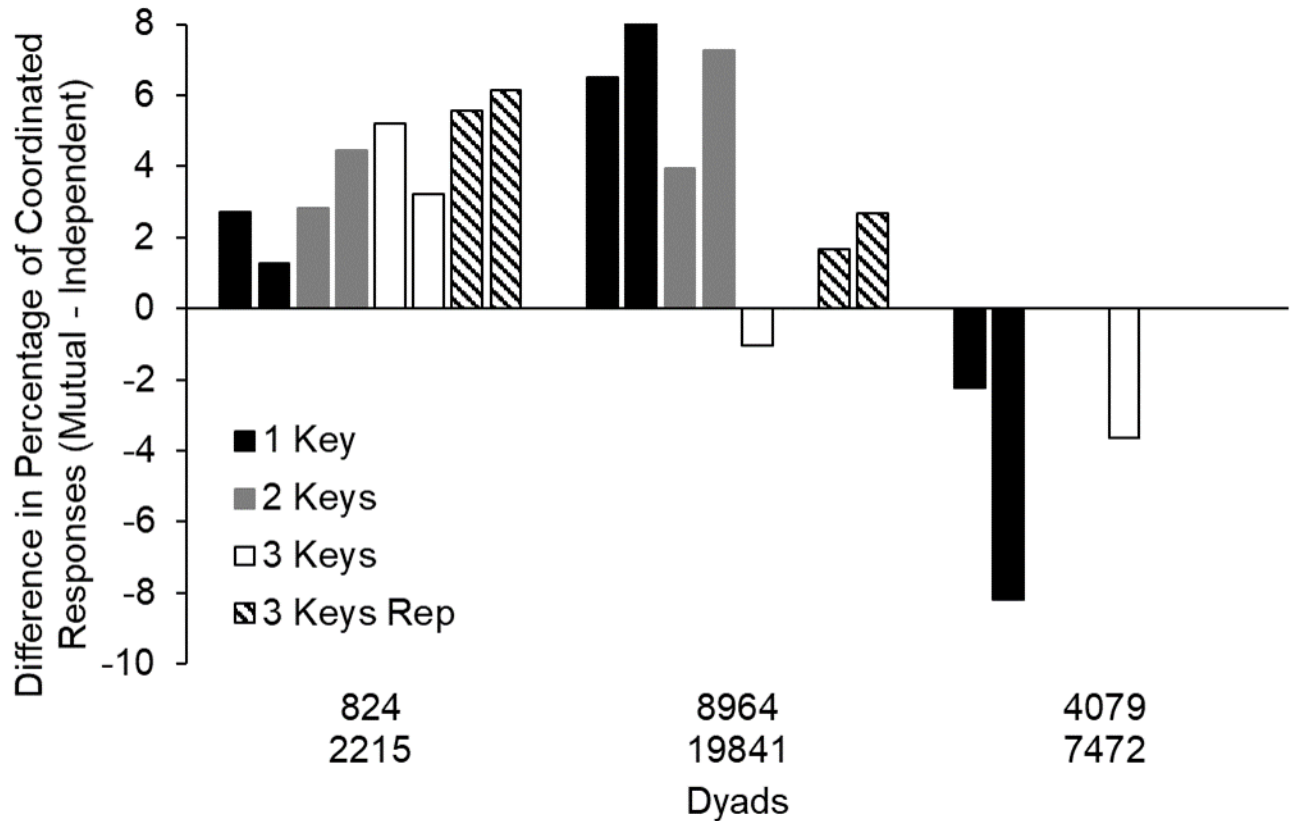
Figure 7 shows differences in coordination percentages between consecutive mutual- and independent-reinforcement phases during each of the three different key conditions for all three dyads. Coordination percentages did not increase under the mutual-reinforcement contingency for Dyad 4079-7472. For Dyad 824-2215, differences in mean coordination percentages between mutual- and independent-reinforcement phases increased as a function of the number of transilluminated keys. Mean coordination percentages were approximately 2.0, 3.6, and 5.0 percentage points greater during mutual-reinforcement phases than independent-reinforcement phases at the one-, two-, and three-key conditions, respectively. Conversely, for Dyad 8964-19841, the opposite relation was observed as differences in mean coordination percentages between mutual- and independent-reinforcement phases decreased with additional transilluminated keys. For this dyad, mean coordination percentages during mutual-reinforcement phases were approximately 7.4, 5.6, and 1.1 percentage points greater than those during independent-reinforcement phases at the one-, two-, and three-key conditions, respectively.

Conclusions

Although Skinner (1962) asserted that coordination across multiple response options could be trained, no empirical data to support this conclusion were presented. Results from the three-key condition of Experiment 1 support Skinner's conclusions by demonstrating greater coordination percentages during mutual- than independent-reinforcement phases. Furthermore, comparisons to conditions with fewer response options extended upon Skinner's findings by revealing that less coordinated responding occurred when more operanda were included. When only one response key was included no increases in coordination percentages during mutual-reinforcement phases occurred, contradicting previous findings by de Carvalho et al. (2018; see

Figure 7

Difference in percentage of coordinated responses across consecutive mutual- and independent-reinforcement phases at each key condition for all three dyads in Experiment 1.



Note. Bars represent differences in mean coordination percentage between each mutual-reinforcement phase and either the immediately preceding (first bar) or following (second bar) independent-reinforcement phase.

also Tan & Hackenberg, 2016). In a subsequent experiment, de Carvalho et al. (2019) demonstrated increased coordinated responding during mutual- compared to independent-reinforcement phases when responding to a single key was reinforced according to a VI schedule of reinforcement. Experiment 2, therefore, was designed to explore the role of intermittent reinforcement on coordinated responding.

Experiment 2

Experiment 2 was designed to (1) assess levels of coordinated responding under a VI schedule of reinforcement, and (2) further explore the effects of the number of response allocation options on levels of coordinated responding.

Method

Subjects and Apparatus

Six new mature male White Carneau pigeons were used for Experiment 2. All were maintained at 80% of their free-feeding weight and housed in the same manner as described previously for Experiment 1. Similarly, the same apparatus as outlined above was used for Experiment 2.

Procedure

Details such as dyad pairings, compartment assignment, and session time were as described in Experiment 1. For two dyads (18057/11829 and 18390/21055) the same 3-min blackout described above preceded each session, but for the third (19222/19957) a 10-min blackout was used.

Training. Dyads first were exposed to seven sessions of FR 1 training as described for Experiment 1. Following the completion of these sessions, an additional five sessions under an FR 5 schedule were conducted. Once all three keys were pecked consistently, key pecking to

each was reinforced according to a VI schedule beginning with the next session. As with the previous sessions, the key associated with the VI schedule varied semirandomly across trials. Across several sessions the average inter-reinforcer interval in effect for the VI schedule was increased gradually (VI 5 s, VI 10 s, VI 20 s, VI 40 s, and VI 60 s; see Bradshaw et al., 1978). The VI schedules in effect throughout these and all subsequent sessions were constructed using Fleshler and Hoffman's (1962) distribution. The terminal VI 60-s schedule was in effect for at least 10 sessions, and until (1) there were no increasing or decreasing trends in response rate over the last three sessions and (2) none of the final five sessions contained either the minimum or maximum response rate observed during VI-60 sessions (cf. Tan & Hackenberg, 2016). The VI 60-s schedule was used only during the Training phase. During all experimental sessions (see next section) a VI 20-s schedule was used.

Assessment of Independent Variables. Dyads were exposed to a series of four (Dyads 19222-19957 and 18057-11829) or five (Dyad 18390-21055) reversal designs between independent- (A) and mutual- (B) reinforcement phases as described in Experiment 1. The only difference was that responses were reinforced according to a VI 20-s schedule instead of according to the FR 1 schedule used in the first experiment. All other aspects of the design – including the manner of transition across phases, details for individual sessions, selection of the active pair, requirements for the completion of the mutual reinforcement contingency, and recorded dependent measures – were as described in Experiment 1. The order of conditions, the arrangement of independent- and mutual-reinforcement phases within each reversal design, and the number of sessions comprising each manipulation for each dyad are shown in the bottom half of Table 1.

Results and Discussion

Results from Experiment 2 are shown in Figures 8 through 13. Each of these figures was constructed as described for Figures 2 through 7, respectively.

