

Determinants of phrasing effects in rat serial pattern learning

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Received: 24 September 2005 / Revised: 25 October 2006 / Accepted: 23 March 2007
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Abstract Two experiments investigated how brief pauses introduced into serial patterns as phrasing cues would affect pattern learning in rats. In Experiment 1, a 24-element pattern consisted of eight 3-element chunks, whereas a 20-element pattern consisted of four 5-element chunks. In both patterns, 3.0-s temporal pauses placed at chunk boundaries (synchronous phrasing cues) facilitated learning compared to no phrasing. Cues “out of sync” with pattern structure (asynchronous phrasing cues) facilitated learning for the 24-element pattern and retarded learning for the 20-element pattern. Evidence suggested that in the latter case, 3.0-s pauses served as “blank” trials that induced rats to “skip” to the next serial position in sequence. In Experiment 2, shorter 0.5-s pauses served as phrasing cues in the 20-element pattern of Experiment 1. Synchronous short cues facilitated learning, whereas asynchronous phrasing cues had no effect. Furthermore, removal of synchronous cues produced deficits in performance on formerly cued trials, whereas removal of asynchronous cues had no effect. The results of Experiment 2 support the notion that in both experiments phrasing cues served as discriminative cues and indirectly suggest that rats are concurrently sensitive to

pattern element cues, extra-sequence cues (such as phrasing cues), and to the relative timing of sequential events.

Keywords Animal serial-pattern learning · Pattern tracking · Rule learning · Phrasing effects · Serial position

Introduction

Serial learning involves learning to track the elements of a sequence of stimuli or learning to generate a sequence of responses. Evidence suggests that both humans and other animals frequently “chunk” sequences to facilitate learning (Capaldi et al. 1999; Capaldi et al. 1986; Fountain 1990; Fountain and Annau 1984; Fountain et al. 1984; Fountain and Rowan 1995a; Restle 1972; Stempowski et al. 1999; Terrace 1987, 2005). Chunking involves transforming a larger set of information into subsets that are more readily encoded. Pigeons and rats have been shown to chunk sequences into subsequences based on perceptual or conceptual properties of elements (Capaldi and Miller 1988; Terrace 1987), and rats have been shown to chunk sequences based on structural relationships of nonadjacent sequence elements (Fountain and Annau 1984; Fountain et al. 1999b).

Experimental “phrasing” manipulations, such as pauses or other cues inserted into a sequence, can either facilitate or retard serial learning for humans and other animals. Phrasing effects caused by temporal pauses in sequences have been interpreted as effects on how pattern structure is detected and encoded (Fountain 1990; Fountain et al. 1984; Restle 1972), as resulting from discrimination learning phenomena such as overshadowing (Capaldi et al. 1984; Fountain et al. 2000; Stempowski et al. 1999), and, as we shall see in the study to be reported here, as related to the

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timing or serial position of sequential events (cf. Fountain et al. 2002). Evidence is also emerging that sequential learning depends on multiple concurrent psychological processes encompassing all the foregoing (Capaldi and Miller 2004; Fountain 2006; Keele et al. 2003), with much evidence to support this idea coming from recent research on serial pattern learning in rats (Capaldi and Miller 2004; Fountain 2006; Fountain and Benson 2006; Fountain and Rowan 2000; Fountain et al. 2002). The present study provides evidence that, despite outcomes suggesting otherwise in other studies (Fountain et al. 2000), temporal phrasing cues may interact with processes involved in encoding the timing or serial position of rats' sequential responses in performing serial patterns.

In the human serial learning literature on rule learning, a variety of work has shown that the outcome of phrasing manipulations depends on the congruence of phrasing cues and pattern formal structure. Formal structure is a systematic relationship or set of relationships among rules relating pattern elements, such as the repeated occurrence of a single rule or of a set of rules always found in the same order. Rules that relate pattern elements are called lower-order rules. In the formally simple pattern of digits, 1-2-3-4-5-6, for example, a lower order “+1” rule adequately describes the relationships between all pairs of successive pattern elements. This type of formal structure, described by a single rule (only one level of structure), is the simplest that can be devised. However, a sophisticated rule-learner should also be able to use higher-order rules to describe the organization of chunks created by other, lower-order rules. Humans, for example, are able to encode and use hierarchical structures composed of many levels. Rules in higher levels can relate rules in lower levels, thus potentially creating a nested organization. If the nesting of rules is complete, the structure is a hierarchical “tree structure” (Restle 1970).

For example, consider one serial pattern of responses on a circular array of eight levers learned by rats (Fountain and Rowan 1995a): 123 234 345 456 567 678 765 654 543 432. This highly organized pattern is described by a completely nested 3-level hierarchical rule structure; elements within 3-element chunks are related by first-order rules, chunks within the first and second halves of the pattern, respectively, are related to each other by second-order rules, and the first half of the pattern is related to the second half of the pattern by a third-order rule. A formal description of this pattern is

$$(M(T_{+1}^4(T_{+1}^2(1))))$$

where “1” refers to the starting lever, T_{+n} represents a “transpose” rule (i.e., to move n units in the indicated direction in a circular array of eight levers, where + indicates clockwise), M represents a “mirror image” rule, and superscripts reflect the number of repeated applications of

the rule that are required. Because of the nested structural organization, the second-order T_{+1} rule applies a “+1” rule to each item in the first chunk to generate the second chunk, and so on. The third-order M rule produces a “mirror image” (a more complex form of a “reverse” rule) of the first half of the pattern to generate the entire second half of the pattern. It should be noted that whereas this is only one of a number of possible coding schemes that have been developed to describe serial patterns, all reduce to systems that are formally (logically) equivalent (Leeuwenberg 1969).

In this example, the highest-order rules relate the largest number of pattern elements and sets of elements, with lower-order structure nested within the higher-order structure. Because serial patterns with multi-level organization are described by more than one rule, changes in formal structure occur at various points throughout the pattern, specifically, at the boundaries of “chunks” (Miller 1956; Simon 1974). Patterns described by few rules are considered formally simple. As the number of rules needed to describe patterns increases, the patterns become more complex and difficult to learn for both humans and rats (Fountain and Rowan 1995a). Pattern elements that are predicted by rules successively higher in the structural hierarchy are also successively more difficult to learn for both humans and rats (Fountain and Rowan 1995a).

According to rule-learning theory, phrasing cues positioned at transitions between formally defined chunks of a pattern, as defined above, facilitate learning by simplifying the task of detecting and encoding pattern and chunk structure. Synchronous phrasing of this sort has been shown generally to facilitate pattern learning in humans (Bower and Winzenz 1969; Restle 1972) and rats (Fountain et al. 1984; Stempowski et al. 1999; Fountain et al. 2000) relative to no phrasing conditions. In contrast, phrasing cues can be positioned within formal chunks rather than at their formal logical boundaries. Asynchronous phrasing of this sort—phrasing cues “out of sync” with pattern element structure—impairs pattern learning in humans (Bower and Winzenz 1969; Restle 1972) and rats (Fountain et al. 1984) relative to no phrasing conditions. The rule-learning hypothesis predicts that synchronous and asynchronous phrasing should always have opposite effects on acquisition and performance, whereas other interpretations might predict other outcomes.

Another prominent hypothesis is that phrasing cues in sequences facilitate chunking by acting as discriminative cues that signal specific stimuli, responses, or sequences of stimuli or responses (Capaldi et al. 1984; Fountain et al. 2000; Stempowski et al. 1999; Terrace 1987). According to this view, phrasing cues facilitate learning by reducing interference in memory for items in sequence or by cueing

specific events or responses (Capaldi et al. 1984; Fountain et al. 2000; Stempowski et al. 1999; Terrace 1987).

Recently, Stempowski et al. (1999) and Fountain et al. (2000) found additional support for the view that discrimination learning mediates phrasing effects. Stempowski et al. (1999) examined 2- and 3-level hierarchical patterns (in “Experiments 1 and 2”, respectively) with either no, short, or long pauses as phrasing cues positioned at the boundaries of formally-defined chunks (synchronous phrasing). “Experiment 1” showed that when distinct temporal intervals preceded chunk boundaries, regardless of whether the intervals were longer or shorter than intervals within chunks, phrasing cues facilitated pattern learning. “Experiment 2” showed that phrasing cue removal produced severe deficits in tracking Element 1 of chunks, the element directly after the phrasing cues during acquisition. The results indicated that rats used both short and long temporal phrasing cues as discriminative cues, and that facilitated learning due to phrasing is not the result of additional processing time provided by longer intertrial intervals at chunk boundaries. Furthermore, many of the finer details of the results could be accounted for by the additional assumption that phrasing cues overshadowed interitem associations (Stempowski et al. 1999). In a related study, Fountain et al. (2000) positioned phrasing cues at four of eight chunk boundaries in an 8-chunk pattern. For some groups, phrasing cues consistently parsed the pattern into “rhythmic” sequences, whereas for other groups, the four phrasing cues appeared at random chunk boundaries that produced an unpredictable “arrhythmic” structure. Rats learned the sequences with the same number of phrasing cues at the same rate no matter how they were presented, so that the effects of temporal phrasing cues were predicted less by their rhythmicity than by the common discrimination learning notion that associative strength is a function of the number of stimulus-response pairings. These results seemed to indicate that the only function that phrasing cues served was to cue the next response after the temporal interval in the manner of traditional discriminative cues, and that the temporal cues played no role in the temporal organization of the pattern. An unanticipated result of the present study will show that temporal intervals inserted into serial patterns as phrasing cues are not restricted to this role in sequence production in rats.

