

Number, But Not Rhythmicity, of Temporal Cues Determines Phrasing Effects in Rat Serial-Pattern Learning

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Recent work on experimental manipulations that affect chunking in sequential learning has shown that cues inserted into a sequence, termed “phrasing cues,” can facilitate learning by serving as discriminative cues that overshadow associations between sequence items (Stempowski, Carman, & Fountain, 1999). This experiment assessed whether rhythmicity is an important determinant of temporal phrasing effects or, instead, that a discrimination learning view can adequately account for the results of manipulating the number and sequential positioning of phrasing cues. Rats learned serial patterns in which the number and organization of phrasing cues were manipulated so that phrasing cues were positioned at the beginning of four or eight chunks in an eight-chunk serial pattern. Alternate Chunks phrasing, Aperiodic phrasing (four cues always positioned before the first, third, fourth, and seventh chunks), and Random phrasing (four cues positioned at four chunks chosen randomly for each new pattern presentation) produced equal facilitation of acquisition for cued chunks relative to a No Phrasing condition, but not as much facilitation as Every Chunk phrasing. Cue removal produced deficits, with greater impairment observed for the eight- versus four-cue conditions. Thus, 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. © 2000 Academic Press

In recent years, animal cognition researchers have investigated a number of factors thought fundamental to how animals encode sequences of events (Capaldi, 2000; Capaldi, Verry, Nawrocki, & Miller, 1984; Fountain, 1990; Fountain, Henne, & Hulse, 1984; Fountain & Rowan, 1995a; Fountain, Wallace, Rowan, & Stempowski, 2000; Swartz, Chen, & Terrace, 1991; Terrace, 1987, 1991, 2000; Terrace & Chen, 1991a, 1991b). Work on experimental

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manipulations that affect chunking has shown that cues inserted into a sequence, termed "phrasing cues," can affect acquisition and performance under a variety of conditions. The manner in which the same sequential elements may be presented in time, space, or in relation to phrasing cues can be manipulated to remarkable effect. The nature of the processes mediating the effects of sequential cues and organization in sequential learning and memory is still a matter of debate. This article explores the mechanisms by which temporal cues facilitate sequential pattern learning in rats, particularly, whether the rhythmic organization and the number of cues determine phrasing effects in rat serial-pattern learning.

One view of phrasing proposed in the animal literature by Fountain et al. (1984) argued that phrasing cues speed learning by facilitating chunking; that is, by facilitating the encoding of pattern structure. In one study, rats were trained to anticipate food quantities (such as 14, 7, 3, 1, or 0 pellets of food) presented in a series of trials in a runway, such as in the five-element pattern, 14-7-3-1-0. Structurally, this pattern is highly organized, that is, it is formally simple, because successive elements can be described by a single "less than" rule (Hulse, 1978). A longer pattern was produced by presenting a 14-7-3-1-0 subpattern of food quantities five times in successive chunks. To assess the role of phrasing in pattern learning, the same pattern was presented under different phrasing conditions to different groups of rats. Fountain et al. (1984) reported that when spatial or temporal cues were placed congruent with boundaries between subpattern chunks, the cues facilitated pattern learning. This result, along with others, supported the notion that phrasing facilitated learning by highlighting salient features of pattern structure such as chunk boundaries rather than by cueing specific responses.

Others have attempted to identify the characteristics of sequential elements and their ordering that determine the perceived location of chunk boundaries and other features of pattern structure. Two factors that have been identified in the human sequential pattern literature as contributing to perceived pattern organization are chunk similarity and hierarchical organization (Boltz & Jones, 1986; Handel & Todd, 1981; Johnson, 1978; Restle, 1972; Restle & Brown, 1970). Handel and Todd (1981), for example, examined human segmentation for seven- and eight-element patterns consisting of dichotomous elements (i.e., series of X's and O's) under different response conditions (writing slashes in the series, drumming the series, and vocally repeating the series) to determine the importance of chunk similarity and hierarchy. They found that subjects most often broke sequences into chunks consistent with principles of numeric balance (i.e., chunks of equal length; e.g., XX/OO/XX/OO), element-level similarity (i.e., chunks of repeating elements; e.g., OOO/X/OOO/XX), subgroup-level equivalence (i.e., repeating chunks; e.g., OOX/OOX/OOX), and subgroup-level symmetry (i.e., mirror-image chunks; e.g., OOX/XOO/OOX). Subjects strongly preferred numerically balanced segmentations, but also used element-level similarity, subgroup-

level equivalence, and subgroup-level symmetry as principles for segmenting sequences based on the factor identified as similarity. Sensitivity to chunk similarity and hierarchical organization is not restricted to human learning and memory for sequences of dichotomous elements; it can also be observed in human auditory streaming (Jones, Maser, & Kidd, 1978), in memory for lists of letters and digits in humans (Kotovsky & Simon, 1973; Simon, 1972; Simon & Kotovsky, 1963), in tracking of patterns of flashing lights in humans (Restle, 1972) and in rats (Fountain, 1990), and in production of patterned response sequences in a circular array in rats and humans (Fountain & Rowan, 1995a; Fountain, Rowan, & Benson, Jr., 1999). Relative to our discussion of the hypothesis that phrasing cues facilitate encoding pattern structure by highlighting chunk boundaries, it follows that cues will facilitate learning when they are placed at the boundaries of numerically balanced and structured chunks.

In accord with the foregoing view, studies of human and animal pattern learning involving sequences of structured events have shown that phrasing cues facilitate serial learning, but only when the cues are congruent with chunk boundaries expected based on the formal structure of the sequence (Fountain *et al.*, 1984; Restle, 1972). For rats presented the same pattern of sequential elements under different phrasing conditions, phrasing cues presented at the boundaries between 14-7-3-1-0 chunks facilitated learning the pattern compared to a no phrasing condition, whereas phrasing cues presented within structurally simple chunks retarded learning compared to the other two conditions (Fountain *et al.*, 1984). Likewise, some ambiguous patterns (such as . . . 3454565676 . . .) can reasonably be segmented in two or more ways that result in mostly numerically balanced and structured chunks. For example, the foregoing sequence can be segmented as "runs" (. . . 345-456-567-6 . . .) or as "trills" (. . . 3-454-565-676- . . . or . . . 34-545-656-76 . . .). For the same pattern of sequential elements under differential phrasing conditions where temporal phrasing cues are positioned at the boundaries of "run" versus "trill" chunks, rats' performance is consistent with the notion that phrasing cues biased rats' interpretation of pattern structure to be consistent with that implied by the phrasing cues (Fountain, 1990; Fountain & Rowan, 1995b).