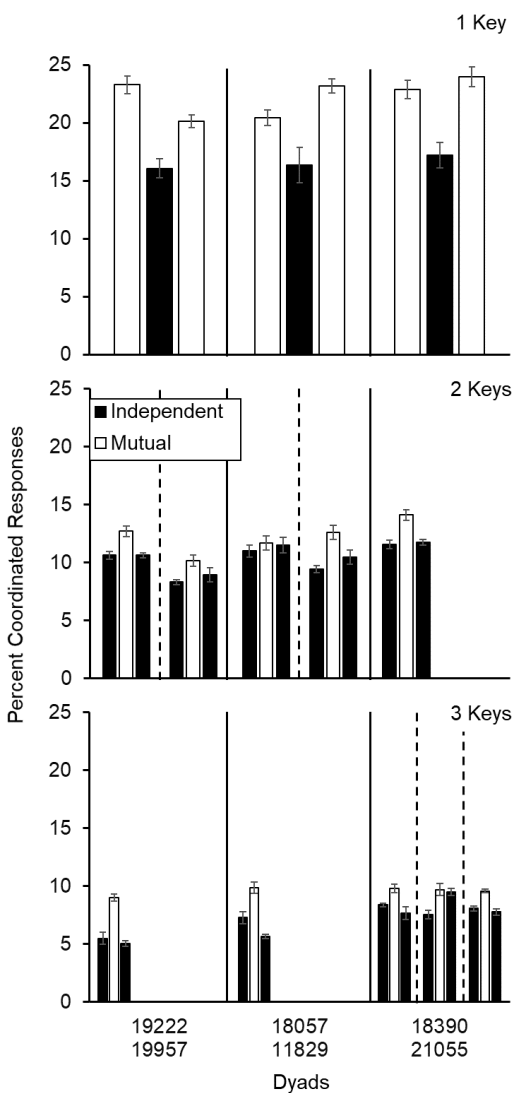
Effects of the Mutual-Reinforcement Contingency

Changes in Coordination Percentages. Figure 8 shows coordination percentages for each dyad as a function of the presence or absence of the mutual-reinforcement contingency. For all three dyads during the one-key condition (top panel), greater coordination percentages occurred during mutual-reinforcement phases (white bars) than during corresponding independent-reinforcement phases (black bars). Across the dyads 20.2-24.0% of responses were coordinated during the mutual-reinforcement phases, and 16.1-17.2% of responses were during the independent-reinforcement phase.

The same general findings from the one-key condition were replicated during the two-key condition (middle panel). For four of the five sequences in this condition, greater coordination percentages were observed during mutual-reinforcement phases (10.2-14.1%) than during corresponding independent-reinforcement phases (8.3-11.8%). The sole exception was the first sequence for Dyad 18057-11829, during which the average coordination percentage from the mutual-reinforcement phase exceeded those obtained from the immediately preceding and following independent-reinforcement phases by less than 1% (11.7% in the mutual-reinforcement phase, and 11.0% and 11.5% in the preceding and following independent-reinforcement phases, respectively). On replication of the sequence with this dyad, however, the coordination percentage from the mutual-reinforcement phase exceeded those obtained from the immediately preceding and following independent-reinforcement phases by 3.2% and 2.2% respectively, replicating results obtained with the other dyads.

Figure 8

Coordination percentages for each dyad in Experiment 2 as a function of the presence or absence of the mutual-reinforcement contingency.



Note. Bars represent mean coordination percentages from the final four sessions of a phase, and error bars represent ± 1 standard error of the mean for those same sessions. Data from the one-, two-, and three-key conditions are shown in the top, middle, and bottom panels of the figure, respectively. Solid vertical lines separate data from different dyads, whereas dashed vertical lines, when present, separate initial, secondary, and tertiary replications of the conditions.

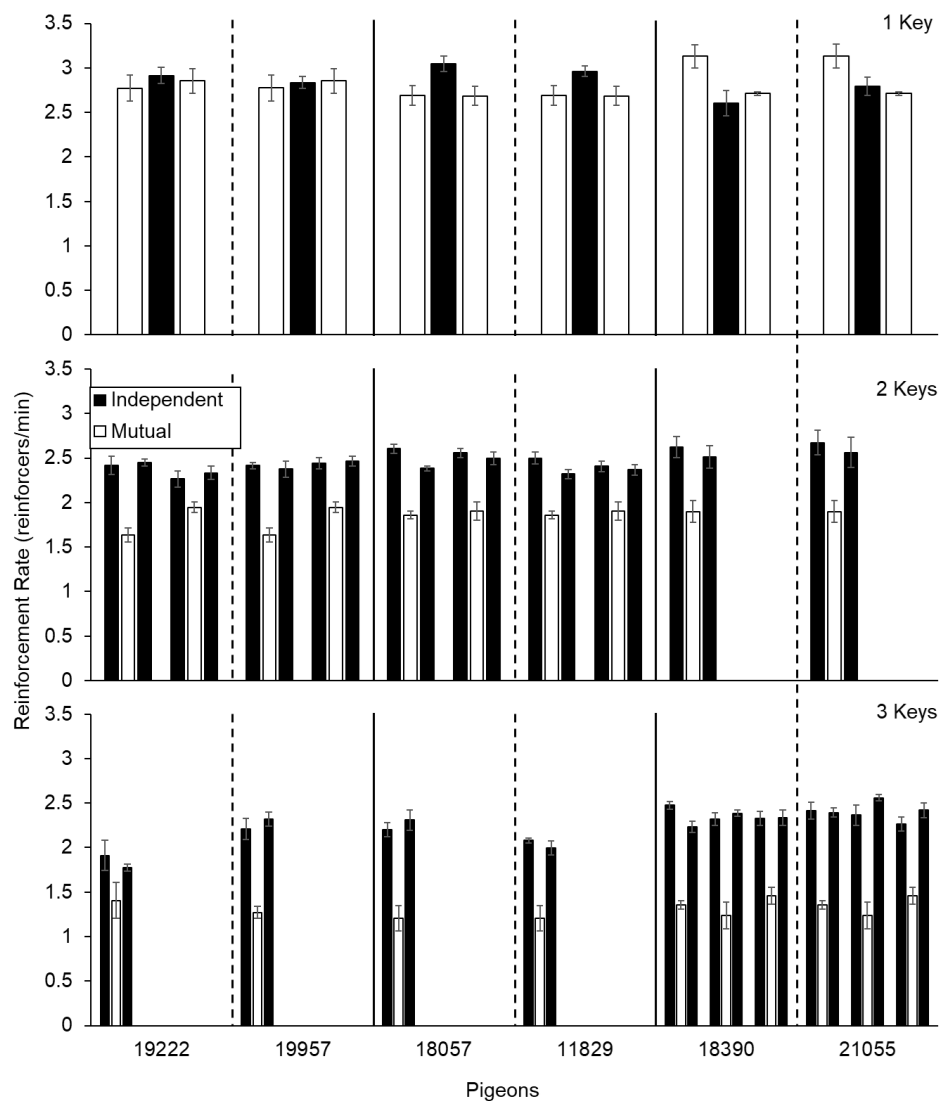
During the three-key condition (bottom panel), greater coordination percentages occurred during mutual-reinforcement phases (9.0-9.9%) than during corresponding independent-reinforcement phases (5.1-9.5%). Across four of the five sequences the pattern of results observed during the one- and two-key conditions was replicated. For the second exposure to this condition for Dyad 18390-21055, however, the average coordination percentage from the mutual-reinforcement phase only exceeded that obtained during the initial independent-reinforcement phase. Coordination percentages across the mutual-reinforcement phase and second iteration of the independent-reinforcement phase differed by less than 1% (9.7% and 9.5%, respectively). During the third exposure to this sequence, however, the coordination percentage from the mutual-reinforcement phase (9.6%) was, as with other dyads, greater than those from both the preceding and following independent-reinforcement phases (8.1% and 7.8%, respectively).

Comparison to Previous Findings. In Experiment 1, only at the two- and three-key conditions were a greater percentage of responses coordinated when such coordination was required for reinforcement compared to when there was no such contingency. Conversely, during Experiment 2, larger coordination percentages occurred during mutual-reinforcement phases than independent-reinforcement phases consistently across all three different key conditions. Implications of and a potential explanation for differences in the one-key condition across experiments will be addressed in the General Discussion.