Earlier studies of synchronous and asynchronous phrasing effects in rats¹ examined the determinants of

¹ It should be noted that in both of the reports by Restle (1972) in humans and by Fountain et al. (1984) in rats, synchronous and asynchronous phrasing manipulations were termed “good” and “bad” phrasing, respectively. They were so named because of the “good” or “bad” correspondence between cues and formally defined pattern structure, not because they produced good or bad performance. We prefer the terms “synchronous” and “asynchronous” phrasing to

phrasing effects when rats anticipated food quantity sequences in runways (Capaldi et al. 1984; Fountain et al. 1984). In contrast, recent studies supporting the discrimination learning view of phrasing employed a quite different serial learning task. In the studies by Stempowski et al. (1999) and Fountain et al. (2000), rats learned to produce a response sequence by anticipating successive lever locations in a circular array of eight levers. Patterns were highly structured response sequences, and phrasing cues were always positioned at the boundaries of formally defined chunks, that is, all experiments employed synchronous rather than asynchronous phrasing manipulations. Thus, it is not clear whether synchronous and asynchronous phrasing effects comparable to those found in earlier food-quantity sequence studies would be observed in this new paradigm, so “Experiment 1” attempted to replicate earlier synchronous versus asynchronous phrasing effects relative to no phrasing control conditions in the patterned response task. “Experiment 2” was designed to examine the nature of the phrasing effects observed in “Experiment 1” that appeared to be due to interactions of temporal phrasing cues with the serial position or timing of rats’ responses.

Experiment 1

In Experiment 1, rats learned to produce a response sequence by anticipating successive lever locations in a circular array of eight levers. Patterns were highly structured response sequences composed of 3-element chunks or 5-element chunks:

3-Element chunks	123-345-567-781-187-765-543-321
5-Element chunks	12345-56781-18765-54321

Digits indicate the order of correct responses on levers in an 8-lever circular array (numbered 1-8 in a clockwise manner). The 3-element chunks pattern has the 3-level “nested” formal structure: $(M(T_{+2}^3(T_{+1}^2(1))))$. The 5-element chunks pattern has the 3-level “nested” formal structure: $(M(T_{+4}^1(T_{+1}^4(1))))$. It should be noted that these are the simplest possible formal descriptions of the patterns, but rats could choose to learn some other representation of the pattern that would require encoding additional information. Phrasing cues were positioned either at the boundaries of formally defined chunks (synchronous phrasing), indicated by the dashes in the patterns above, or between elements within formally defined chunks (asynchronous phrasing). For each pattern type, a control group experienced the pattern without phrasing.

Footnote 1 continued

“good” and “bad” phrasing because the former clearly refer to the positioning of phrasing cues relative to element structure.

It is important to note that the term “chunk” as used here thus refers to the logical grouping of elements as defined by the formal structure of the pattern, not by the placement of phrasing cues. In this definition of the term, it follows that chunks do not change by positioning cues differently in the pattern. Phrasing cue conditions, then, are designated in terms of the positioning of cues relative to the boundaries of these formally defined structural chunks.

The rule learning view of phrasing predicts that synchronous phrasing should always facilitate pattern learning and tracking performance relative to no phrasing, whereas asynchronous phrasing should always retard pattern learning and impair performance. The discrimination learning view, on the other hand, predicts that element anticipation should be a function of the validity, salience, and discriminability of cues that signal the element (Capaldi et al. 1999; Fountain et al. 2000; Stempowski et al. 1999). Generally, phrasing cues should either facilitate learning when they are more valid, discriminable, or salient than other cues, or they should have no effect on acquisition when they are not. In the latter case, less valid, discriminable, or salient phrasing cues should be overshadowed by other cues. The discrimination learning view does not predict that asynchronous phrasing cues should retard pattern learning.

Method

Subjects

The subjects were 36 naïve male hooded rats. All were implanted with bipolar electrodes (MS301, Plastic Products, Roanoke, VA) for hypothalamic brain-stimulation reward (coordinates, skull level: 4.5 mm posterior, 1.5 mm lateral, 8.5 mm below the surface of the skull). Rats were deeply anesthetized by 35.56 mg/kg ketamine and 3.56 mg/kg xylazine i.p. injection before surgery and received antibiotics (60,000 units of penicillin intramuscularly) to reduce the chance of infection after surgery. They were also carefully monitored for infection after surgery and were provided at least 1 week for recovery from surgery. Rats were housed in individual cages with food and water freely available on a 14:10 h light:dark cycle and were tested during the light portion of the cycle.

Apparatus

Two shaping chambers (30 × 30 × 30 cm), each equipped with a single response lever and a commutating device centered in the ceiling, were used for shaping the lever press response for brain-stimulation reward. Each was

constructed of clear Plexiglas with a floor of stainless steel rods, and each was enclosed in a sound-attenuating shell made of particle board (20 × 60 × 65 cm). These shaping chambers were housed in a room different from that of the test chamber.

The test chamber was octagonal in shape (walls are 15 cm wide and 30 cm tall; it measured approximately 40 cm between parallel walls) and was composed of clear Plexiglas walls and a floor of hardware cloth (Fountain and Rowan 1995a, b). A retractable response lever was centered on each wall 5.0 cm above the floor. Each lever required approximately 0.15 N force for activation. Rats in the testing chamber were connected to a stimulator by way of a flexible cord (Plastic Products MS304) and a commutating device centered in the ceiling of the chamber. The operant chamber was located in a testing room (approximately 2 × 2.6 m) illuminated throughout testing by fluorescent lighting. In addition to the test chamber, the room also contained a small table and a closed circuit TV camera on a tripod. Experiments were controlled from an adjoining room using a microcomputer and interface (interface and Med-State Software; Med Associates Inc., Fairfield, VT).

Procedure

Throughout the experiment, rats received reinforcement consisting of single 250-ms brain-stimulation reward “pulses” of a 60-Hz sinusoidal pulse train from a constant current source of 20–80 μ A. In all procedures, rats received one such pulse for each correct response.

After at least 1 week of recovery from surgery, rats were shaped to lever press for brain-stimulation reward in a Plexiglas shaping chamber. Rats that failed to learn to lever press in two 30-min sessions were excluded from the experiment. As is common in studies involving hypothalamic implants, approximately 20% of the implanted rats failed to meet the lever-pressing criterion and were excluded from the study.

After the rats were shaped to lever press for brain-stimulation reward pulses, they were randomly divided into equal groups and trained daily in the octagonal operant chamber in a discrete-trial 8-choice procedure with correction for errors. At the beginning of each trial, all eight levers were inserted into the chamber. If a correct choice was made, all levers were retracted and brain-stimulation reward was administered. If an incorrect choice was made, all levers but the correct lever were withdrawn and the rat was required to produce the correct response to obtain brain-stimulation reward before continuing to the next trial. That is, rats were never reinforced for incorrect responses, and they were always forced back “on track” after an error

before continuing through the pattern. On each trial, the lever chosen and the latency to the first response were recorded.

Groups differed in the pattern they were required to learn and in where phrasing cues were positioned within the pattern. Three groups of rats in each of two pattern conditions received either no, synchronous, or asynchronous phrasing cues. Three groups of rats received the following 3-element-chunks patterns:

No phrasing	12334556778187765543321...
Synchronous phrasing	123-345-567-781-187- 765-543-321-...
Asynchronous phrasing	1-233-455-677-811-877- 655-433-21...

Three other groups of rats received the following 5-element chunks patterns:

No phrasing	12345567811876554321...
Synchronous phrasing	12345-56781-18765-54321-...
Asynchronous phrasing	123-45567-81187-65543-21...

For all groups, the digits indicate the clockwise position of the correct lever in the chamber (lever 1 was always the same lever in a given chamber) on a given trial, dashes indicate 3-s pauses that served as phrasing cues, and all other intervals between trials were 1 s. All rats received 20 repetitions of their assigned pattern without breaks between pattern repetitions each day for 14 days. For the no phrasing groups, their pattern was presented 20 repetitions per day without breaks between chunks or pattern repetitions, that is, as an uninterrupted sequence of 480 or 400 trials separated by 1-s ITIs for the 3- and 5-element-chunks patterns, respectively. It should be noted that for asynchronous phrasing groups, no break between pattern repetitions produced chunks spanning the boundaries of patterns in the manner of ...-211-... for the 3-element-chunks pattern and ...-21123-... for the 5-element-chunks pattern. Thus the number of phrasing cues encountered by phrased conditions was approximately the same within pattern types. The 3-element-chunks groups encountered 159 and 160 phrasing cues daily in the synchronous and asynchronous conditions, respectively. Similarly, the 5-element-chunks groups encountered 79 and 80 phrasing cues daily in the synchronous and asynchronous conditions, respectively.