Another view consistent with the foregoing data is that temporal phrasing cues facilitate pattern learning by producing appropriate rhythmic organization of sequences. Following earlier work in the human literature, we define rhythm as relative timing of sequential events (Martin, 1972). Rhythm can be studied independent of pattern structure, for example, in the case where a sequence is composed of the repeated presentation of a single event and the relative timing of the sequential elements is manipulated. "Rhythmic patterning" occurs when relative timing is hierarchically organized independent of the pattern elements involved; that is, when the relative timing has a structure of its own (Martin, 1972). Several lines of work have shown that

both humans and animals are sensitive to rhythm as a factor independent of pattern element structure (e.g., Hulse, Humpal, & Cynx, 1984a; Martin, 1972). Although work on animal sensitivity to rhythm per se is limited, Hulse et al. (1984a, 1984b) demonstrated that starlings could discriminate rhythmic from arrhythmic patterns of artificial sounds. They also showed that rhythm discriminations were perceptually invariant over a range of tempos (Hulse et al., 1984a, 1984b).

If animals and humans are sensitive to rhythmic patterning, one hypothesis is that rhythmic patterning and sequential element patterning must be congruent to facilitate pattern learning. In support of this view, Boltz and Jones (1986) showed that human memory for melodies is facilitated when pattern tonal contour (i.e., changes in melodic rule structure or upward and downward shifts in pitch) maps onto the rhythmic pattern of tone presentation. Quadruple and sextuple rhythm produces different temporal groupings of information. The former groups together sets of four notes or beats, whereas the latter groups together sets of six notes or beats. Boltz and Jones (1986) used a design common to several earlier studies already discussed; they imposed different phrasing conditions on the same sequence of stimulus elements (viz., the notes of the melody) to identify which phrasing conditions would facilitate later recall. They designed melodies so that quadruple rhythm resulted in phrasing cues that coincided with changes in melodic rule structure, whereas sextuple rhythm did not follow the melodic contour of the same pattern. Melodies were recalled better when presented with quadruple rhythm than when presented with sextuple rhythm. Thus, rhythm facilitated later sequence recall when rhythmic patterning complemented sequence element patterning; that is, when there was congruence between rhythmic patterning (phrasing) and melodic structure (the pattern of the notes). Stated another way, rhythmic patterning facilitated sequence recall under conditions of "good rhythmicity" defined as phrasing that highlighted boundaries between chunks of equal length (numeric balance) and structured content (structural subgroup-level equivalence, symmetry, and other relations).

Capaldi et al. (1984) also studied the effects of different phrasing conditions applied to the same pattern of sequential elements. They replicated the effects of spatial cues reported by Fountain et al. (1984), but argued that phrasing effects, like other aspects of serial-pattern learning, should be explained by appealing to traditional discrimination learning rather than rule-learning processes. Two recent experiments on the effects of temporal phrasing in rat serial pattern learning employed a similar strategy of applying different phrasing conditions to the same pattern of sequential elements to evaluate phrasing effects. Consistent with the views of Capaldi and associates, they showed that temporal intervals positioned at chunk boundaries facilitated serial-pattern learning by serving as discriminative cues that overshadowed associations between sequence items (Stempowski *et al.*, 1999). One experiment showed that rat serial-pattern learning could be facilitated

when distinct temporal intervals preceded chunk boundaries regardless of whether the intervals were longer or shorter than intervals within chunks. A second experiment replicated the acquisition results of the first with a different, more difficult serial pattern. In addition, after both 14 and 35 days of acquisition with phrasing cues, cue removal produced severe deficits in tracking the first element of chunks, the element directly after the phrasing cues during acquisition (Stempowski *et al.*, 1999). The results indicated that rats used both short and long temporal phrasing intervals as discriminative cues. 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).

Stempowski *et al.*'s (1999) results, along with those of Capaldi *et al.* (1984), clearly showed that discriminability and overshadowing are important factors mediating phrasing cue effects. On the other hand, evidence in both the rat and human literatures suggests that the correspondence between phrasing cues and sequential element organization may also be important determinants of chunking and phrasing effects. However, it is not clear from Stempowski *et al.*'s (1999) results what role factors related to chunk similarity—numeric balance, element-level similarity, subgroup-level equivalence, and subgroup-level symmetry—might play in determining the effects of phrasing cues. For example, recent work in our lab indicates that when rats learn sequences comparable to those used by Stempowski *et al.* (1999), after training with phrasing cues, rats are sensitive to changes in chunk length when responding to phrasing cues (Fountain, Muller, & Wallace, 2000), suggesting a possible role of numeric balance and subgroup-level equivalence in phrasing effects. It should be noted that in Stempowski *et al.*'s (1999) experiments such effects could not be observed because phrasing cues were positioned at each chunk boundary, producing a sequence with chunks of equal size and parallel content, and chunk length was never manipulated in transfer to assess control by serial position, trial counting, timing, or hierarchical organization.