Differences in coordinated responding across phases cannot be attributed to changes in the schedule of or delay to reinforcement, as in past experiments (e.g., de Carvalho et al., 2018, 2019; Tan & Hackenberg, 2016), as both of these variables were controlled. Additionally, Figure 9 shows changes in reinforcement rates across phases for all six pigeons at all three different key

Figure 9

Reinforcement rates for each pigeon in Experiment 2 as a function of the presence or absence of the mutual-reinforcement contingency.



Note. Bars represent mean reinforcement rates from the final four sessions of a phase, and error bars represent ± 1 standard error of the mean for those same sessions. Data from the one-, two-, and three-key conditions are shown in the top, middle, and bottom panels of the figure, respectively. Solid vertical lines separate data from different dyads and dashed vertical lines separate data from different pigeons within the same dyad.

conditions. Reinforcement rates during mutual-reinforcement phases consistently were equal to or lower than those from corresponding independent-reinforcement phases. Increases in coordination percentages during mutual-reinforcement phases therefore cannot be attributed to increases in reinforcement rates, which supports the conclusion that mutual-reinforcement contingencies lead to greater levels of coordinated responding.

The present results, therefore, both support and extend those of Tan and Hackenberg (2016), de Carvalho et al. (2018, 2019), and Experiment 1 by demonstrating that the imposition of a mutual-reinforcement contingency generates more coordinated responding even when the schedule of reinforcement does not change along with the change in contingencies and variable, unsignaled delays to reinforcement are eliminated from the independent-reinforcement phase. Furthermore, the use of a VI schedule in contrast to the ratio schedules used in previous experiments illustrates that mutual-reinforcement contingencies can reinforce coordination according to an interval schedule, and thus extends the scope of schedules under which coordination has been documented to occur.

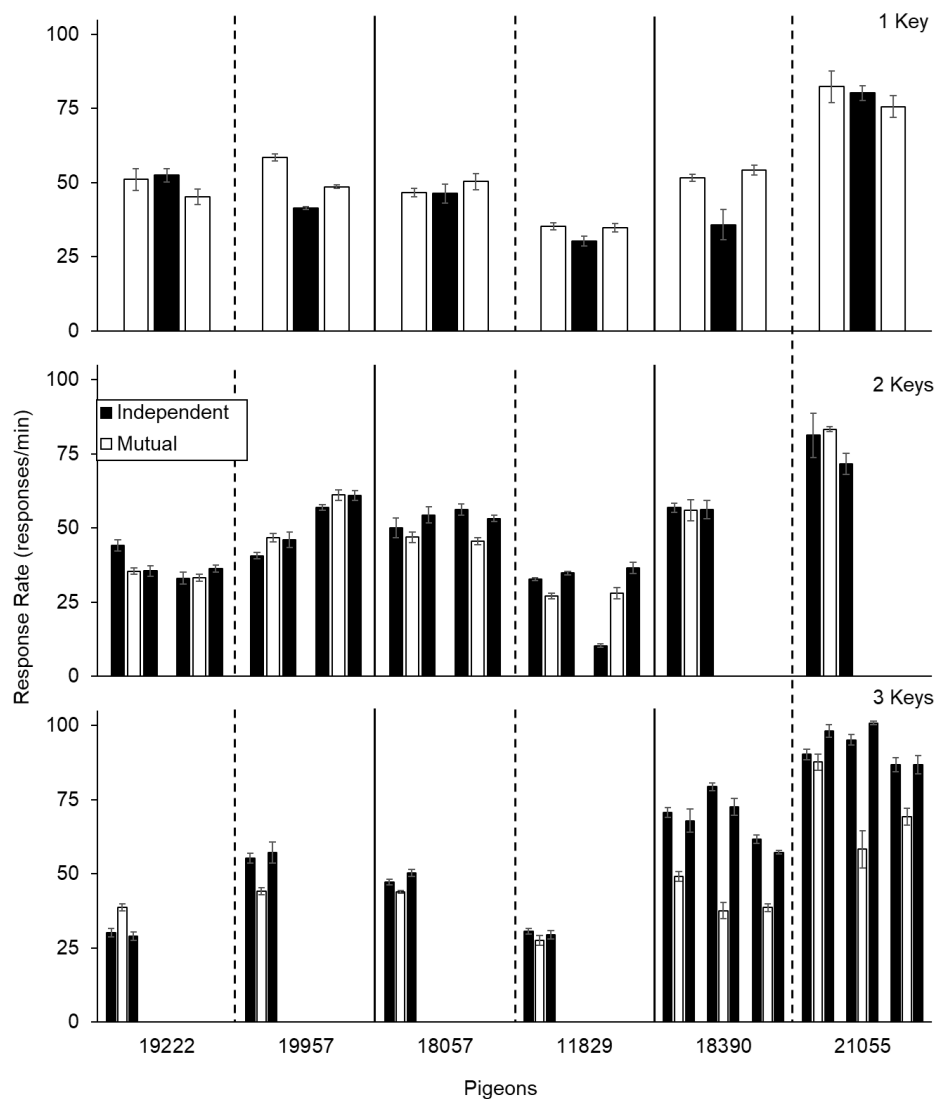
Coordination Magnitude. Coordination percentages from the independent-reinforcement phase of the present one-key condition (16.6% on average across all dyads) were substantially greater than those reported previously by both Tan and Hackenberg (2016) and de Carvalho et al. (2018, 2019; 2.9-10.6% across the three experiments). This disparity may be attributed to differences in how independent-reinforcement phases were conducted across the four experiments. In prior experiments, as noted in the introduction, either the functional control of one dyad member's responding by a VT schedule (de Carvalho et al., 2018; Tan & Hackenberg, 2016) or variable, unsignaled delays to reinforcement (de Carvalho et al., 2019) may have contributed to the sharp declines in coordination percentages.

Conversely, in the present experiment, these limitations were addressed by enacting separate VI schedules for each dyad member during independent-reinforcement phases. Because reinforcement during both phases depended on responding from both dyad members and occurred immediately on completion of the programmed schedule requirements, responding by both dyad members was maintained during both mutual- and independent-reinforcement phases. This is shown in Figure 10, in which response rates are plotted as a function of the presence or absence of the mutual-reinforcement contingency under all key conditions for all six pigeons. These data suggest that in these previous experiments the magnitude of the effect of the mutual-reinforcement contingency may have been overestimated. As response-independent reinforcement (Zeiler, 1968; Rescorla & Skucy, 1969) and long delays to reinforcement (Arbuckle & Lattal, 1988; Lattal, 2010; Richards, 1981; Sizemore & Lattal, 1978) decrease the rate of responding, coordination is less likely. This stands in contrast to simply setting up a context in which responses were reinforced, but simultaneously coordinated responses were not required for reinforcement, as in the present experiment. Thus, the present procedures serve as a clarification of the potential impact of the selective reinforcement of coordinated responses on behavior.

Effects of Keylight Consistency Across Trials. The active pair of keys for each trial of a session was determined as described for Experiment 1, and thus the order of active pairs was not held constant across sessions. To determine if, as in Experiment 1, this influenced coordination percentages, Figure 11 shows coordination percentages plotted as a function of the percentage of trial-to-trial transitions during which the transilluminated key(s) did not change. During both conditions, coordination percentages decreased slightly with increases in the frequency of consecutive-key trials for all three dyads. Simple linear regressions did not reveal