Results

Acquisition

Results from the acquisition phase of the experiment showed that phrasing cues produced different results in the two types of patterns. In the 3-element-chunks pattern, both

synchronous and asynchronous phrasing facilitated learning relative to no phrasing. In the 5-element-chunks pattern, synchronous phrasing facilitated learning as it did for the 3-element-chunks pattern, but asynchronous phrasing did not. In the 5-element-chunks pattern, asynchronous phrasing briefly retarded learning relative to no phrasing.

Figure 1 shows daily mean errors compared for rats of no, synchronous, and asynchronous phrasing conditions over the course of the 14 days of training with the 3-element-chunks pattern (top panel) and the 5-element-chunks pattern (bottom panel). For the 3-element-chunks pattern, the results show that when the pattern had synchronous or asynchronous phrasing, it was easier to learn than when it had no phrasing. An analysis of variance (ANOVA) was conducted on rats' daily mean percent errors (pooled across pattern elements). The ANOVA indicated significant main effects for days, $F_{(13,195)} = 289.84$, $P < 0.001$, and a significant interaction of phrasing groups \times days, $F_{(26,195)} = 2.82$, $P < 0.001$. Planned comparisons based on the appropriate error term from the ANOVA showed that

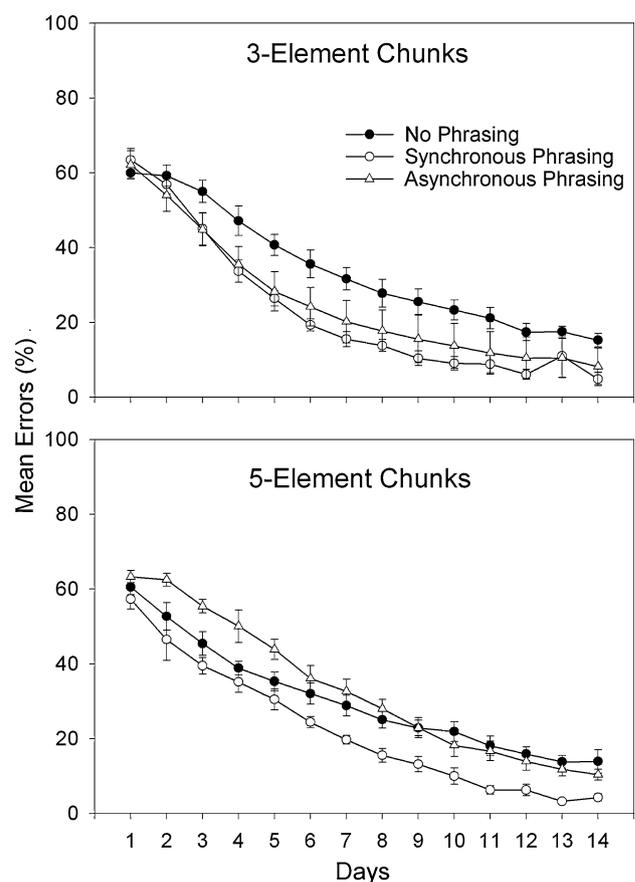


Fig. 1 Acquisition for groups learning the 3-element-chunks pattern or the 5-element chunks pattern (top and bottom panel, respectively) with no phrasing, synchronous phrasing, or asynchronous phrasing over the 14 days of acquisition of “Experiment 1”. Daily mean errors were averaged across elements of the patterns

synchronous and asynchronous phrasing rats trained with the 3-element-chunks pattern produced significantly fewer errors compared to no phrasing rats on days 3–14 of the experiment. Synchronous and asynchronous phrasing groups never differed ($P > 0.05$).

For the 5-element-chunks pattern, the results (Fig. 1, bottom panel) show that when the pattern had synchronous phrasing, it was easier to learn than when it had no phrasing. However, asynchronous phrasing briefly retarded learning relative to no phrasing (see planned comparisons below). An analysis of variance (ANOVA) conducted on rats' daily mean percent errors indicated significant main effects for phrasing groups, $F_{(2,15)} = 8.77$, $P = 0.003$, and days, $F_{(13,195)} = 297.69$, $P < 0.001$, and a significant interaction of phrasing groups \times days, $F_{(26,195)} = 2.77$, $P < 0.001$. Planned comparisons showed that synchronous phrasing rats produced significantly fewer errors compared to no phrasing rats beginning on day 2 (excepting day 4) and asynchronous phrasing rats produced significantly more errors compared to no phrasing rats on days 2–5, and more than synchronous phrasing rats every day.

Error profiles and intrusions in 3-element-chunks patterns

The top and bottom panels of Fig. 2 show rats' group mean element-by-element percent error rates for the 14 days of the experiment for the no, synchronous, and asynchronous phrasing groups of the 3- and 5-element-pattern groups, respectively. The series of correct lever choices is shown on the lower x -axis of each panel, whereas the serial position of each trial is shown on the top. The boundaries of formally defined chunks are indicated by vertical dashed lines. Phrasing cue locations are indicated by breaks in lines connecting successive points in the figures. Thus, breaks in lines connecting the points of the synchronous phrasing group occur at the same positions as the vertical lines indicating formally defined chunk boundaries, whereas breaks in error curves for asynchronous phrasing occur at other positions within formally defined chunks. Group mean percent error was calculated as the average of rats' percentage of error on a given trial across all 14 days of training. It should be noted that by the end of training, rats' performance was quite good throughout the patterns, with error rates on any element of the patterns for all phrasing groups not exceeding 30% except for a single trial (SP 12 in the asynchronous 5-element chunk group).

The most salient feature of the error profiles for the 3-element chunks groups (shown in the top panel of Fig. 2) was the difficulty rats in all groups had learning to respond to the second element of Chunks 1 and 5 (i.e., SP 2 and 14). For all three groups, these pattern elements produced significantly more errors than any other element of their

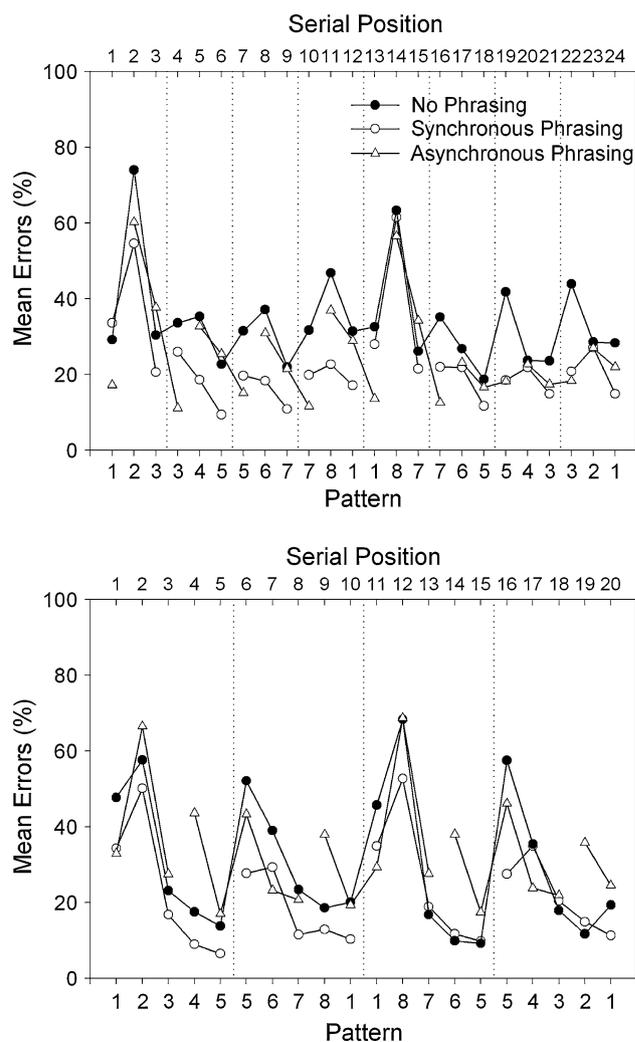


Fig. 2 Group mean element-by-element errors for the 3-element-chunks pattern or the 5-element chunks pattern (*top and bottom panel*, respectively) with no phrasing, synchronous phrasing, or asynchronous phrasing. *Vertical dotted lines* indicate boundaries between structural chunks of the pattern, whereas breaks in lines connecting data points indicate the locations of pauses that served as phrasing cues. Errors were averaged across the 14 days of “Experiment 1”

respective patterns; similar increases in error rates were not observed on the second element of other chunks. These results fit well with the rule-learning prediction that chunks at higher-order rule transitions in patterns should be more difficult than those at lower-order rule transitions, but the fact that it is the second element of these chunks that are difficult, not the first, suggests that rats did not learn the simplest possible nested structure that describes the pattern. Another important observation was that on these trials the asynchronous phrasing group made high rates of errors that were either perseverations of the last response or apparent rule-consistent overextensions of the run of the preceding chunk, but they did not appear to cognitively “skip” trials 2 and 13 to produce a “3” response in SP 2 or a “7”

response on SP14 (both these responses represented only a 0.02 average proportion of the errors observed on those trials). Synchronous phrasing rats also showed a low rate of errors on trials following phrasing cues that would appear to be “skipped” trials.