The experiment described in this article explored the extent to which phrasing effects in rats can be described in terms of temporal patterning and "good rhythmicity" versus stimulus control and discrimination learning. In order to evaluate the characteristics of phrasing, as opposed to characteristics of sequential elements, that contribute to pattern tracking, the same strategy was adopted in this study that has been employed in most of the studies described above: The same sequential pattern was presented in acquisition with different configurations of phrasing cues. This allows for disentangling effects of phrasing from effects related to the ordering of sequential elements. Thus, rats in the present experiment learned a serial pattern in which the number and organization of phrasing cues were manipulated across groups. To facilitate comparisons with earlier studies, rats were trained on the same highly structured serial pattern used in Experiment 1 of Stempowski *et al.*

(1999) and in other studies with rats (Fountain & Rowan, 1995a, 1995b; Fountain & Rowan, 2000) and mice (Fountain, Krauchunas, & Rowan, 1999). Also, the temporal phrasing cues that were used here were the same as the Short cues used by Stempowski *et al.* (1999). Rats learned the pattern under one of five phrasing conditions: No Phrasing, Every Chunk (eight temporal cues at the beginning of each of the eight chunks of the pattern), Alternate Chunks (four cues at alternate chunks beginning with the first), Aperiodic (four cues always positioned before the first, third, fourth, and seventh chunks), and Random (four cues positioned at four chunks chosen randomly for each new pattern presentation). Thus the No Phrasing and Every Chunk groups replicated the training and transfer procedures of Stempowski *et al.* (1999), but the addition of the three four-cue conditions that were not a part of the Stempowski *et al.* (1999) study provided both a test of the role of temporal patterning in phrasing effects and a test of the effects of manipulating the number of phrasing cues. After an initial training phase of 14 days, the distinctive temporal intervals at chunk boundaries were removed and replaced with the same intervals found between elements within chunks; that is, all phrased groups were transferred to a No Phrasing condition.

One goal was to determine whether temporal phrasing cues must produce “good rhythmicity”—temporal patterning that implies chunks with numeric balance and subgroup-level equivalence—to facilitate pattern learning. To answer this question, in two groups, the Every Chunk and Alternate Chunks groups, phrasing cues had hierarchical temporal patterning, whereas in two other groups, the Aperiodic and Random groups, phrasing cues had little or no temporal patterning. For the Every Chunk and Alternate Chunks groups, temporal phrasing cues were positioned at chunk boundaries so as to produce “good rhythmicity” emphasizing numeric balance, subgroup-level equivalence, and a hierarchical interpretation of the periodic structure of pattern elements. For the Aperiodic and Random groups, phrasing cues were likewise positioned at chunk boundaries, but the temporal cues were arrhythmic and thus could not imply numeric balance and subgroup-level equivalence in the accompanying sequence of pattern elements. The critical comparison was between rhythmic and arrhythmic groups, particularly comparing groups in which the number of temporal cues has been equated, namely the Alternate Chunks, Aperiodic, and Random groups. These groups each received four temporal phrasing cues per pattern, and the view that the correspondence of temporal patterning and element organization is critical would predict that Alternate Chunks phrasing should produce significantly better performance than Aperiodic and Random phrasing. In fact, this hypothesis might predict that Aperiodic and Random phrasing could impair learning by obscuring the periodicity of the hierarchically organized pattern elements. Finally, savings after cue removal in Every Chunk and Alternate Chunks groups relative to No Phrasing would tend to support a rule-learning interpretation of phrasing

effects; that is, that rhythmic phrasing cues facilitated encoding pattern structure per se.

A second goal was to assess the extent to which a discrimination learning view of phrasing could account for the results of manipulating the number and sequential positioning of phrasing cues. If phrasing cues can be described simply as discriminative cues as suggested by Stempowski et al. (1999), then facilitated performance under phrasing cues might depend solely on the number of cues located at chunk boundaries—eight cues should be better than four cues in any arrangement, and four cues should be better than No Phrasing. Thus the discrimination learning view predicts the greatest facilitation for the eight-cue Every Chunk phrasing compared to No Phrasing and somewhat less facilitation for the three four-cue conditions (Alternate Chunks, Aperiodic, and Random phrasing), with no overall differences between the four-cue conditions relative to No Phrasing. It also follows that performance deficits following cue removal, especially for the element immediately after the cue at the chunk boundary, would provide support for the discrimination learning view that temporal phrasing cues cued the next response rather than structural features of the pattern (cf. Stempowski *et al.*, 1999). If the foregoing evidence in favor of a discrimination learning interpretation is obtained, the outcome would fit well with the idea that the number of phrasing cues per pattern repetition should be a determinant of phrasing effects as predicted by the generally accepted notion that associative strength grows with practice.

To summarize, the results were expected to indicate whether the effects of temporal phrasing cues are accounted for more by their rhythmicity and organization or by the number of stimulus–response pairings of phrasing cue and a left turn experienced per pattern. Evidence for the importance of rhythmicity would be obtained if two results are observed: (1) when the number of cues is held constant, patterned temporal cues (Alternate Chunks phrasing) facilitate pattern tracking more than temporal cues in a haphazard arrangement (Aperiodic or Random phrasing) and (2) upon cue removal, savings are observed. On the other hand, evidence supporting a discrimination learning view of phrasing would be obtained if (1) more phrasing cues lead to better pattern tracking compared to fewer cues with no overall differences among conditions with equal numbers of cues and (2) upon cue removal, deficits are observed, particularly on formerly cued trials.

METHOD

Subjects

The subjects were 36 naïve male hooded rats (*Rattus norvegicus*) at least 90 days of age at the time of surgery. All rats 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). Prior to surgery, rats were deeply anesthetized by 35.56 mg/kg ketamine and 3.56 mg/kg xylazine i.p. injection. Rats also received antibiotics (60,000 units penicillin i.m.) following surgery to reduce the chance of infection. They were carefully monitored for infection following surgery and were allowed at least 1 week for recovery from surgery. Rats were housed in individual cages with food and water freely available. They were maintained on a 15:9-h light–dark cycle. Testing occurred during the light portion of the cycle.

Apparatus

Pretraining. Two shaping chambers (30 × 30 × 30 cm), each equipped with a single retractable response lever mounted 5.0 cm above the floor and a commutating device centrally located in the ceiling, were used for shaping the lever-press response for brain stimulation reward. Each box was constructed from clear Plexiglas with a floor of stainless steel rods. Each was enclosed in a sound-attenuating shell made of particleboard (80 × 60 × 45 cm). These shaping chambers were housed in a room separate from those of the test chambers.

Training. The test chamber (Fountain & Rowan, 1995a, 1995b) was octagonal in shape with clear Plexiglas walls 15 cm wide by 30 cm tall and measured approximately 40 cm between parallel walls. The chamber rested upon a floor of hardware cloth. A retractable response lever was centered on each wall 5.0 cm above the floor. Each lever required an 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 centrally located in the ceiling of the chamber. Three such operant chambers were each located in separate testing rooms (approximately 2 × 2.6 m) illuminated throughout testing by fluorescent lighting. Mounted above each chamber was a closed-circuit television camera so that the rats' activity could be monitored throughout testing. The experiment was controlled from an adjoining room using a microcomputer and interface (interface and Med-State Software, Med Associates, Inc., Fairfield, VT).