Figure 10

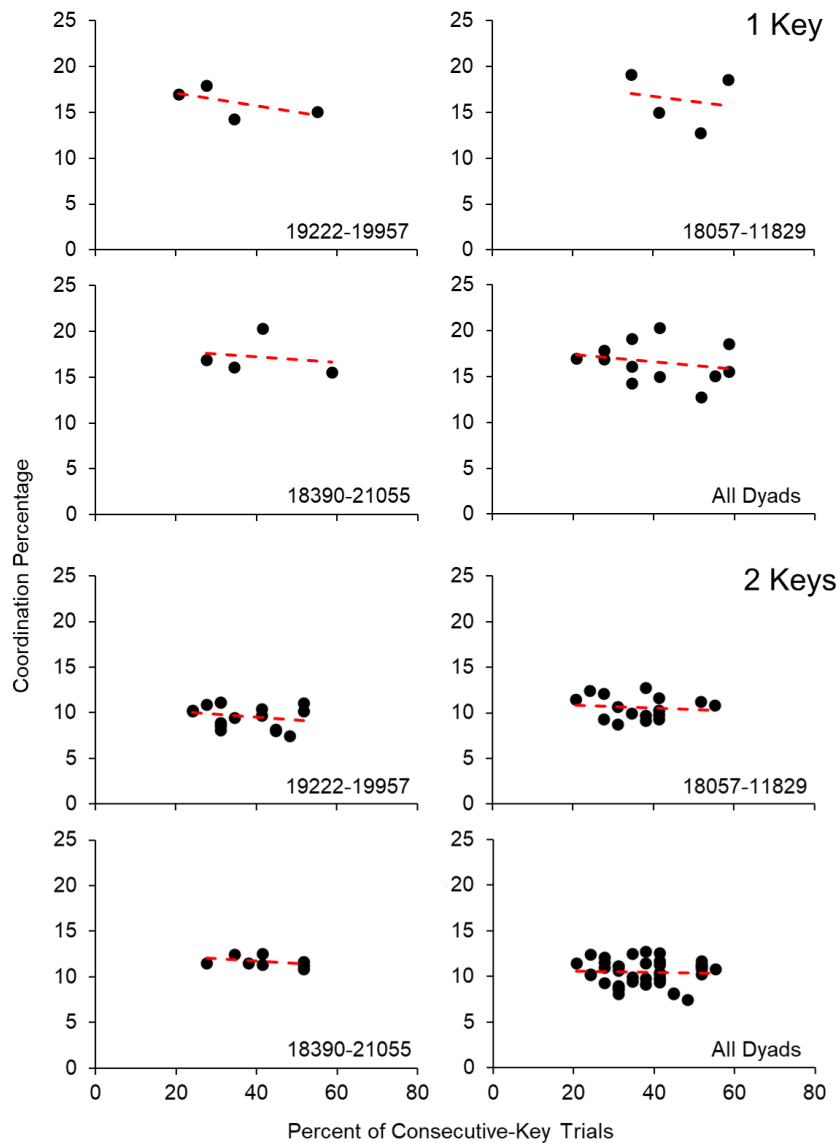
Response rates for each pigeon in Experiment 2 as a function of the presence or absence of the mutual-reinforcement contingency.



Note. Bars represent mean response rates from the final four sessions of a phase, and error bars represent ± 1 standard error of the mean for those same sessions. Data from the one-, two-, and three-key conditions are shown in the top, middle, and bottom panels of the figure, respectively. Solid vertical lines separate data from different dyads and dashed vertical lines separate data from different pigeons within the same dyad.

Figure 11

Coordination percentages for each dyad in Experiment 2 as a function of the percentage of trial-to-trial transitions that the active pair remained constant.



Note. The top and bottom four panels show data from the one- and two-key conditions, respectively. Within each condition, the first three panels show data from individual dyads, and the bottom-right panel shows data from all three dyads. Dashed lines show linear regressions calculated to fit the data.

significant relations between the two variables at either the one- ($p = 0.38$ for Dyad 19222-19957, $p = 0.81$ for Dyad 18057-11829, and $p = 0.81$ for Dyad 18390-21055) or two-key conditions ($p = 0.39$ for Dyad 19222-19957, $p = 0.67$ for Dyad 18057-11829, and $p = 0.33$ for Dyad 18390-21055). The absence of a significant relation between the two variables at both conditions was replicated when the data from all three dyads were compiled together ($p = 0.46$ during the one-key condition and $p = 0.77$ during the two-key condition). The implications of this analysis will be explored in the General Discussion section.

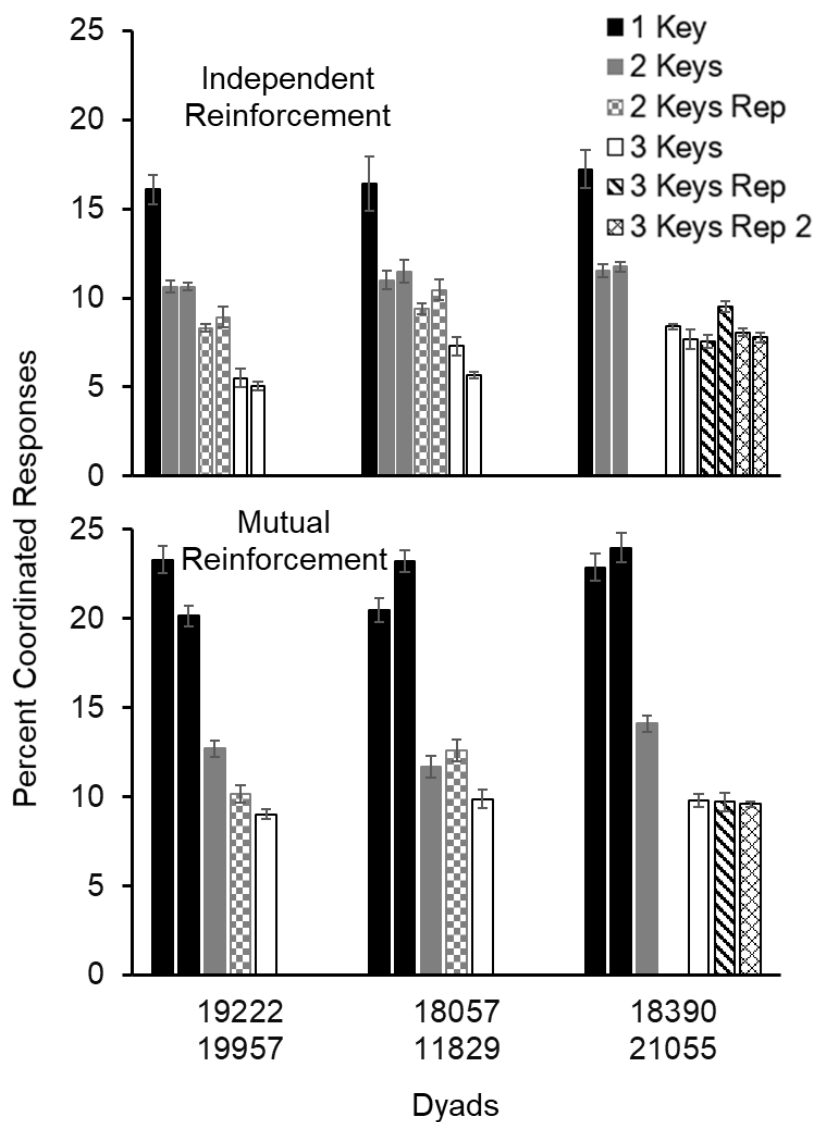
Effects of the Number of Keys

Changes in Coordination Percentages. Mean coordination percentages for each dyad from the final four sessions of each phase – the same data depicted in Figure 8 – are shown in Figure 12 as a function of the number of keys across which responses could be distributed. For all three dyads during independent-reinforcement phase sessions (top panel), progressively lower coordination percentages were obtained with the addition of pairs of keys in addition to the active pair. Across dyads, between 16.1% and 17.2% of responses were coordinated with a single key, between 8.3% and 11.8% with two keys, and between 5.1% and 9.5% with all three keys (these ranges for the two- and three-key conditions include data from both the initial exposure and replications). This same pattern occurred across key conditions during the mutual-reinforcement phase. Across dyads, between 20.2% and 24.0% of responses were coordinated with a single key, between 10.2% and 14.1% with two keys, and between 9.0% and 9.9% when all three keys were transilluminated (note that the ranges for the two- and three-key conditions include data from both the initial exposure and replications).

Comparison to Previous Findings. As with Experiment 1, The data in Figure 12 show a negative, roughly logarithmic change in coordination percentages as the number of pairs of keys

Figure 12

Coordination percentages for each pigeon in Experiment 2 as a function of the number of transilluminated keys.



Note. Bars represent mean coordination percentage from the final four sessions of a condition, and error bars represent ± 1 standard error of the mean for those same sessions. Data from the independent- and mutual-reinforcement phases are shown in the top and bottom panels of the figure, respectively.

increases (replications are grouped with the initial condition). For this experiment, however, the effect was replicated throughout both independent- and mutual-reinforcement phases. During independent-reinforcement phases mean coordination percentages for all three dyads were 16.6%, 10.6%, and 6.6% when 1, 2, or 3 pairs of keys, respectively, were present. Thus, there was a 6.0 percentage-point decrease with the addition of a second key, but only a further 4.0 percentage-point decrease when a third pair of keys was in effect. During the mutual-reinforcement phase mean coordination percentages for all three dyads were 22.3%, 12.6%, and 9.5% at the one-, two-, and three-key conditions, respectively. Thus, there was a 9.7 percentage-point decrease with the addition of a second key, but only a 3.1 percentage-point decrease when adding a third key during the independent-reinforcement phase.