It was also observed during acquisition that in the 3-elements-chunks pattern, both synchronous and asynchronous phrasing facilitated overall pattern learning relative to no phrasing. The results in the top panel of Fig. 2 show that synchronous phrasing facilitated learning of elements much more uniformly throughout the pattern relative to no phrasing than did asynchronous phrasing. Asynchronous phrasing facilitated learning most for the first elements of logical chunks, which was the third element after presentation of the asynchronous phrasing cue. A detailed analysis of differences that contributed to these between and within groups effects for rats trained on the 3-element chunks pattern follows.

For the 3-element chunks groups, an ANOVA on element-by-element means for the data pooled for the entire experiment indicated a significant main effect for chunks, $F_{(7,105)} = 64.02$, $P < 0.001$, and elements within chunks, $F_{(2,30)} = 25.82$, $P < 0.001$. The chunks factor refers to performance on the eight 3-element chunks of the pattern, and elements within chunks refers to performance on the three pattern elements within each chunk. Significant interactions included groups \times chunks, $F_{(14,105)} = 2.17$, $P = 0.014$, groups \times elements, $F_{(4,30)} = 5.01$, $P = 0.003$, chunks \times elements, $F_{(14,210)} = 23.12$, $P < 0.001$, and groups \times chunks \times elements, $F_{(28,210)} = 2.36$, $P < 0.001$. Other effects were not significant ($ps > 0.05$).

Planned comparisons for the data shown in Fig. 2 (top panel) indicated that synchronous phrasing improved performance relative to no phrasing more uniformly throughout the pattern than did asynchronous phrasing. Specifically, synchronous phrasing rats produced fewer errors relative to no phrasing rats at serial positions (SPs) 2, 5–12, 16, 19, 22, and 24. Asynchronous phrasing rats produced fewer errors relative to no phrasing rats at SPs 1, 2, 4, 7, 10, 13, 16, 19, and 22. Closer examination shows that, of these SPs, 8 of 13 were within-chunk elements (the second or third elements of chunks) for synchronous phrasing rats, whereas 8 of 9 were the first elements of chunks for asynchronous phrasing rats. For no phrasing rats, the last element of chunks, found in SPs 3, 6, 9, 12, 15, 18, 21, and 24, were easier to learn than the first elements of their respective chunks in Chunks 2, 6, 7, and 8 (SPs 4, 16, 19, and 22) and the second elements in Chunks 1–5 (SPs 2, 5, 8, 11, and 14). Similarly, results for synchronous phrasing rats show that the last element of Chunks 1, 2, 5, 6, and 8 (SPs 3, 6, 15, 18, and 21) were easier to learn than the first element of their respective chunks in Chunks 1, 2, and 6 (SPs 1, 4, and 16) and the second element in Chunks

1, 5, and 8 (SPs 2, 14, and 23). For asynchronous phrasing rats, the first element of Chunks 1–6, found in SPs 1, 4, 7, 10, 13, and 16, were easier to learn than the second elements of their respective chunks in Chunks 1–6 (SPs 2, 5, 8, 11, 14 and 17) and the third elements in Chunks 1, 2, 4, and 5 (SPs 3, 6, 12, and 15). The specific kinds of incorrect responses, termed “intrusions,” rats made during the 14 days of the experiment were examined. On trials following chunk boundaries, namely, SPs 1, 4, 7, 10, 13, 16, 19, and 22, a response to the last correct lever or “same lever” response was correct. However, a common intrusion was to produce the same left or right turn that produced the last correct response. Thus, the no phrasing group produced 0.75 average proportion of right turns during the first half of the pattern (SPs 1, 4, 7 and 10) and 0.74 average proportion left turns during the second half of the pattern (SPs 13, 16, 19, and 22). Comparable average proportions were obtained with the asynchronous phrasing group, namely, 0.62 average proportion of right turns during the first half of the pattern (SPs 1, 4, 7 and 10) and 0.72 average proportion left turns during the second half of the pattern (SPs 13, 16, 19, and 22). In the synchronous phrasing group, but not in the other groups, phrasing cues were positioned just before these target trials. The synchronous phrasing group produced 0.33 average proportion of right turns during the first half of the pattern (SPs 1, 4, 7 and 10) and 0.33 average proportion left turns during the second half of the pattern (SPs 13, 16, 19, and 22). Thus synchronous phrasing cues before these trials reduced the tendency to repeat right or left turn responses and increased the likelihood of a correct “same lever” response. Asynchronous phrasing cues did not have the former effect of reducing the tendency to repeat right or left turns, but they did increase the likelihood of a correct response.

Error profiles and intrusions in 5-element-chunks patterns

For the 5-element-chunks pattern, acquisition data showed that synchronous phrasing, but not asynchronous phrasing, facilitated overall pattern learning compared to no phrasing. As shown in the bottom panel of Fig. 2, synchronous phrasing rats produced fewer errors relative to no phrasing rats at a number of points throughout the pattern. Asynchronous phrasing, on the other hand, produced paradoxical effects, namely, fewer errors relative to no phrasing on the first one or two elements of structural chunks but more errors than no phrasing on elements immediately after the misplaced phrasing cue (at SPs 4, 9, 13, and 19). An examination of the kinds of errors committed on these trials revealed that in the 5-elements-chunks pattern, rats in the asynchronous phrasing group committed many errors that can be characterized as

“skipping” a trial. That is, on Trial 4 of Chunk 1 (with the sequence 1-2-3-4-5), rats responded “5” rather than “4” on Trial 4. This type of error occurred more than twice as often in the asynchronous phrasing group as in the no or synchronous phrasing groups (0.31 vs. 0.14 and 0.16 of the time, respectively), and this was the most frequent error type on these trials for asynchronous phrasing rats. Thus, asynchronous phrasing in the 5-element-chunks pattern increased the likelihood that rats would “skip” a trial at the point of the phrasing cue.

In addition to the foregoing differences between groups, a salient feature of the error profiles for all groups was rats’ difficulty learning to respond to the second element of Chunks 1 and 3 (i.e., SPs 2 and 12). For all three groups, these pattern elements produced significantly more errors than any other element of their respective patterns with the exception of SP 16 for the no phrasing pattern ($P > 0.05$). Rats did tend to find the first elements of chunks to be more difficult than elements late in logical chunks, but not as difficult as the second elements of the first and third chunks. These results, like the corresponding results for the 3-element chunk groups, fit well with the rule-learning prediction that chunks at higher-order rule transitions in patterns should be more difficult than those at lower-order rule transitions, but the fact that it is the second element of these chunks that are difficult, not the first, suggests that rats did not learn the simplest possible nested structure that describes the pattern. A detailed analysis of differences that contributed to these between and within groups effects for rats trained on the 3-element chunks pattern follows.

For the 5-element chunks groups, an ANOVA on element-by-element means for the data pooled for the entire experiment indicated a significant main effect for groups, $F_{(2,15)} = 9.02$, $P = 0.003$, chunks, $F_{(3,45)} = 6.68$, $P < 0.001$, and elements, $F_{(4,60)} = 127.10$, $P < 0.001$. Significant interactions included groups \times elements, $F_{(8,60)} = 12.56$, $P < 0.001$, chunks \times elements, $F_{(12,180)} = 31.16$, $P < 0.001$, and groups \times chunks \times elements, $F_{(24,180)} = 4.04$, $P < 0.001$.

Planned comparisons indicated significant differences between elements in the discussion that follows. Synchronous phrasing rats produced fewer errors relative to no phrasing rats at SPs 1, 6–8, 10–12, and 16. Asynchronous phrasing, on the other hand, produced paradoxical effects, namely, fewer errors relative to no phrasing on the first one or two elements of structural chunks (at SPs 1, 6–7, 11, and 16–17) but more errors than no phrasing on elements adjacent to the misplaced phrasing cue (at SPs 4, 9, 13–14, and 19). Additionally, no and synchronous phrasing rats produced significantly more errors on the second element of Chunks 2 and 4 (SPs 7 and 17) relative to the third, fourth, and fifth elements of all chunks. The latter effect was not observed in the asynchronous phrasing condition.