Procedure

Throughout all phases of the experiment, rats received reinforcement consisting of a single 200-ms brain stimulation reward (BSR) "pulse" of a 60-Hz sinusoidal pulse train from a constant current source of 20–100 μ A. In all procedures, rats received one such pulse for each correct response.

Pretraining. After at least 1 week's recovery from surgery, rats were shaped to lever-press for brain stimulation reward in a shaping chamber. At the beginning of the session, the lever was inserted into the chamber and remained inserted throughout the session. The lever remained in this position until a half-hour had elapsed. Rats were required to make at least 1000 bar-

press responses within a 30-min session and received up to two sessions to meet criterion. Rats that failed to meet the criterion were excluded from the study.

Pattern acquisition. After 30 rats were shaped to lever-press, they were randomly divided into five experimental groups and trained daily in the octagonal operant chamber. Using a discrete-trial, eight-choice procedure with correction, all eight retractable levers were inserted into the chamber at the beginning of each trial. If the rat made a correct choice, all eight levers were retracted and a pulse of BSR was administered. If an incorrect choice was made, as was common at the very beginning of training when rats had little or no basis for making a choice, a correction procedure was implemented in which all levers except for the correct one were retracted. The rat was subsequently required to press this correct lever in order to receive BSR and to move on to the next trial. For each trial, the lever chosen and the latency to respond were recorded.

For all five experimental groups used, the required pattern of responses to be learned was the same. Groups differed in the way the pattern was phrased: that is, in the number and location of temporal pauses at chunk boundaries:

No Phrasing:	1 2 3 2 3 4 3 4 5 4 5 6 5 6 7 6 7 8 7 8 1 8 1 2
Every Chunk:	1 2 3 2 3 4 3 4 5 4 5 6 5 6 7 6 7 8 7 8 1 8 1 2
Alternate Chunks:	1 2 3 2 3 4 3 4 5 4 5 6 5 6 7 6 7 8 7 8 1 8 1 2
Aperiodic:	1 2 3 2 3 4 3 4 5 4 5 6 5 6 7 6 7 8 7 8 1 8 1 2
Random:	*1 2 3*2 3 4*3 4 5*4 5 6*5 6 7*6 7 8*7 8 1*8 1 2

The digits represent the clockwise position of levers in the octagonal chamber. Spaces represent 2.0-s temporal intervals between elements in the pattern, whereas vertical bars (|) represent 0.5-s intervals that served as phrasing cues (cf. Stempowski et al., 1999). Thus, the Every Chunk condition received a phrasing cue before every structural chunk of the eight-chunk pattern, resulting in a total of eight phrasing cues. In contrast, the Alternate condition received phrasing cues at every other chunk boundary, resulting in a total of four phrasing cues in the pattern. The Aperiodic group also received four cues, but the cues were not in a rhythmic, alternating arrangement. It should be noted that while the distribution of these cues was aperiodic within the pattern, they were periodic in the sense that their position was fixed from pattern to pattern as the pattern repeated 20 times a day. Finally, the Random condition also received four cues at chunk boundaries, but the position of these cues shifted from one pattern presentation to next. Asterisks (*) in the pattern listed above for the Random group indicate that cues could occur at any four of the eight chunk boundaries, and a new random selection of four chunks was made for each pattern presentation within a daily session. Each group received 20 repetitions of their assigned pattern each day for 14 days of the pattern learning phase (Days 1–14).

Phrasing cue removal. 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.

Random group replication. After training and transfer for the foregoing five conditions were complete, it was recognized that in the data that were collected for the Random condition, it was not possible to identify on a pattern-by-pattern basis which chunks had been cued and which had not. To better evaluate the effects of Random phrasing, the computer program was modified to record the necessary data and an additional six rats were prepared as before and were trained and transferred under the same conditions as the original Random condition.

RESULTS

Pattern Acquisition

In all reported analyses, main effects and interactions were considered significant if $p < .05$. An ANOVA conducted on rats' daily mean errors (pooled across pattern elements) for the 14 days of pattern acquisition indicated a significant main effect for days, $F(13, 325) = 122.16$. The main effect of groups and the Groups \times Days interaction were not significant ($p > .05$). Thus, over the course of training, all groups improved their performance of the pattern, but groups did not differ in the overall rate at which they did so. However, because there appeared to be differences between experimental conditions at asymptote, another ANOVA was computed on the data for Days 12–14 only. This ANOVA indicated a significant main effect for groups, $F(4, 25) = 3.52$. The main effect of Days and the Groups \times Days interaction were not significant ($p > .05$). Planned comparisons based on the appropriate error term from the ANOVA for Days 12–14 revealed that the Every Chunk condition made significantly fewer errors overall compared to all other groups. There were no significant differences between the No Phrasing, Alternate, Aperiodic, and Random conditions. However, as indicated below, averaging across all elements of patterns obscured systematic effects of phrasing that were revealed by an element-by-element analysis.

To better characterize the effects of various phrasing conditions on pattern tracking, error-rate data were analyzed in greater detail on an element-by-element basis. An ANOVA was computed on weekly group-mean-error rates for each element of the pattern. The ANOVA indicated significant main effects for weeks, $F(1, 25) = 255.25$; chunks, $F(7, 175) = 14.35$; and elements, $F(2, 50) = 75.97$. Significant interactions included Groups \times Chunks, $F(28, 175) = 8.73$; Groups \times Elements, $F(8, 50) = 7.85$; Weeks \times Chunks, $F(7, 175) = 7.14$; Weeks \times Elements, $F(2, 50) = 7.60$; Chunks \times Elements, $F(14, 350) = 12.95$; Groups \times Weeks \times Chunks, $F(28, 175) = 4.13$; Groups \times Chunks \times Elements, $F(56, 350) = 7.83$; and Groups \times Weeks \times Chunks

× Elements, $F(56, 350) = 2.99$. Other main effects and interactions were not significant.