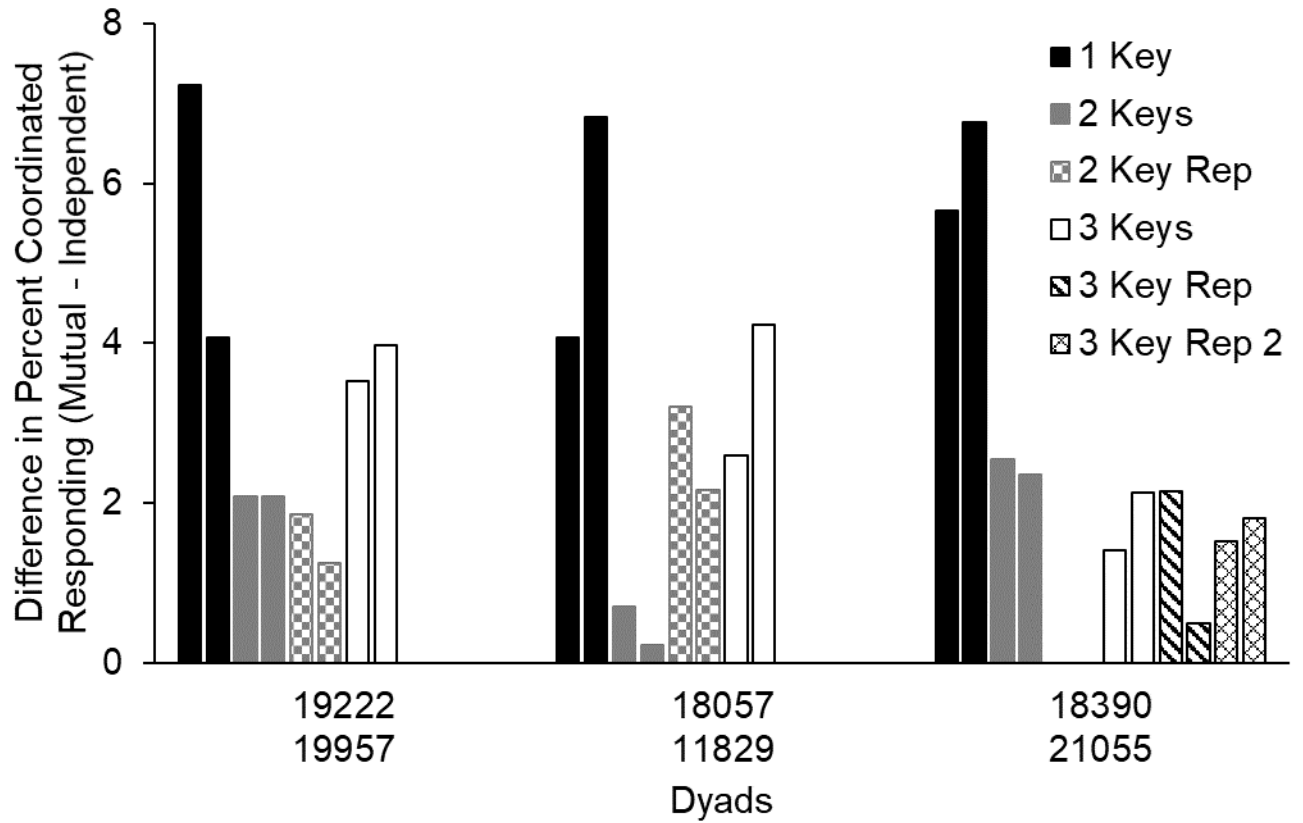
The analysis of the two- and three-key conditions in the present experiment thus extends the results reported in Experiment 1 by demonstrating the two principle effects reported during the two- and three-key conditions with a different schedule of reinforcement besides FR 1. Less coordinated responding occurred with the inclusion of other pairs of keys besides the active pair, and the majority of the decreases in coordinated responding with additional keys occurred when just one operandum was included. Additional investigations under other schedules of reinforcement and with additional numbers of response options are warranted to confirm the generality of these effects.

Interaction Between the Mutual-Reinforcement Contingency and the Number of Keys

Figure 13 shows differences in coordination percentages between corresponding mutual- and independent-reinforcement phases across each of the three different key conditions for all three dyads. For all three dyads the largest difference in coordination percentages between mutual- and independent-reinforcement phase sessions occurred during the one-key condition,

Figure 13

Difference in percentage of coordinated responses across consecutive mutual- and independent-reinforcement phases at each key condition for all three dyads in Experiment 2.



Note. Bars represent differences in mean coordination percentage between each mutual-reinforcement phase and either the immediately preceding (first bar) or following (second bar) independent-reinforcement phase.

similar to one of the two dyads from Experiment 1. Averaging across dyads, coordination percentages were approximately 5.8 percentage points larger in the mutual- than in the independent-reinforcement phase. Although this same general pattern was obtained with the other two keys, the difference between mutual-reinforcement phase and independent-reinforcement phase sessions was larger during the three-key condition than during the two-key condition. Averaging across dyads, overall coordination percentages in the mutual-reinforcement phase were approximately 1.9 percentage points larger than those in the independent-reinforcement phase during the two-key condition, and 2.9 percentage points greater in the three-key condition.

The presence of a second pair of keys diminished the difference in coordination percentages between mutual- and independent-reinforcement phases. Adding a third pair of keys did not further systematically diminish this distinction, as – compared to the differences between the one- and two-key conditions – little differences were observed between the two- and three-key conditions.

General Discussion

Across two experiments, alternations between mutual- and independent-reinforcement phases generally revealed greater coordination percentages when coordinated responding was required for reinforcement than when it was not. The one condition during which this did not occur was the one-key condition of Experiment 1, when an FR 1 schedule was used. Barring this exception, coordination percentages were greater during mutual- than independent-reinforcement phases regardless of the schedule of reinforcement or the number of operanda across which responses could be distributed. The number of response options, however, did influence

coordination, as coordination percentages – regardless of experimental phase – decreased as more keys were transilluminated.

To determine if mutual-reinforcement contingencies truly induce coordinated responding, rather than responding that merely appears to be coordinated due to the independent control by two identical schedules of reinforcement across subjects, past experimenters compared behavior under mutual-reinforcement phases in which coordinated responding was reinforced selectively and independent-reinforcement phases in which it was not (i.e., de Carvalho et al., 2018, 2019; Tan & Hackenberg, 2016). Although results from these earlier experiments suggested that mutual-reinforcement contingencies increase the frequency of coordinated responding, changes in multiple variables across phases of the experiments, differences in the schedule functionally in place between pairs of coordinating subjects, and the absence of requirements for spatial coordination all have precluded an unequivocal conclusion of such.

In the present experiments, all three limitations were addressed. By holding the schedule of reinforcement constant across phases and between dyad members, the results of prior assessments of coordinated responding (e.g., de Carvalho et al., 2018, 2019; Tan & Hackenberg, 2016) were supported by demonstrating that increased coordinated responding during mutual-reinforcement phases was a consequence of the mutual-reinforcement contingency, and not due to byproduct mutualism or other changes in conditions across phases. Furthermore, the inclusion of conditions with more than a single response option built upon Skinner's (1962) observations by demonstrating that greater coordination percentages occurred during mutual- than independent-reinforcement phases even in contexts in which responses could be distributed across multiple operanda.

Prior assessments of coordinated responding, with only the exception of Skinner (1962), have reinforced coordination across a single pair of response options (de Carvalho et al., 2018, 2019, 2020; Łopuch & Popik, 2011; Tan & Hackenberg, 2016). Although Skinner reinforced coordinated responding across three pairs of response options, comparisons to conditions with fewer pairs of operanda were not included. Thus, the present experiments are the first to explore the effects of the number of response options on coordinated responding. As described previously for both experiments, coordination percentages were greatest during the one-key condition, regardless of whether coordinated responding selectively was reinforced. Increasing the number of response options produced decreases in coordinated responding, and the largest decreases occurred with the addition of just one more key. Furthermore, differences in coordination percentages between mutual- and independent-reinforcement phases generally were less pronounced when more response options were included. The present results, therefore, not only provide empirical support for Skinner's assertion that a mutual reinforcement contingency can maintain coordinated responding across three pairs of responses options, but also reveal that the number of response options affects the amount of coordination. This demonstrates the importance of the environmental context with regard to how a mutual-reinforcement contingency influences coordinated responding.