Results for no phrasing rats indicate that the last three elements of chunks, found in SPs 3–5, 8–10, 13–15, and 18–20, were easier to learn than the first two elements of their respective chunks in SPs 1–2, 6–7, 11–12, and 16–17. The same pattern of results was obtained for synchronous phrasing rats with the exception that error rates did not differ for SPs 16 versus 18 ($P > 0.05$). Asynchronous phrasing rats made fewer errors on the last element of structural chunks (SPs 5, 10, 15, and 20) than on the first elements of chunks (SPs 1, 6, 11, and 16). On trials following chunk boundaries, namely, SPs 1, 6, 11, and 16, for 3-element-chunks groups, a common intrusion was to produce the same left or right turn that produced the last correct response. Thus, the no phrasing group produced 0.70 average proportion of right turns during the first half of the pattern (SPs 1 and 6) and 0.76 average proportion left turns during the second half of the pattern (SPs 11 and 16). Comparable average proportions were obtained with the asynchronous phrasing group, namely, 0.71 average proportion of right turns during the first half of the pattern (SPs 1 and 6) and 0.77 average proportion left turns during the second half of the pattern (SPs 11 and 16). The synchronous phrasing group produced 0.29 average proportion of right turns during the first half of the pattern (SPs 1 and 6) and 0.29 average proportion left turns during the second half of the pattern (SPs 11 and 16). Thus synchronous phrasing cues before these trials reduced the tendency to repeat right or left turn responses and increased the likelihood of a correct “same lever” response, as they did for the 3-element-chunks pattern. Asynchronous phrasing cues did not have the former effect of reducing the tendency to repeat right or left turns, but they did increase the likelihood of a correct response.

Discussion

Rats in all groups of “Experiment 1” found the first chunk of each half of their pattern to be more difficult than other chunks. The second element of these two chunks were the most difficult to anticipate compared to all other elements of the pattern. In general, the first element of all chunks were the next most difficult to learn, with elements at the end of chunks typically the easiest to learn. These results are consistent with the predictions of rule-learning theory which states that the difficulty of pattern elements should be directly related to the hierarchical level of rules required to predict the element, since within-chunk elements should be predicted or generated based on lower-order rules, chunk boundary elements should be predicted or generated by second-order rules, and the beginning elements of each half of the pattern should be predicted or generated by third-order (the highest-order) rules. The exception to this

general claim is that errors should be most frequent at the first element of chunks at the beginning of each half of the pattern; in “[Experiment 1](#)”, errors were concentrated at the second element of these chunks. This effect probably resulted from rats’ tendency, like that of humans, to make frequent errors of overextending lower-order structures, namely, to continue applying the same rules in these chunks that were appropriate for earlier chunks in the pattern. Such overextensions in this pattern actually produce correct responses at the critical chunk boundaries: an overextension of the sequence 123 345 567 781 would naturally lead to a “1” response, which would be a correct response in this pattern. Continuing the overextension would lead to high error rates on the next trial, where rats produced high rates of “2” errors as expected from this overextension of pattern structure. Once this error was corrected, rats generally produced low error rates on successive trials until the next chunk boundary. By the end of the experiment, rats with synchronous and asynchronous phrasing cues averaged less than 20% errors on these trials, indicating that though these pattern locations were more difficult to learn, rats did in fact learn how to perform at these transition points without permanently relying on errors as feedback cues to control their behavior at higher-order rule transitions in the pattern.

Both long and short temporal pauses used as phrasing cues at chunk boundaries (synchronous phrasing) have been shown to facilitate serial pattern learning relative to no phrasing when the cues signal a consistent left or right turn (Stempowski et al. 1999, Experiment 1; Fountain et al. 2000) and when the cues signal a left turn in one half of a pattern and a right turn in the other half (Stempowski et al. 1999, Experiment 2). In Experiment 1 here, a long pause positioned at chunk boundaries facilitated serial pattern learning in both 3- and 5-element-chunks patterns relative to no phrasing, and the cue signaled a repetition of the response after the cue. Thus, as a general rule, long and short pauses have been shown to facilitate acquisition relative to no phrasing when they are positioned at chunk boundaries, but the results of “[Experiment 1](#)” show that the same temporal pause that facilitated pattern acquisition when positioned at chunk boundaries (synchronous phrasing) may interfere with learning when positioned within chunks (asynchronous phrasing).

Synchronous and asynchronous phrasing produced results predicted by the rule learning view for patterns composed of 5-element chunks, that is, synchronous phrasing facilitated acquisition and asynchronous phrasing retarded acquisition relative to no phrasing as similar manipulations do in food quantity patterns (Capaldi et al. 1984; Fountain et al. 1984). However, the results for patterns composed of 3-element chunks contradicted predictions of the rule learning view of phrasing effects and

failed to replicate the synchronous versus asynchronous phrasing effects that have been observed in the rat food quantity series literature (Capaldi et al. 1984; Fountain et al. 1984). In patterns composed of 3-element chunks, both synchronous and asynchronous phrasing facilitated pattern acquisition. The latter effect—facilitated acquisition due to asynchronous phrasing—was not predicted a priori by the rule learning view.

The results of “[Experiment 1](#)” also seem to contradict predictions of the discrimination learning view. When rats learned patterns composed of 5-element chunks with asynchronous phrasing, their performance was disrupted on trials immediately following phrasing cues. The discrimination learning view has difficulty explaining such effects because this view does not predict conditions under which an added cue can retard acquisition. Because the discrimination learning view predicts that cues acquire associative strength as a function of their validity, discriminability, and salience (Capaldi et al. 1999; Fountain et al. 2000; Stempowski et al. 1999), a cue such as the temporal cue in asynchronous phrasing should have the capacity to facilitate acquisition, but should never retard acquisition through discrimination learning processes. Such a cue can conceivably facilitate acquisition, but it should simply not acquire associative strength if it is not more valid. Facilitated acquisition for synchronous phrasing in both patterns and asynchronous phrasing in the 3-element-chunks pattern is consistent with this view. However, retarded acquisition on trials following asynchronous temporal cues in the 5-element-chunks pattern is not consistent with this view of phrasing cues as discriminative cues.

Closer inspection of the intrusion analysis for “[Experiment 1](#)” turned up effects suggesting yet another explanation of the observed phrasing effects. Rats with asynchronous phrasing, after experiencing the pause between Elements 3 and 4 in each chunk, on Element 4 produced the response appropriate for Element 5 of the chunk, and they did so at more than twice the rate of rats with synchronous or no phrasing. Given that the phrasing cue interval was 3 s, which is approximately the duration of a normal trial and ITI, it seemed possible that rats treated the phrasing cue as a “blank” trial, which led to a mistaken perception of their serial position in the pattern. “[Experiment 2](#)” was designed to evaluate the extent to which the synchronous and asynchronous phrasing effects observed in “[Experiment 1](#)” could be accounted for by rule learning, discrimination learning, and sensitivity to serial position.

Experiment 2

The goal of Experiment 2 was to pit the discrimination learning view along with the idea of sensitivity to serial

position against rule learning explanations of phrasing effects. Why this particular configuration of explanations? Recent studies have strongly supported the view that phrasing effects in this paradigm can be described as discrimination learning phenomena (Fountain et al. 2000; Stempowski et al. 1999). The only phenomenon observed in “Experiment 1” that would contradict this view was retardation of acquisition caused by asynchronous phrasing in 5-element-chunks patterns, and this effect can potentially be accounted for by mistakes in perception of serial position induced by temporal pauses inserted in the sequence.

To test the idea that phrasing effects can be accounted for by discrimination learning, “Experiment 2” attempted to disentangle the effects of temporal intervals as discriminative cues from the potential effects of temporal intervals on rats’ perception of serial position. The logic was to replace the long (3.0 s) temporal intervals used as cues in “Experiment 1” with shorter (0.5 s) temporal intervals in “Experiment 2” to minimize the perception of “skipped trials” that might be caused by longer temporal breaks in a pattern. It should be noted that 0.5-s temporal intervals were used as phrasing cues by Stempowski et al. (1999), and 0.5-s intervals were found to be at least as effective as longer intervals as cues even though they were shorter than ITIs between within-chunk elements. In “Experiment 2”, rats experienced the same 5-elements-chunks pattern with the same positioning of cues in synchronous and asynchronous phrasing as employed in “Experiment 1”, and the only difference was that phrasing cues were 0.5-s rather than 3.0-s intervals (ITIs were 1.0-s intervals as in “Experiment 1”).

Several predictions were made a priori based on the ideas that phrasing effects are the result of discrimination learning processes and that short cues would not affect rats’ perception of serial position. First, because the temporal intervals were short, asynchronous phrasing should not produce an increased tendency to “skip” a trial after the cue. Second, given that right turns frequently signal other right turns in the first half of the pattern, and left turns frequently signal other left turns in the second half, temporal phrasing cues positioned within chunks (asynchronous phrasing) should be overshadowed by proprioceptive cues for signaling what response to perform on Element 4 of chunks. Therefore, we predicted little if any effect of asynchronous phrasing on acquisition. Third, because temporal intervals are much more valid than proprioceptive cues for anticipating what to do at chunk boundaries, synchronous phrasing should acquire significant amounts of associative strength and should facilitate learning relative to no phrasing. Finally, the discrimination learning view predicts that effects of cue removal should depend on the amount of associative strength acquired by a cue. This view predicts that removal of synchronous phrasing cues will produce severe deficits in

responding at chunk boundaries, but removal of asynchronous phrasing cues will produce little or no effect.