Planned comparisons on data collapsed across all 14 days of the experiment revealed that rats in the No Phrasing, Alternate, Aperiodic, and Random groups made more errors on Element 1 of three-element chunks than on Elements 2 and 3 (with no differences between the latter). Rats in the Every Chunk group performed much better on Element 1 compared to every other group, resulting in equally low error rates for Elements 1–3 of three-element chunks. Closer scrutiny revealed that for cued chunks, rats in the Alternate and Aperiodic groups made significantly fewer errors compared to Element 1 of corresponding three-element chunks in the No Phrasing condition. For uncued chunks, Alternate and Aperiodic rats made more errors on Element 1 than No Phrasing rats. Therefore, phrasing cues facilitated acquisition on Element 1 of cued chunks, the element immediately after the cue. This was true regardless of the number of phrasing cues in the pattern (i.e., eight or four) and regardless of their arrangement (i.e., Alternate or Aperiodic). It was also clear that phrasing cues retarded acquisition for Element 1 of uncued chunks relative to No Phrasing. Interestingly, the No Phrasing group made significantly fewer errors on Element 2 of three-element chunks compared with all other experimental groups. Also, No Phrasing rats committed significantly fewer errors on Element 3 of chunks as compared with all chunks of the Aperiodic and Random groups and of all chunks except Chunk 6 of the Alternate group.

The specific kinds of incorrect responses rats made, termed “intrusions,” were examined. For Element 1 of chunks (i.e., immediately following chunk boundaries), the most frequent type of intrusion for the No Phrasing group tended to reflect overextensions of the preceding chunk (e.g., a “4” response following the 123 series of Chunk 1). For No Phrasing rats, overextension errors accounted for .595 of errors for Element 1 of three-element chunks. In contrast, in Every Chunk rats produced mainly perseveration errors on Element 1 (.547 of errors on that element); that is, they chose the lever rewarded on the previous trial. The rates of perseveration errors in the No Phrasing group and of overextension errors in the Every Chunk group were relatively low (.242 and .328, respectively). Thus, phrasing changed the type of errors committed on the first element of chunks when the phrasing cue was placed at every chunk boundary. Rats in the Alternate group showed a fairly even split between overextension and perseveration errors (.464 and .449, respectively) on Element 1 regardless of whether the chunk was cued or uncued. In contrast, errors committed by the Aperiodic group on Element 1 depend on the chunk being analyzed. Cued chunks displayed more perseveration errors than overextension errors (.587 and .349, respectively). Errors on the Element 1 of uncued chunks consisted of a fairly even split between overextension and perseveration errors (.524 and .423, respectively).

The foregoing effects were still apparent on Day 14, the last day of the

Day 14 of Acquisition

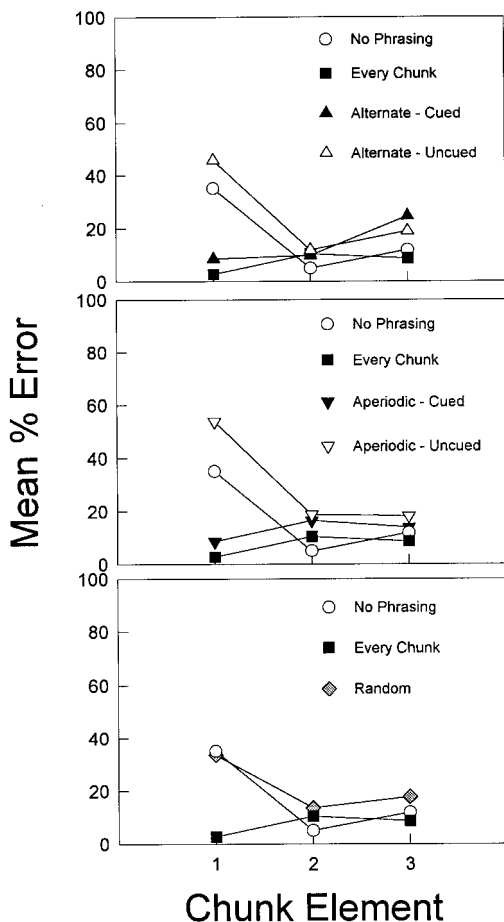


FIG. 1. Group mean element-by-element errors for 3-element chunks of the 24-element pattern on Day 14, the last day of acquisition under the various phrasing conditions. Groups with either No Phrasing (open circles) or Every Chunk phrasing (filled squares) are shown in each panel for comparison to conditions with four phrasing cues at Alternate chunk boundaries (top panel), at Aperiodic chunk boundaries (middle panel), or Random sets of four chunks chosen anew for each pattern presentation (bottom panel). Data are presented separately for cued and uncued chunks for the Alternate and Aperiodic groups.

pattern acquisition phase. Figure 1 shows rats' mean errors for each element position within three-element chunks (collapsed across chunks and pattern presentations) for Day 14. The three panels show data for the Alternate, Aperiodic, and Random groups (top to bottom, respectively) compared to data from the No Phrasing and Every Chunk groups in each panel. An

ANOVA conducted on error rates on an element-by-element basis for the last day of training (Day 14) and for the day of cue removal (Day 15) revealed a main effect for Days, $F(1, 25) = 91.74$; Chunks, $F(7, 175) = 5.90$; and Elements, $F(2, 50) = 61.95$. Significant interactions included Groups \times Days, $F(4, 25) = 29.35$; Groups \times Chunks, $F(28, 175) = 5.77$; Days \times Chunks, $F(7, 175) = 2.94$; Days \times Elements, $F(2, 50) = 87.18$; Chunks \times Elements, $F(14, 350) = 5.75$; Groups \times Days \times Chunks, $F(28, 175) = 2.41$; Groups \times Days \times Elements, $F(8, 50) = 13.34$; Groups \times Chunks \times Elements, $F(56, 350) = 3.25$; Days \times Chunks \times Elements, $F(14, 350) = 2.71$; and Groups \times Days \times Chunks \times Elements, $F(56, 350) = 2.32$. Other main effects and interactions were not significant.