Coordination Magnitude

Previously, de Carvalho and colleagues reported coordination percentages between 8.8 (de Carvalho et al., 2019) and 15.7 (Tan & Hackenberg, 2016) percentage points greater during mutual- than independent-reinforcement phases. Table 2 shows average differences in coordination percentages across mutual- and independent-reinforcement phases in all three conditions of both present experiments for each dyad that showed an effect of the

Table 2

Average differences in coordination percentages between mutual- and independent-reinforcement phases during each condition of Experiments 1 and 2

Experiment	Dyad	1 Key	2 Keys	3 Keys
1	824/2215	2.0	3.6	5.0
	8964/19841	7.4	5.6	2.2*
	Average	4.7	4.6	3.6
2	19222/19957	5.7	1.8	3.7
	18057/11829	5.5	1.6	3.4
	18390/21055	6.2	2.5	1.6
	Average	5.8	1.9	2.9

Note . Only conditions in which mean coordination percentages during mutual-reinforcement phases were greater than that of independent-reinforcement phases, irrespective of variability, are shown. Consequently, the first exposure of the indicated condition was excluded. If the difference in coordination percentages for this transition is included in the calculation, the average difference between the phases is 1.1 percentage points.

mutual-reinforcement contingency. As described above, differences between mutual- and independent-reinforcement phases were most pronounced during the one-key condition for four of the five dyads across both experiments. However, even during this condition, the effects of the mutual-reinforcement contingency on coordinated responding were not as pronounced as those reported in prior experiments.

There are, at least, two explanations for the smaller differences in coordination percentages across phases compared to that of prior experiments. First, the previous experimental evaluations of coordinated responding involved a single response option. In the present experiments, including just one additional response option generally reduced differences in coordinated responding across phases relative to that observed with one operandum. Thus, it appears that conclusions from prior assessments of coordinated responding are not fully generalizable to settings involving a greater number of response options. The influence of the number of response options, however, does not fully account for the discrepancy with past results because even differences in coordination percentages across phases at the one-key condition were smaller than those reported previously, calling for further explanation.

Table 3 shows average coordination percentages during mutual- and independent-reinforcement phases from both present experiments (only for dyads for which the mean of the former was greater than that of the latter), de Carvalho et al. (2018, 2019), and Tan and Hackenberg (2016) grouped by the schedule of reinforcement in effect during the mutual-reinforcement phase. Generally, coordination percentages from mutual-reinforcement phases in the present experiments were comparable to those obtained under similar schedules of reinforcement in previous experiments. Coordination percentages during independent-reinforcement phases, conversely, were larger than their counterparts from previous experiments.

Table 3

Average differences in coordination percentages between mutual- and independent-reinforcement phases with a single operandum across different experiments

Schedule of Reinforcement	Experiment	Schedule During Mutual-Reinforcement Phase	Mutual Reinforcement	Independent Reinforcement	Difference
FR	Tan & Hackenberg (2016)	FR 1	18.6	2.9	15.7
	de Carvalho et al. (2018)	FR 6	20.3	5.5	14.8
	de Carvalho et al. (2019)	FR 6	20.6	10.6	10.0
	Katz (2021)	FR 1	27.3*	22.6*	4.7*
VI	de Carvalho et al. (2019)	VI 26.4 s	19.4	10.6	8.8
	Katz (2021)	VI 20 s	22.3	16.6	5.8

Note . For the present experiments, only dyads for which mean coordination percentages during mutual-reinforcement phases were greater than that of independent-reinforcement phases, irrespective of variability, are shown. Consequently, Dyad 4079-7472 was omitted from the indicated averages. If coordination percentages for this dyad are included, the averages for the mutual- and independent-reinforcement phases are 25.7% and 24.3%, respectively, for a difference of 1.4 percentage points. The VI schedule from de Carvalho et al. (2019) is the average of the different VI schedules for each dyad.

This suggests that the disparity in the effects of the mutual-reinforcement contingencies in the present and past experiments is driven largely by differences in coordination across independent-reinforcement phases.

The differences in coordination percentages across independent-reinforcement phases of different experiments may be attributed to disparities in how these phases were conducted. During the present experiments, reinforcers during this phase were delivered immediately following responses according to asynchronous schedules for each dyad member. Thus, responding was maintained for both dyad members and, consequently, coordinated responding, which requires responses from both dyad members, could occur. Conversely, as noted in the introduction, the conditions of at least some reinforcer deliveries during independent-reinforcement phases in previous experiments likely led to lower response rates from one dyad member and, consequently, impeded coordination. Because independent-reinforcement phases in previous experiments were designed in a way that impeded coordinated responding, the impact of the mutual-reinforcement contingency likely was overestimated. Nonetheless, despite the smaller differences between phases in the present experiments, these differences were – with one exception – consistent, attesting to the reliability of the effects of the mutual-reinforcement contingency.

FR 1 Considerations

The one exception to the above trend was in the one-key condition of Experiment 1, during which no changes in coordination percentages occurred across phases. This stands in contrast to the results from past experiments concerning coordination under FR 1 schedules (e.g., Tan & Hackenberg, 2016) or with only a single response option (e.g., de Carvalho et al., 2018, 2019; Tan & Hackenberg, 2016), in which greater coordination percentages occurred during

mutual- than independent-reinforcement phases. Furthermore, across both present experiments, the one-key condition of Experiment 1 was the only condition in which no substantial differences in coordination percentages across mutual- and independent-reinforcement phases occurred. Results from this condition therefore stand out as an exception to the general trends reported in the literature concerning coordinated responding.

For all three dyads during the one-key condition in Experiment 1, the variability in coordination percentages during independent-reinforcement phases encompassed that of the mutual-reinforcement phase. By contrast, during all other conditions of both experiments, variability in coordination percentages was comparable across mutual- and independent-reinforcement phases and was less than that of the independent-reinforcement phase during the one-key condition of Experiment 1. Thus, it appears that the absence of a change in coordination percentages across phases during the one-key condition of Experiment 1 may be attributed to the variability in coordination percentages during the independent-reinforcement phase. The variability, in turn, may have been a consequence of using two independent FR 1 schedules during the independent-reinforcement phase.

Consequences of Independent Schedules

By using two independent schedules in the independent-reinforcement phase, reinforcers were delivered (1) according to the same schedule of reinforcement as in the mutual-reinforcement phase, (2) dependent on a response from a dyad member, and (3) immediately following a response without a variable, unsignaled delay to reinforcement. Thus, several limitations of previous assessments of coordinated responding (i.e., de Carvalho et al., 2018, 2019; Tan & Hackenberg, 2016) were addressed by more closely equating the conditions of reinforcement across the mutual- and independent-reinforcement phases. Despite these

similarities, however, dyad members could progress through independent-reinforcement sessions asynchronously and earn reinforcers at different points in time from each other, even though the numbers of reinforcers earned always was the same for both conditions.

Furthermore, because the schedules were independent, it was possible for a given key to be transilluminated in one dyad member's compartment and not the other. During all three different conditions, this could occur if one dyad member was responding while the other was consuming a reinforcer or already had finished the session. Additionally, during the one- and two-key conditions, this was a possibility if dyad members were on different trials with different arrangements of transilluminated keys. As described in the Data Analysis section, responses to a key that was not transilluminated concurrently in the other compartment were omitted from coordination percentage calculations because they could not possibly have been coordinated.