In contrast, the rule learning view predicts that synchronous and asynchronous phrasing with short (0.5-s) cues will parallel the effects observed in “Experiment 1”. That is, synchronous phrasing should facilitate acquisition because it highlights pattern structure, and asynchronous phrasing should retard acquisition because it obscures pattern structure. Furthermore, according to the rule learning view, synchronous phrasing cues facilitate learning by highlighting salient features of pattern structure such as chunk boundaries. According to this hypothesis, synchronous phrasing cues do not cue responses; rather, they facilitate encoding pattern structure. Thus, the rule learning view predicts savings in pattern tracking relative to no phrasing even after synchronous phrasing cues are removed (for a similar argument, see Fountain et al. 1984; Stempowski et al. 1999).

Method

Subjects

The subjects were 17 naïve male hooded rats prepared and maintained as in “Experiment 1”.

Apparatus

The apparatus was the same as that used in “Experiments 1”.

Procedure

In Experiment 2, the training procedures were the same as those reported in “Experiment 1” for 5-element-chunks patterns with the exception that rats experienced phrasing cues of different temporal duration. For all rats, the correct response sequence was the same. Groups differed according to the placement of phrasing cues they received within the 5-element-chunks pattern; they received synchronous, asynchronous, or no phrasing cues, as shown below.

Synchronous phrasing	12345 * 56781 * 18765 * 54321 *...
No phrasing	12334556778187765543321...
Asynchronous phrasing	123 * 45567 * 81187 * 65543 * 21...

As before, for all groups, the digits indicate the clockwise position of the correct lever on a given trial, asterisks indicate 0.5-s intertrial intervals that served as phrasing

cues, and all other intervals between trials were 1.0 s. As before, rats received 20 repetitions of their pattern (i.e., 400 trials) without interruption each day for 14 days. On day 15, all rats trained with phrasing cues were transferred to the no phrasing condition. As before, each rat received 20 repetitions of the pattern on day 15.

Results

Acquisition

The top panel of Fig. 3 shows daily mean errors compared for rats of the no, synchronous, and asynchronous phrasing conditions over the course of the 14 days of training. Acquisition was faster under synchronous phrasing than under no and asynchronous phrasing. An analysis of variance (ANOVA) was conducted on rats' daily mean percent errors (pooled across pattern elements). The ANOVA indicated significant main effects for phrasing groups, $F_{(2,14)} = 4.96$, $P = 0.024$, and days, $F_{(13,182)} = 94.25$, $P < 0.001$. The groups \times days interaction was not significant ($P > 0.05$). Planned comparisons based on the appropriate error term of the foregoing ANOVA indicated that for the acquisition phase rats in the synchronous phrasing condition produced significantly fewer errors overall than rats in the no and asynchronous phrasing conditions, which never differed significantly.

Error profiles and intrusions

The bottom panel of Fig. 3 shows rats' group mean element-by-element percent error rates for the 14 days of the experiment for the no, synchronous, and asynchronous phrasing groups. The results show that synchronous phrasing rats produced fewer errors relative to no phrasing rats on the trial following the phrasing cue, namely, on Trial 1 of each 5-element chunk of the pattern. Synchronous phrasing rats also produced fewer errors relative to no phrasing rats on Trial 2 of each 5-element chunk. In contrast, asynchronous phrasing rats received their phrasing cues just before Trial 4 of 5-element chunks, and error rates on Trial 4 were not significantly different from those of no phrasing rats. Generally, performance under asynchronous phrasing did not differ from that under no phrasing.

The specific kinds of intrusions rats made during the 14 days of the experiment were examined. On trials following chunk boundaries, namely, SPs 1, 6, 11, and 16, a common intrusion was to produce the same left or right turn that produced the last correct response. Thus, the no phrasing group produced 0.71 average proportion of right turns during the first half of the pattern (SPs 1 and 6) and

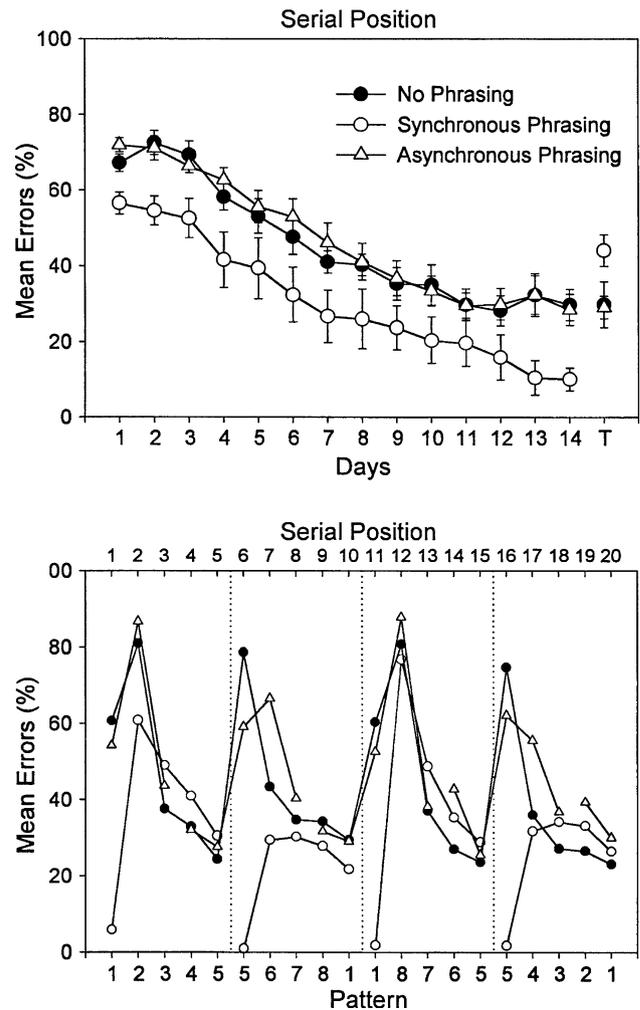


Fig. 3 *Top panel* Acquisition for groups learning the 5-element-chunks pattern with no phrasing, synchronous phrasing, or asynchronous phrasing over the 14 days of acquisition and 1 day of cue removal transfer (*T*) of “Experiment 2”. Daily mean errors were averaged across elements of the patterns. *Bottom panel* Group mean element-by-element errors for the 5-element-chunks pattern with no phrasing, synchronous phrasing, or asynchronous phrasing. *Vertical dotted lines* indicate boundaries between structural chunks of the pattern, whereas *breaks in lines* connecting data points indicate the locations of pauses that served as phrasing cues. Errors were averaged across the 14 days of “Experiment 2”

0.70 average proportion left turns during the second half of the pattern (SPs 11 and 16). High intrusion rates were also obtained with the asynchronous phrasing group, namely, 0.55 average proportion of right turns during the first half of the pattern (SPs 1 and 6) and 0.63 average proportion left turns during the second half of the pattern (SPs 11 and 16). In the synchronous phrasing group, but not in the other conditions, phrasing cues were positioned just before these target trials. The synchronous phrasing group produced 0.39 average proportion of right turns during the first half of the pattern (SPs 1 and 6) and 0.39 average proportion left turns during the second half of the pattern (SPs 11 and

16). Thus synchronous phrasing cues before these trials reduced the tendency to repeat right or left turn responses and increased the likelihood of a correct “same lever” response, as they did in “[Experiment 1](#)”. Asynchronous phrasing cues reduced the tendency to repeat right or left turn responses only moderately, but did consistently increase the likelihood of a correct response.

An ANOVA conducted on the element-by-element means for the data pooled across all 14 days of testing indicated a significant main effect for groups, $F_{(2,14)} = 4.87$, $P = 0.025$; chunks, $F_{(3,42)} = 13.09$, $P < 0.001$; and elements, $F_{(4,56)} = 58.07$, $P < 0.001$. Significant interactions included groups \times chunks, $F_{(6,42)} = 2.94$, $P = 0.017$; groups \times elements, $F_{(8,56)} = 29.90$, $P < 0.001$; and chunks \times elements, $F_{(12,168)} = 21.77$, $P < 0.001$. Planned comparisons indicated significant differences between elements in the discussion above.

Cue removal transfer

The top and bottom panels of Fig. 4 show rats’ performance on day 14 (the last day of training) and day 15 (the day of cue removal transfer), respectively. On day 15, all rats trained with phrasing cues were transferred to the no phrasing condition. The effect of this transfer on daily mean errors is shown in the top panel of Fig. 4; cue removal caused a dramatic increase in errors for the synchronous phrasing group, but had no effect on daily mean errors for the asynchronous phrasing groups.