Planned comparisons on Day 14 data, shown in Fig. 1, revealed that rats in the No Phrasing, Alternate, Aperiodic, and Random groups made more errors on Element 1 of three-element chunks than on Elements 2 and 3 (with no differences between the latter). Rats in the Every Chunk group performed much better on Element 1 compared to every other group, resulting in equally low error rates for Elements 1–3 of three-element chunks. Closer scrutiny revealed that for cued chunks, rats in the Alternate and Aperiodic groups made significantly fewer errors compared to Element 1 of corresponding three-element chunks in the No Phrasing condition. For uncued chunks, Alternate and Aperiodic rats made more errors on Element 1 than No Phrasing rats. Element 1 error rates for the Random and No Phrasing groups were not significantly different, but it should be recalled that Random rats' data presented in Fig. 1 represent an average of cued and uncued chunks (because they could not be distinguished). Data for cued and uncued chunks for the Random Group Replication are presented below. Also on Day 14, the No Phrasing group made fewer errors on Element 2 than the Aperiodic and Random groups. There were no differences between the No Phrasing, Every Chunk, and Alternate groups for Element 2. Within the Alternate condition, fewer errors were found to occur on Element 2 than on Element 3. Finally, on Element 3, Every Chunk rats made fewer errors than the Alternate and Random groups, and No Phrasing rats made fewer errors than the Alternate group.

Intrusion data for Day 14 revealed that the No Phrasing group made mostly overextension errors on Element 1 of chunks (.647 of errors on that element), while they made very few perseveration errors (.199). In contrast, the Every Chunk group committed mostly perseveration errors on Element 1 (.427) and fewer overextension errors (.250). On cued chunks in the Alternate group, the majority of errors on Element 1 of chunks consisted of perseveration errors (.558) and some overextension errors (.259). Uncued chunks in the Alternate group made nearly equal numbers of overextension and perseveration errors on Element 1 (.444 and .461, respectively). Aperiodic rats made slightly more overextension errors (.518) than perseveration errors (.394) on Element 1 of cued chunks and nearly equal numbers of overextension and persevera-

tion errors on uncued chunks (.472 and .427, respectively). Finally, the Random condition rats made both run overextension and perseveration errors on Element 1 (.474 and .438, respectively).

Phrasing Cue Removal

Figure 2 shows rats' mean errors for each element position within three-element chunks (collapsed across chunks and pattern presentations) for Day 15, the day of phrasing cue removal. Planned comparisons based on the appropriate error term from the ANOVA reported above (evaluating results for Days 14 and 15) indicated that on Day 15, rats in the Every Chunk, Alternate, Aperiodic, and Random conditions made significantly more errors on Element 1 of three-element chunks than they did on Day 14, the last day of training with phrasing cues. For the Alternate and Aperiodic groups, this significant increase in errors was true for both previously cued and uncued trials.

After cue removal, the Every Chunk group made significantly more errors on Element 1 of chunks than the Alternate, Aperiodic, and Random groups. The Alternate group had the lowest error rate on Element 1. All of these formerly phrased groups made significantly more errors on Element 1 than the No Phrasing group. It is important to note that the Every Chunk condition, which had the lowest error rate on Day 14, exhibited the highest error rate on Day 15. Element 2 or 3 performance was affected to a lesser degree in some groups, but the effects were not systematic. Thus, when phrasing cues were removed, the primary element to be affected was Element 1, though other elements were affected to a lesser degree.

When an intrusion analysis similar to those described above was conducted for Day 15, the cue removal day, a different pattern of errors was observed compared to Day 14, the last day of pattern acquisition. As expected, the No Phrasing rats continued to display the same pattern of results obtained on Day 14. In contrast, for the Every Chunk group the rate of overextension errors on Element 1 of chunks nearly doubled (.454 of errors), whereas perseveration errors increased only slightly (.507). Similarly, for the Alternate group, overextension errors nearly doubled (.508), whereas perseveration errors actually decreased on cued chunks (.406). Errors on Element 1 of previously uncued chunks continued to display a split between overextension and perseveration errors (.488 and .437, respectively). The Aperiodic condition continued to make errors in the pattern observed on Day 14 (overextension errors at .593 and .493 for previously cued and uncued chunks, respectively). Random condition animals made more overextension errors (.592) than perseveration errors (.348) on Element 1 of chunks.

Random Group Replication

One remaining question is whether phrasing cues in the Random condition produced effects paralleling those observed in the Alternate and Aperiodic

Day 15 - Cue Removal

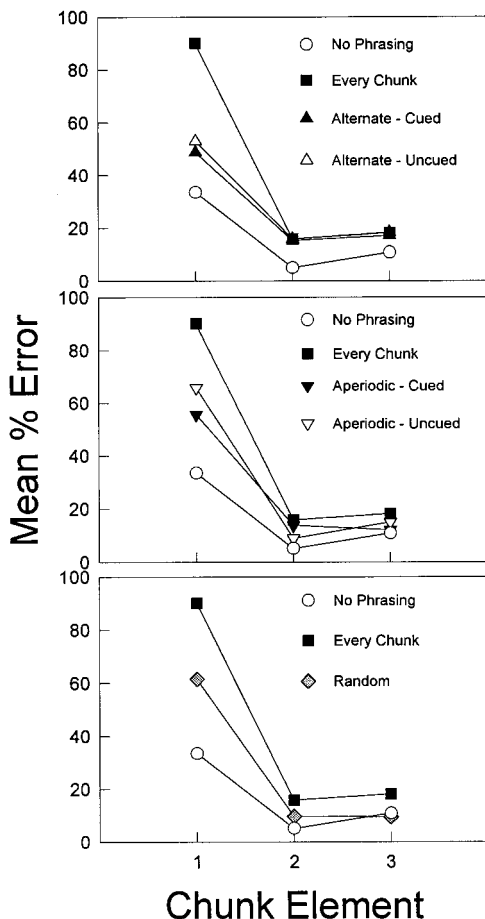


FIG. 2. Group mean element-by-element errors for 3-element chunks of the 24-element pattern on Day 15, the day of phrasing cue removal. Groups that had either No Phrasing (open circles) or Every Chunk phrasing (filled squares) in acquisition are shown in each panel for comparison, as in Fig. 1. These conditions are compared to conditions that during acquisition had four phrasing cues at Alternate chunk boundaries (top panel), at Aperiodic chunk boundaries (middle panel), or Random sets of four chunk boundaries chosen anew for each pattern presentation (bottom panel). Data are presented separately for formerly cued and uncued chunks for the Alternate and Aperiodic groups.