Effects of Correcting for Potentially Coordinated Responses

This correction procedure appears to have contributed to the variability observed in the one-key condition of Experiment 1. Table 4 compares the average total and corrected number of responses (i.e., all responses and only those made when that same key was transilluminated in the other compartment) made across dyads during independent-reinforcement phases of all three conditions in both experiments. During the one-key condition of Experiment 1 only 60 responses were made because sessions ended after both dyad members earned 30 reinforcers. This number, which already was smaller than the total number of responses during the other conditions of both experiments, was reduced further when only counting responses with the opportunity for coordination. In the one-key condition of Experiment 1 only 12.7 responses on average across all three dyads were used in the denominator of coordination percentage calculations. Given this small value, even minor changes in coordination from session to session would result in

Table 4

Average number of total and corrected responses during each condition of Experiments 1 and 2

Experiment	Dyad	1 Key		2 Keys		3 Keys	
		Total	Corrected	Total	Corrected	Total	Corrected
1	824/2215	60.0	14.0	281.6	117.5	514.6	393.7
	8964/19841	60.0	12.4	221.5	74.4	375.7	325.3
	4079/7472	60.0	11.8	271.8	96.5	488.0	457.0
	Average	60.0	12.7	258.3	96.1	459.4	392.0
2	19222/19957	982.8	756.8	1106.2	780.9	1232.0	1141.8
	18057/11829	764.5	579.3	1057.4	788.1	1095.4	1054.2
	18390/21055	1274.5	1047.5	1558.8	1242.4	2045.6	2070.9
	Average	1007.3	794.5	1240.8	937.1	1457.6	1422.3

relatively large fluctuations in coordination percentages, leading to the greater variability that occurred in this condition of Experiment 1 exclusively.

The correction procedure also affected the one-key condition to a greater extent than the other conditions because the single transilluminated key could change location from one trial to the next. Although the active key could change location across trials during all conditions, during the one-key condition the active key was the only operative key at any given time. Thus, virtually all responses made throughout a session were directed to the active key and, because an FR 1 schedule was in effect, produced reinforcers and ended the current trial. Sessions were designed so that the active pair was distributed equally across all three keys throughout each session, and thus the start of a new trial often coincided with the active pair changing location to a new key. Because of this rapid switching of the active pair from key to key, only a fraction of the total responses from a session occurred when the same keys were transilluminated in both compartments. During the two-key condition of Experiment 1, by contrast, a second key was transilluminated during each trial. On some trials, responses were made to this key before a response was made to the active key to produce a reinforcer. Therefore, in general there were more responses during trials in the two-key condition of Experiment 1, and consequently more responses that potentially could have been coordinated occurred. The addition of a third transilluminated key in the three-key condition further increased opportunities for coordination.

The VI schedule used in Experiment 2 similarly increased the number of responses that could be made on any given trial. Even during the one-key condition, the fact that, on average, 20 s needed to pass before a response produced a reinforcer meant that more time was spent with the same key transilluminated across compartments, and thus more responses with the potential

for coordination were made. This effect was even more pronounced with the presence of additional keys during the two- and three-key conditions.

Effects of Changing Keys on Coordinated Responses

As noted in the Results section of Experiment 1, the order in which keys were transilluminated during the one- and two-key conditions varied from session to session. Thus, there were differences across sessions in the number of consecutive trials across which the keys that were transilluminated remained the same. In Experiment 1, the more frequently the active pair remained consistent across trials the higher the coordination percentage (Figure 5, top panels). Conversely, when a second key (Figure 5, bottom panels), VI schedule (Figure 11, top panels), or both (Figure 11, bottom panels) were used, no significant relation between the two variables was obtained. These differences suggest that the switching of transilluminated keys further contributed to the variability in coordination percentages during the one-key condition of Experiment 1.

Taken together, the asynchronous FR 1 schedules during the independent-reinforcement phase limited the number of responses with the potential for coordination. Furthermore, session-to-session changes in the number of trials across which the transilluminated keys changed induced variability in the number of coordinated responses across sessions. As a result of the diminished number of potentially coordinated responses, even small changes in the number of coordinated responses across sessions resulted in relatively large changes in coordination percentages.

Future Directions

In addition to demonstrating how mutual-reinforcement contingencies can promote coordinated responding across different schedules of reinforcement and numbers of response

options, the present results suggest several directions for further analysis of coordinated responding as an operant.

Asynchronous Independent Schedules

Addressing the limitations that the use of asynchronous, independent schedules of reinforcement imposed during the one-key condition of Experiment 1 is necessary to eliminate the variability during the independent-reinforcement phase and determine if greater coordination percentages occur during mutual-reinforcement phases under these conditions. This could be done by holding the location of the active pair constant across trials, as opposed to having it distributed equally across all three response options throughout a session. This would have two benefits. First, because the active key would no longer potentially change location with each response, the same pair of keys would remain transilluminated – outside of reinforcer deliveries – for the entire session. Thus, the number of potentially coordinated responses in a given session likely would increase, and any slight session-to-session variations in the number of coordinated responses would have a smaller impact on coordination percentages. Second, the number of consecutive trials across which the same active key was transilluminated would be constant across sessions. Therefore, an additional source of variability in the number of coordinated responses, and in turn coordination percentages, would be eliminated.

Delays to Reinforcement

As described previously, one purpose of the asynchronous, independent schedules of reinforcement during independent-reinforcement phases was to eliminate variable, unsigned delays to reinforcement (cf. de Carvalho et al., 2019). Such delays, however, persisted during the mutual-reinforcement phase because reinforcement was dependent on a pair of responses, one from each dyad member. Whichever dyad member initiated a coordinated response earned a

reinforcer after, at most, a 0.5-s delay (the duration of the mutual-reinforcement contingency), whereas the dyad member to complete the coordinated response earned a reinforcer immediately. Thus, although the elimination of variable, unsigned delays to reinforcement from the independent-reinforcement phase addressed the limitations of de Carvalho et al. (2019) noted in the introduction, it also introduced a difference in conditions across phases that may have influenced the coordination percentages.

One way to address this confounding variable would be to record, throughout the mutual-reinforcement phase, the delays to reinforcement incurred by each dyad member. An average delay to reinforcement then could be calculated for each and introduced to the independent-reinforcement phases as a tandem variable-time (VT) schedule. This would, effectively, yoke delays to reinforcement across mutual- and independent-reinforcement phases, and control for such as a confounding variable that may influence coordination percentages.

Further Assessments of Interval Schedules

Comparatively little attention has been given to coordination under interval schedules (e.g., de Carvalho et al., 2019) compared to under ratio schedules (e.g., de Carvalho et al., 2018, 2019, 2020; Skinner, 1962; Łopuch & Popik, 2011; Tan & Hackenberg, 2016). As such, variables influencing coordinated responding under interval schedules have not been explored sufficiently. One such variable that has been shown to influence coordination under ratio schedules is the schedule of reinforcement. As found by de Carvalho et al. (2018), coordination ratios are significantly greater under intermittent schedules compared to a schedule of continuous reinforcement, and under VR compared to FR schedules. Additionally, the response requirement of a given ratio schedule appears to influence coordination. For instance, de Carvalho et al. (2020) reinforced coordinated responding according to eight different FR schedules and found

that as response requirements increased beyond FR 1 both coordinated response rates and coordinated ratios increased to a point, beyond which they decreased. No similar assessments regarding (1) differences in coordination percentages between FI and VI schedules, as was done for FR and VR schedules, or (2) changes in coordination percentages as a function of rate of reinforcement (interval duration) have been conducted, and thus serve as a promising avenue for future experimentation.

Conclusions

The present results confirm Skinner's (1962) general conclusion that coordination can function as an operant, and extend this finding to other conditions not explored previously by Skinner or others (i.e., de Carvalho et al., 2018, 2019; Tan & Hackenberg, 2016). Coordination percentages systematically decreased as the number of response options increased, demonstrating that the environmental context plays a role in the extent to which coordination occurs. Furthermore, the fact that the effect of the mutual-reinforcement contingency generally decreased with increasing numbers of response options indicates that the effects of mutual-reinforcement contingencies documented in prior experiments using only a single response cannot necessarily be generalized to other contexts.

That the arranged contingencies selectively reinforced coordinated responding indicates that coordination can function as an operant. It therefore follows that, outside of laboratory settings, cooperation among humans could be promoted by enacting similar contingencies selectively reinforcing coordinated responding. Based on the present results, training coordinated responding may be most successful when only one response option with a history of reinforcement is available. Take, for example, a pair of students who together must complete three group projects: one each in Biology, Chemistry, and Physics. Coordinated progress on any

one project during the corresponding class period may be facilitated by putting the materials for the others away, thus precluding work on those subjects.