An ANOVA was conducted on element-by-element means for day 14, the last day of acquisition, and day 15, the day of cue removal transfer. The ANOVA indicated a significant main effect for days, $F_{(1,14)} = 60.81$, $P < 0.001$; and elements, $F_{(9,126)} = 61.81$, $P < 0.001$. Significant interactions included groups \times days, $F_{(2,14)} = 48.46$, $P < 0.001$; groups \times elements, $F_{(18,126)} = 2.81$, $P < 0.001$; days \times elements, $F_{(9,126)} = 9.46$, $P < 0.001$; and groups \times days \times elements, $F_{(18,126)} = 11.29$, $P < 0.001$. Planned comparisons showed that the pattern of results for no and asynchronous phrasing groups did not change between the last day of acquisition (day 14) and cue removal transfer (day 15). In contrast, after cue removal, performance by rats in the synchronous phrasing condition deteriorated dramatically, particularly on Trials 1 and 2 of chunks, the two trials immediately following phrasing cues during the acquisition phase of the experiment. In fact, a gradient of effects was observed in each chunk of the pattern, where performance was most disrupted relative to day 14 levels of performance on the formerly cued trial (Trial 1 of chunks—SPs 1, 6, 11, and 16) and was successively less disrupted on each successive trial of chunks. After cue removal on day 15, performance by synchronous phrasing rats was significantly

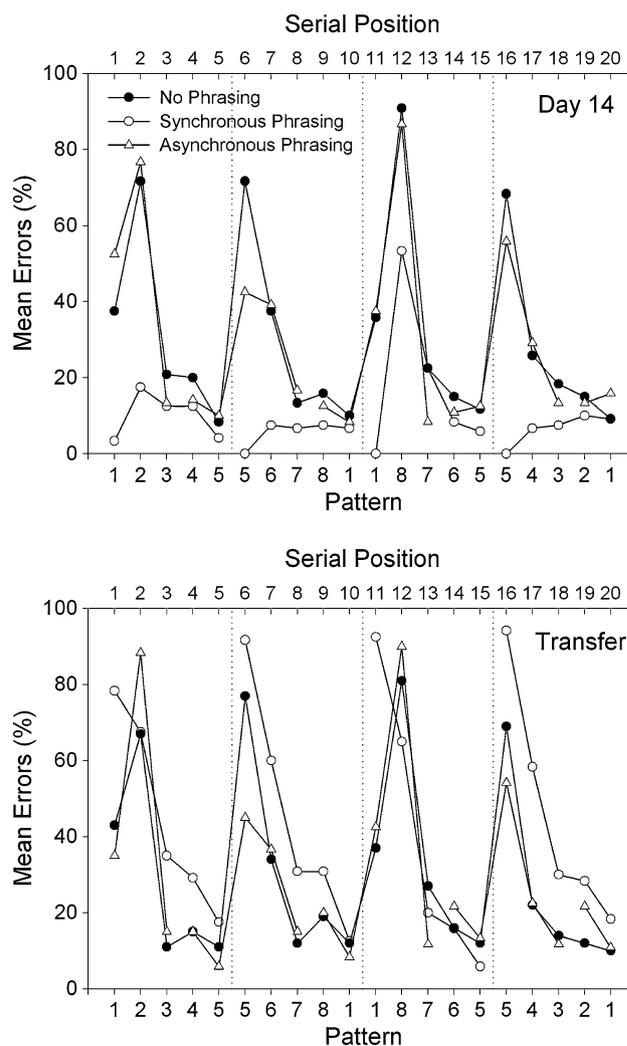


Fig. 4 Group mean element-by-element errors for the 5-element-chunks pattern with no phrasing, synchronous phrasing, or asynchronous phrasing for day 14, the last day of acquisition, and day 15, the day of cue removal transfer (*top and bottom panel*, respectively). Vertical dotted lines indicate boundaries between structural chunks of the pattern, whereas breaks in lines connecting data points indicate the locations of pauses that served as phrasing cues

poorer compared to that of no phrasing rats on Trials 1, 3, and 4 of Chunk 1; on Trials 1–3 of Chunk 2; on Trial 1 of Chunk 3; and on Trials 1–4 of Chunk 4.

Discussion

The results of “[Experiment 2](#)” support the discrimination learning view of synchronous and asynchronous phrasing effects. The a priori predictions based on the discrimination learning view were generally confirmed. First, it was predicted that because asynchronous phrasing cues were short (0.5 s), asynchronous phrasing should not produce an increased tendency to “skip” a trial. In “[Experiment 2](#)”,

error rates on trials following asynchronous phrasing cues did not differ from those observed on the same trials for the no phrasing group, as predicted. Second, it was predicted that asynchronous phrasing would have little if any effect on acquisition, and this was the overall result observed in “[Experiment 2](#)”. Third, because synchronous phrasing cues are much more valid than proprioceptive cues for anticipating what to do at chunk boundaries, it was predicted that synchronous phrasing should facilitate acquisition relative to no phrasing, and this effect was observed. Finally, the discrimination learning view predicts that effects of cue removal should depend on the amount of associative strength acquired by a cue (Fountain et al. 2000; Stempowski et al. 1999). The predictions from the discrimination learning view were that removal of synchronous phrasing cues should produce severe deficits in responding at chunk boundaries, but removal of asynchronous phrasing cues should produce little or no effect. In “[Experiment 2](#)”, removal of synchronous cues did in fact produce severe deficits in anticipating the correct response on formerly cued trials at chunk boundaries, but removal of asynchronous cues produced no change in performance. Altogether, every a priori prediction of the discrimination learning view was confirmed.

In contrast, the rule learning view predicted that synchronous phrasing should facilitate acquisition, and asynchronous phrasing should retard acquisition (Bower and Winzenz 1969; Fountain et al. 1984; Restle 1972). Additionally, the rule learning view predicted savings in pattern tracking even after synchronous phrasing cues are removed. This pattern of results was not observed in “[Experiment 2](#)”. Although synchronous phrasing facilitated acquisition as it did in “[Experiment 1](#)”, asynchronous phrasing had no effect on acquisition. Furthermore, removal of synchronous phrasing cues produced deficits, not savings (Fountain et al. 2000; Stempowski et al. 1999). Thus the results of “[Experiment 2](#)” offer little support for the rule learning view of phrasing effects.

General discussion

“[Experiments 1](#)” and “[2](#)” examined the effects of synchronous and asynchronous phrasing manipulations. Although much of the trial-by-trial and intrusion error data from both experiments were consistent with the rule learning view, this idea has difficulty accounting for three phenomena, namely, facilitation of pattern learning by asynchronous phrasing in the 3-element-chunks pattern in “[Experiment 1](#)”, no effects of asynchronous phrasing either in acquisition or cue removal in “[Experiment 2](#)”, and deficits rather than savings following removal of synchronous cues in “[Experiment 2](#)”.

“[Experiment 2](#)” provided support for interpreting the results of both experiments from a discrimination learning perspective. According to this perspective, synchronous and asynchronous phrasing effects can generally be interpreted as discrimination learning phenomena, though inserting long pauses into sequences can have additional effects as well. For example, long pauses such as those used in “[Experiment 1](#)” can affect rats’ perception of serial position within the sequence, thus producing characteristic errors that appear to be related to rats’ “skipping” trials at points in the sequence where long pauses are encountered. Furthermore, “[Experiment 2](#)” showed that phrasing effects, both during acquisition and after cue removal, could be accounted for by cue validity, as predicted by the discrimination learning view of phrasing (Fountain et al. 1999a; Stempowski et al. 1999). We next consider the discrimination learning account of these data in greater detail.

The discrimination learning view of phrasing

There are three key phenomena that need to be accounted for by the discrimination learning view: (1) phrasing effects with long (3.0 s) phrasing cues in “[Experiment 1](#)”, with particular attention to how asynchronous phrasing facilitates acquisition in 3-element-chunks patterns, (2) phrasing effects with short (0.5 s) phrasing cues in “[Experiment 2](#)”, and (3) the cue removal results of “[Experiment 2](#)”. We examine each of these in turn.

In “[Experiment 1](#)”, long phrasing cues were positioned either at chunk boundaries (synchronous phrasing) or between elements within chunks (asynchronous phrasing). In the case of synchronous phrasing, phrasing cues provided unambiguous (high validity) signals for repeating the last response. Without the phrasing cues in the No Phrasing condition, rats would have to rely on proprioceptive cues or item cues that have lower validity or discriminability. Lower validity might be expected due to the problem of sequential “branching,” the problem created when the same cue signals two or more different responses. Thus, synchronous phrasing cues facilitated acquisition because they provided better cues for signaling the unique responses that were required at chunk boundaries.

Consider now the patterns of “[Experiment 1](#)” composed of 3- or 5-element chunks with asynchronous phrasing. If these patterns are recoded in terms of proprioceptive and extra-sequence cues, it can be shown that the introduction of asynchronous phrasing into the 3-element-chunks pattern clearly disambiguates the pattern by reducing sequential “branching.” Because the asynchronous phrasing cues have benefits with regard to sequential cue validity in this case, one might expect that asynchronous phrasing cues in this pattern should acquire associative strength and

should facilitate acquisition. The data from “[Experiment 1](#)” is consistent with this prediction of the discrimination learning view of phrasing.