Random Group Replication

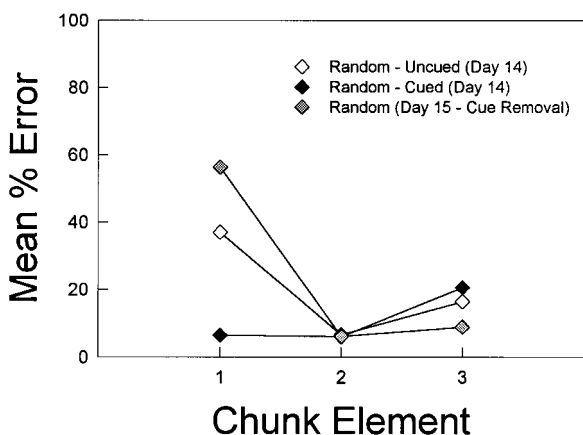


FIG. 3. Random condition group mean element-by-element errors for 3-element chunks of the 24-element pattern on Day 14, the last day of acquisition, and Day 15, the day of phrasing cue removal, for the Random Group Replication. For Day 14, data are presented separately for the cued and uncued chunks that had been randomly assigned for each new pattern presentation within the day.

groups. This question could not be answered based on data reported above from the original Random condition because cued and uncued chunks could not be identified from the data collected. Thus, the foregoing results for the Random condition are based on averages of cued and uncued effects, if any exist. To ascertain the effects of phrasing cues under Random phrasing conditions, a second group of six rats, the Random Group Replication, was trained and transferred under Random phrasing conditions, and data were recorded that allowed data to be sorted by cued and uncued chunks. Figure 3 shows results from the Random Group Replication for Day 14, the last day of training with Random phrasing cues, and Day 15, the day of cue removal. The results parallel those observed for Alternate and Aperiodic groups: Random phrasing facilitated performance for Element 1 of cued chunks relative to uncued chunks on Day 14, and cue removal resulted in a severe decrement in performance on Element 1 of chunks on Day 15.

DISCUSSION

This experiment had two principal goals. The first was to assess whether factors contributing to “good rhythmicity”—particularly, phrasing cue organization that implies numeric balance and subgroup-level equivalence—are important determinants of phrasing effects in rat sequential learning. The second goal was to assess the extent to which a discrimination learning view

of phrasing could account for the results of manipulating the number and sequential positioning of phrasing cues. We discuss each in turn.

Temporal Phrasing and Rhythmicity

We found little evidence to support the view that temporal phrasing cues facilitate pattern learning by producing good correspondence between phrasing cues and chunk organization; that is, by producing "good rhythmicity." We conclude that in this paradigm, positioning phrasing cues in sequential patterns so as to produce numeric balance and subgroup-level equivalence (chunks of equal length and content) (Handel & Todd, 1981) does not differentially facilitate learning relative to other arrangements of the same number of phrasing cues. Evidence to support this conclusion is that during acquisition, approximately equal amounts of facilitation were observed for Element 1 of chunks in groups trained with four phrasing cues in different arrangements, namely the Alternate, Aperiodic, and Random phrasing conditions. Thus, phrasing cues always facilitated learning whether or not they broke the pattern into consistently repeating chunks, a result that directly contradicts what would be predicted if rats were sensitive to "good rhythmicity" in temporally phrased patterns.

Implied by the term "good rhythmicity" is the notion that the correspondence between hierarchical temporal patterning and element structure emphasizes hierarchical structure in sequential patterns (Martin, 1972; Restle, 1972). This view is similar to the hypothesis that temporal cues bias perception of pattern organization (Fountain *et al.*, 1984, 2000). According to the latter view, temporal cues identify salient features of pattern structure by, for example, indicating transitions between numerically balanced and hierarchically structured chunks. According to the hypothesis that temporal phrasing cues serve as cues for structure, the differential temporal intervals located at chunk boundaries simply facilitate encoding pattern structure by highlighting chunk boundaries. Since, according to this view, phrasing cues facilitate encoding of structure rather than cueing specific responses, training with phrasing cues should produce savings in pattern tracking even after the phrasing cues are removed (for a similar argument, see Fountain *et al.*, 1984). Savings after cue removal in Every Chunk and Alternate Chunks groups relative to No Phrasing would have supported a rule-learning interpretation of phrasing effects; that is, that rhythmic phrasing cues facilitated encoding pattern structure, but no such savings were observed. In fact, cue removal produced approximately equal deficits in performance for Element 1 of chunks in these conditions.

Thus, despite earlier evidence that rats are sensitive to the organization of pattern elements under some conditions in this paradigm (Fountain & Rowan, 1995a; Fountain *et al.*, 1999), that they may use chunk length to anticipate the position of phrasing cues in this task (Fountain *et al.*, 2000), and that other nonhuman species are sensitive to rhythm (Hulse *et al.*, 1984a,

1984b), the results of this study indicate that rats were insensitive to direct manipulations of temporal patterning in this task. The results fit much better with the notion that phrasing cues can be described simply as discriminative cues, as suggested by Stempowski *et al.* (1999; cf. Capaldi, Birmingham, & Miller, 1999).