Nevertheless, the fact that more coordinated responding occurred with a single response option does not mean that only one coordinated response may be trained at a time. During the present experiments, for example, three distinct coordinated responses were trained simultaneously. The effectiveness of the mutual-reinforcement contingency, however, was greater when only the operanda for a single coordinated response were presented (the one-key condition) compared to when the operanda for multiple coordinated responses were available (the two- and three-key conditions). Extending from the example above, the science teachers would not need to coordinate among themselves so that only a single project was assigned at a time. Merely establishing a context in which only one project presently is being worked on – even when the others may be in the future – appears to be sufficient to facilitate coordinated responding.

In the present experiments, manipulating the number of available response options amounted to turning on or off the other pairs of response keys other than the active pair. Outside of the laboratory, however, arranging the environment so that response options are limited may not be accomplished as readily. Continuing with the example above, the equivalent to turning off two of the response keys, thus leaving a single source of reinforcement remaining, would be to restrict access to all other sources of reinforcement in the classroom besides coordinated work on that class's group project. Thus, it is necessary to identify other influences that promote coordinated responding that may be simple to enact in situations in which the number of response options cannot be modified.

According to Skinner (1953), the ultimate goal of behavior analysis is the prediction and control of behavior. To that end, “Any condition or event which can be shown to have an effect upon behavior must be taken into account” (Skinner, 1953, p. 23) as an influence on behavior. According to the present results, coordinated responding functions as an operant sensitive to contingencies of reinforcement. As such, it appears that coordinated responding, and by extension social behavior more generally, can be predicted and controlled within the same general framework as operant behavior examined with single organisms. The present experiments serve as a foundation for future research in a wider array of contexts to explore additional influences on coordination, and in turn establish a broader degree of prediction and control of social behavior.

References

- Arbuckle, J. L., & Lattal, K. A. (1988). Changes in functional response units with briefly delayed reinforcement. *Journal of the Experimental Analysis of Behavior*, *49*(2), 249–263.
<https://doi.org/10.1901/jeab.1988.49-249>
- Bradshaw, C. M., Szabadi, E., & Bevan, P. (1978). Relationship between response rate and reinforcement frequency in variable-interval schedules: The effect of the concentration of sucrose reinforcement. *Journal of the Experimental Analysis of Behavior*, *29*(3), 447–452. <https://doi.org/10.1901/jeab.1978.29-447>
- Chalmeau, R., Visalberghi, E., Gallo A. (1997). Capuchin monkeys, *Cebus apella* fail to understand a cooperative task. *Animal Behaviour*, *54*(5), 1215–1225.
<https://doi.org/10.1006/anbe.1997.0517>
- Crossman, E. L., Bonem, E. J., & Phelps, B. J. (1987). A comparison of response patterns on fixed-, variable-, and random-ratio schedules. *Journal of the Experimental Analysis of Behavior*, *48*(3), 395–406. <https://doi.org/10.1901/jeab.1987.48-395>
- Crossman, E. K., Heaps, R. S., Nunes, D. L., & Alferink, L. A. (1974). The effects of number of responses on pause length with temporal variables controlled. *Journal of the Experimental Analysis of Behavior*, *22*(1), 115–120.
<https://doi.org/10.1901/jeab.1974.22-115>
- Davison, M. & McCarthy D. (1988). *The matching law*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc. <https://doi.org/10.4324/9781315638911>
- de Carvalho, L. C., dos Santos, L., Barbosa, T. B., da Silva, R. F., de Souza, D. D. G., & Sandaker, I. (2018). Cooperative responding in rats maintained by fixed- and variable-

- ratio schedules. *Journal of the Experimental Analysis of Behavior*, *110*(1), 105–126.
<https://doi.org/10.1002/jeab.457>
- de Carvalho, L. C., dos Santos, L., Regaço, A., & de Souza, D. D. G. (2019). Effects of response-reinforcer relations on the maintenance of coordinated responding under schedules of simultaneous reinforcement. *Mexican Journal of Behavior Analysis*, *45*, 382–397. <https://doi.org/10.5514/rmac.v45.i2.75573>
- de Carvalho, L. C., dos Santos, L., Regaço, A., Couto, K. C., de Souza, D. D. G., & Todorov, J. C. (2020). Cooperative responding in rats: II. Performance on fixed-ratio schedules of mutual reinforcement. *Journal of the Experimental Analysis of Behavior*, *114*(3), 291–307. <https://doi.org/10.1002/jeab.628>
- Felton, M., & Lyon, D. O. (1966). The post-reinforcement pause. *Journal of the Experimental Analysis of Behavior*, *9*(2), 131–134. <https://doi.org/10.1901/jeab.1966.9-131>
- Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement*. New York, NY: Appleton-Century-Crofts. <https://doi.org/10.1037/10627-000>
- Fleshler, M. & Hoffman, H. S. (1962). A progression for generating variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, *5*, 529–530.
<https://doi.org/10.1901/jeab.1962.5-529>
- Hake, D. F. & Vukelich, R. (1972). A classification and review of cooperation procedures. *Journal of the Experimental Analysis of Behavior*, *18*, 333–343.
<https://doi.org/10.1901/jeab.1972.18-333>
- Hake, D. F. & Vukelich, R. (1973). Analysis of the control exerted by a complex cooperation procedure. *Journal of the Experimental Analysis of Behavior*, *19*(1), 3–16.
<https://doi.org/10.1901/jeab.1973.19-3>

- Lattal, K. A. (1991). Scheduling positive reinforcers. In I. H. Iversen & L. A. Lattal (Eds.), *Experimental analysis of behavior* (pp. 87–134). New York: Elsevier.
- Lattal, K. A. (2010). Delayed reinforcement of operant behavior. *Journal of the Experimental Analysis of Behavior*, *93*(1), 129–139. <https://doi.org/10.1901/jeab.2010.93-129>
- Lattal, K. A., & Ziegler, D. R. (1982). Briefly delayed reinforcement: an interresponse time analysis. *Journal of the Experimental Analysis of Behavior*, *37*(3), 407–416. <https://doi.org/10.1901/jeab.1982.37-407>
- Łopuch, S., & Popik, P. (2011). Cooperative behavior of laboratory rats (*Rattus norvegicus*) in an instrumental task. *Journal of Comparative Psychology*, *125*(2), 250–253. <https://doi.org/10.1037/a0021532>
- Powell, R.W. (1968). The effect of small sequential changes in fixed-ratio size upon the post-reinforcement pause. *Journal of the Experimental Analysis of Behavior*, *11*(5), 589–593. <https://doi.org/10.1901/jeab.1968.11-589>
- Rescorla, R. A., & Skucy, J. C. (1969). Effect of response-independent reinforcers during extinction. *Journal of Comparative and Physiological Psychology*, *67*(3), 381–389. <https://doi.org/10.1037/h0026793>
- Richards, R. W. (1981). A comparison of signaled and unsignaled delay of reinforcement. *Journal of the Experimental Analysis of Behavior*, *35*(2), 145–152. <https://doi.org/10.1901/jeab.1981.35-145>
- Sidman, M. (1960). *Tactics of scientific research*. Authors Cooperative, Inc.
- Sizemore, O. J., & Lattal, K. A. (1978). Unsignaled delay of reinforcement in variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, *30*(2), 169–175. <https://doi.org/10.1901/jeab.1978.30-169>

- Skinner, B. F. (1953). *Science and human behavior*. New York, NY: Appleton-Century-Crofts.
- Skinner, B. F. (1962). Two “synthetic social relations.” *Journal of the Experimental Analysis of Behavior*, 5(4), 531–533. <https://doi.org/10.1901/jeab.1962.5-531>
- Tan, L. & Hackenberg, T. D. (2016). Functional analysis of mutual behavior in laboratory rats (*Rattus norvegicus*). *Journal of Comparative Psychology*, 130(1), 13–23. <https://doi.org/10.1037/com0000015>
- Visalberghi, E., Quarantotti, B. P., & Tranchida, F. (2000). Solving a cooperation task without taking into account the partner's behavior: The case of capuchin monkeys (*Cebus apella*). *Journal of Comparative Psychology*, 114(3), 297–301. <https://doi.org/10.1037/0735-7036.114.3.297>
- Zeiler, M. D. (1968). Fixed and variable schedules of response-independent reinforcement. *Journal of the Experimental Analysis of Behavior*, 11(4), 405–414. <https://doi.org/10.1901/jeab.1968.11-405>