Now consider the no phrasing condition with the 5-elements-chunks pattern. According to the discrimination learning view, cue validity would predict that asynchronous cues should not acquire associative strength in this case because the asynchronous cue is no better at signaling the correct turn than proprioceptive or other cues would be; left and right turns or spatial locations of levers in the apparatus are as good predictors of the next correct response as the phrasing cue, which on some occasions signals left and, at other times, right turns. The fact that asynchronous cues did not acquire associative strength was masked, we propose, by another effect of the long phrasing cue in “[Experiment 1](#)”, namely, that long pauses caused rats to behave as if a trial had passed during the long 3-s interval used as asynchronous phrasing cues in the 5-element-chunks pattern of “[Experiment 1](#)”. The errors that resulted from this “skipped trials” problem could easily be mistaken for evidence suggesting discrimination learning or rule learning effects of the cues, but “[Experiment 2](#)” demonstrated unequivocally that asynchronous phrasing cues had no effect on serial pattern acquisition or cue removal performance when the tendency to “skip” trials was controlled by reducing the phrasing cue interval.

A critical finding from the cue removal phase of “[Experiment 2](#)” was that cue removal in the synchronous phrasing condition produced significant performance deficits, particularly for Trial 1 of chunks, that is, the element immediately after the phrasing cue, whereas cue removal in the asynchronous phrasing condition had no detectable effect on performance. For the synchronous and asynchronous phrasing groups, the magnitude of the observed deficit appeared to be inversely related to acquisition performance: better performance on Trial 1 of chunks prior to cue removal for synchronous compared to asynchronous phrasing conditions predicted poorer performance after cue removal. This is consistent with the notion that temporal phrasing cues served as discriminative cues, and the more rats relied on the cue in acquisition, the greater the deficit when the cue was removed. Taken together, the results of both experiments support the earlier contention in the literature that rats use phrasing cues as discriminative cues that facilitate learning by overshadowing less valid inter-item associations (Capaldi et al. 1984; Fountain et al. 2000; Stempowski et al. 1999).

Sensitivity to serial position

The results of “[Experiment 2](#)” suggest indirectly that errors caused by asynchronous phrasing effects in

“[Experiment 1](#)” were the result of mistakes in perception of serial position induced by long (3.0 s) pauses within patterns. Between experiments, the length of the temporal phrasing cue interval was manipulated, and the results showed that retardation of acquisition caused by asynchronous phrasing was due to the length of the cue interval, not to interfering with rule abstraction or discrimination learning. The evidence is consistent with the idea that the longer temporal interval induced rats to behave as if they had “skipped” a trial, suggesting that the 3.0-s interval was perceived as a “blank” trial. The results suggest that in addition to using pattern elements and extra-sequence stimuli as discriminative cues, rats may also learn to respond to sequential events in relation to their serial position, that is, in relation to the relative timing of trials. Recent work has shown that when monkeys learn to respond to four 4-item sequences composed of complex visual stimuli, they do so by associating each stimulus with its serial position (Chen et al. 1997; cf. Harris and Washburn 2005; Terrace 2005). Other work has produced evidence consistent with the idea that rats also may learn about the serial position of items presented sequentially (Burns et al. 1999; Roitblat et al. 1983), but that interpretation can be challenged. The results of “[Experiment 1](#)” are consistent with these earlier studies in that the results can be taken as evidence that rats are sensitive to serial position. Furthermore, the results suggest that in this case rats seemed to be determining serial position by using elapsed time rather than counting; had rats been counting trials rather than timing, they would not have been affected by the insertion of an “empty” temporal interval that appeared to serve as a “blank” trial. One potentially important implication of this outcome is that the results provide modest evidence that rats appear to be sensitive concurrently to sequential cues (pattern elements), extra-sequential cues (phrasing cues), and the temporal arrangement of sequential events. Further investigation into how rats integrate multiple cues or cue and serial position information into compound or configural cues may help clarify why drug-induced hippocampal dysfunction seems to impair some aspects of serial pattern learning (viz., anticipation of chunk boundaries cued by phrasing cues) while sparing other aspects of pattern learning (viz., anticipation of within-chunk elements) in this task (Fountain and Rowan 2000; Fountain et al. 2002).

Conclusions

The results of two experiments indicate that rats use synchronous and asynchronous phrasing cues as discriminative cues to guide responding, but only when the phrasing cues are more valid than item cues. The results suggest that in

addition to using pattern elements and extra-sequence stimuli as discriminative cues, rats may also learn to respond to sequential events in relation to their serial position, that is, in relation to the relative timing of trials. This idea is consistent with other work showing that rats and monkeys can learn about the serial position of events encountered in sequential patterns (Burns et al. 1999; Burns et al. 2000; Chen et al. 1997; Fountain 2006; Fountain et al. 2002; Roitblat et al. 1983; Terrace 2005). One important implication of the results is that rats appear to be sensitive concurrently to sequential cues (pattern elements), extra-sequential cues (phrasing cues), and the temporal arrangement of sequential events.

One potential objection to our design and analysis is that rats exposed to synchronous and asynchronous phrasing cues had to learn different responses after phrasing cues, and thus comparisons between these groups are logically problematic. That is true. Fortunately, those are not the comparisons of interest in these studies. The critical comparisons should test predictions of rule learning theory. Do synchronous phrasing cues always facilitate pattern learning compared to no phrasing? Do asynchronous cues always retard pattern learning? If not, can we explain the effects of phrasing cues by identifying the psychological processes they recruit? Clearly, our results speak to these questions. Synchronous phrasing does consistently facilitate learning relative to no phrasing, as predicted by the view that phrasing cues cause their effects by interacting with rule learning mechanisms. On the other hand, asynchronous phrasing does not consistently retard acquisition of serial patterns as predicted by the view that asynchronous phrasing should interfere with higher-order rule induction, suggesting that phrasing cues produce their effects through other mechanisms in rat serial pattern learning. As the foregoing reasoning shows, these conclusions do not depend on comparisons between acquisition rates in synchronous and asynchronous phrasing groups. In fact, these comparisons are problematic at best, as they typically are in most studies of phrasing effects in human and nonhuman animals. It should be noted, though, that analyses of the specific kinds of errors induced by phrasing can often reveal the nature of psychological processes involved, as they did in our study here, revealing that rats encode the relative timing of events in sequences in addition to other information about the sequence such as interitem associations.

It should be noted that these results add to a growing body of evidence from different paradigms and different species for this discrimination learning interpretation of phrasing effects in animal serial learning. Capaldi et al. (1984), studying phrasing effects in rats tracking sequences of food reward quantities, concluded that phrasing effects were the result of discrimination learning processes.

Terrace (1987), studying serial learning in pigeons, found that items at the beginning and end of a list (i.e., items marked by temporal breaks between sequences) were one type of item that served as discriminative cues that controlled responses. Fountain et al. (1999a), studying serial learning in mice in a paradigm similar to that employed here, found phrasing effects remarkably similar to those found in rats. Taking together the results of all of these studies, including those reported here, it is tempting to conclude, first, that these paradigms may not be as different as they appear superficially and, second, that common discrimination learning processes may underlie phrasing effects in all of these quite different paradigms and species. These paradigms involve food quantity anticipation in rats, sequential ordering of responses to visual stimuli in pigeons, and motor response patterning in rats and mice. Each paradigm, because of differences in stimulus modality and response requirements, must surely recruit very different brain systems compared to those recruited by the others, yet a common process may underlie phrasing in all of these cases. Can the same be said when comparing phrasing effects in humans and nonhumans? The answer is not clear because little work in humans has employed comparable cue removal and transfer techniques to evaluate the basis of phrasing phenomena, but there is a good correspondence between the results obtained with human and nonhuman animals, for example, in synchronous and asynchronous phrasing effects. These results may have important implications for human research on serial learning because they suggest a role for cue competition and overshadowing that has not been recognized in the human literature.

It is necessary to end with a comment on terminology. Synchronous and asynchronous phrasing can be described by these terms because of the positioning of phrasing cues relative to features of pattern formal structure, such as formally defined chunk boundaries. However, despite earlier claims that phrasing effects depend on interactions between phrasing and pattern element structure and despite attempts to obtain evidence supportive of this view (Fountain et al. 1984, 2000; Stempowski et al. 1999), there is little evidence that phrasing effects depend on such an interaction (Capaldi et al. 1984; Fountain et al. 2000; Stempowski et al. 1999). Instead, the evidence weighs heavily in favor of the discrimination learning view of phrasing. On the other hand, the accumulated results do not rule out the idea that rats may use rule-learning processes to encode other aspects of sequential patterns, such as some aspects of element structure, under appropriate conditions (Fountain and Rowan 1995a; Fountain et al. 1999). The picture of rat sequential learning that is emerging, like that emerging for primates and humans (Botvinick and Plaut 2004; Chen et al. 1997; Harris and Washburn 2005; Keele

et al. 2003; Marshuetz 2005; Palmer and Pfordresher 2003; Terrace 2005, 2003; Treichler and Van Tilburg 2002), is perhaps more complex than is generally imagined, with the rat concurrently monitoring several sources of information and encoding the most valid information selected from the stimulus characteristics of pattern elements, the structural relations among elements, the characteristics of extra-sequence cues, and the relative timing of sequential events (Fountain 2006; Fountain and Benson 2006; Fountain et al. 2002, 2006).

Acknowledgments This work was supported in part by the National Institute of Mental Health Grant MH48402. We thank Michael L. Nering and Andrew W. Proctor for assistance in conducting surgery and collecting data.

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