Temporal Phrasing and Discrimination Learning

Four results were observed that unambiguously supported a discrimination learning view of phrasing effects. First, temporal phrasing cues facilitated acquisition in all conditions, primarily for the pattern element immediately after the cue; that is, for Element 1 of chunks. Stempowski *et al.* (1999) reported evidence from two experiments that rat serial-pattern learning could be facilitated when distinct temporal intervals preceded chunk boundaries regardless of whether the intervals were longer or shorter than intervals within chunks. In the study reported here, temporal phrasing cues consisted of shorter ITI's at chunk boundaries than within chunks, and these "short" temporal cues facilitated acquisition in all phrasing conditions relative to no phrasing as they did in Stempowski *et al.* (1999). However, in the present study, phrasing cues facilitated performance for Element 1 of cued chunks, but not that of uncued chunks. In addition, performance on Element 1 of uncued chunks of phrased patterns was poorer than in the No Phrasing condition. Second, Stempowski *et al.* (1999) reported that removing phrasing cues produced severe deficits in performance for Element 1 of chunks. The same pattern of results was reported here for all chunks of all phrasing conditions, whether or not the chunks had been cued in acquisition. Third, during acquisition, approximately equal amounts of facilitation were observed for Element 1 of chunks by Alternate, Aperiodic, and Random phrasing. Cue removal produced approximately equal deficits in performance for Element 1 of chunks in these conditions. Fourth, during acquisition, Every Chunk phrasing produced greater facilitation than Alternate, Aperiodic, and Random phrasing. During cue removal, Every Chunk rats were more severely impaired on Element 1 of chunks than were Alternate, Aperiodic, and Random rats.

These results replicate and extend those of Stempowski *et al.* (1999). In addition to finding no evidence to support "good rhythmicity" as a factor in phrasing in favor of accepting a discrimination learning view, this article is the first to describe the effects of manipulating the number of phrasing cues in the same pattern. In acquisition, four phrasing cues per eight-chunk pattern in the Alternate, Aperiodic, and Random (four-cue) phrasing conditions facilitated acquisition for Element 1 of cued chunks, but not as much as Every Chunk (eight-cue) phrasing did. Conversely, performance on Element 1 of uncued chunks in these four-cue conditions was poorer than in the No Phrasing (zero-cue) condition. The results fit well with the idea that rats in four-cue conditions had less experience learning to use phrasing cues

than rats in the eight-cue condition (Every Chunk), and so their performance on cued chunks lagged behind the Every Chunk condition. Similarly, the results fit with the idea that rats in the four-cue conditions had less experience with uncued chunk boundaries than rats in the zero-cue condition (No Phrasing), and so their performance on uncued chunks lagged behind the No Phrasing condition. In looking across the three four-cue conditions, little evidence could be found to contradict the foregoing principles. That is, there was little evidence that the organization of phrasing cues in the four-cue conditions was important with regard to the effects of phrasing cues on acquisition.

In the cue removal phase of the experiment, four phrasing cues per eight-chunk pattern in the Alternate, Aperiodic, and Random (four-cue) phrasing conditions produced deficits for Element 1 of all chunks, but not as much as Every Chunk (eight-cue) phrasing did. Conversely, performance on Element 1 of all chunks in these four-cue conditions was poorer than in the No Phrasing (zero-cue) condition. Here again, the results fit well with the idea that rats in the four-cue conditions had less experience with uncued chunk boundaries than rats in the zero-cue condition (No Phrasing), and rats in the eight-cue (Every Chunk) condition had the least experience with uncued chunks of all. Thus, rats in the Every Chunk condition became highly dependent on temporal cues to signal the correct response on Element 1 of chunks, whereas rats in the four-cue conditions were less so due to their experience with uncued chunks in acquisition. Here again, in looking across the three four-cue conditions, little evidence could be found to contradict the foregoing principles. That is, there was little evidence that the organization of phrasing cues in the four-cue conditions was important with regard to the effects of phrasing cue removal.

Altogether, the foregoing results and conclusions support the more general principle that temporal phrasing cues serve as discriminative stimuli to cue specific responses for the pattern element immediately after the cue, as concluded by Stempowski et al. (1999). The results also fit well with the notion that phrasing cues overshadow interitem associations (Capaldi *et al.*, 1999; Stempowski et al., 1999) that typically would be formed at chunk boundaries in uncued conditions. Overshadowing of interitem associations by phrasing cues explains (1) why performance deficits appear after cue removal and (2) why competence on uncued chunks in acquisition and cue removal depends on the number of uncued chunks experienced during acquisition. In the former case, overshadowing of interitem associations by phrasing cues leads to a situation in cue removal where the necessary cue to guide behavior is no longer available for some proportion of chunk boundaries. In the latter case, overshadowing predicts competence on Element 1 of uncued chunks in acquisition and after cue removal will be directly proportional to the number of uncued chunks in original training. This follows because associations learned for Element 1 of cued chunks are irrelevant for guiding responses on uncued chunks. Severe and predictable performance deficits following

cue removal under phrasing conditions ranging from Every Chunk to Random provide strong support for the view that temporal phrasing effects can be described as discrimination learning phenomena across a broad range of conditions of periodicity and temporal organization.

In conclusion, this experiment demonstrated that manipulating the number of cued and uncued chunks in a serial pattern produced results consistent with well-established associative principles of learning. Acquisition and performance for both cued and uncued chunks was a function of the number of cued and uncued chunks, respectively, that rats encountered in each sequence repetition. Faster learning and better performance on cued chunks relative to No Phrasing was observed as the number of cued chunks was increased from four (Alternate, Aperiodic, and Random conditions) to eight (Every Chunk condition). Similarly, faster learning and better performance on uncued chunks relative to Every Chunk phrasing was observed as the number of uncued chunks was increased from four (Alternate, Aperiodic, and Random conditions) to eight (No Phrasing condition). After cue removal, performance on the first element of chunks was a direct function of the number of uncued chunks in training. That is, better performance was observed as the number of uncued chunks in training was increased from zero (Every Chunk condition) to four (Alternate, Aperiodic, and Random conditions) to eight (No Phrasing condition). These data are directly predicted by the widely accepted notion that associative strength grows with practice and that valid cues overshadow less valid cues (e.g., Blough, 1975; Rescorla & Wagner, 1972).

One might wonder why, based on associative theory, phrasing cues facilitate learning at all. The fact is that phrasing cues are better predictors of the proper response at chunk boundaries than elements of the pattern sequence. Each pattern element (lever locations or left- and right-turn responses) predicts both left and right turns at different points in the sequence, whereas phrasing cues always cue a left turn. Thus, based on stimulus validity alone, phrasing cues should quickly acquire associative strength for a single response (a left turn) and overshadow pattern elements as cues, and the time course should be a function of the number of phrasing cues in the sequence. Better learning and performance as a function of the number of phrasing cues in the pattern independent of their organization is particularly compelling evidence in support of this associative interpretation of phrasing effects in rat serial-pattern learning.

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