Chunking, rule learning, and multiple item memory in rat interleaved serial pattern learning

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Abstract

Nonhuman animals, like humans, appear sensitive to the structure of the elements of sequences, perhaps even when the structure relates nonadjacent elements. In the present study, we examined the contribution of chunking, rule learning, and item memory when rats learned serial patterns composed of two interleaved subpatterns. In one group, the first interleaved subpattern was a formally simple sequence, whereas in two other groups the first subpattern was formally more complex, containing 2 or 4 violation elements, respectively. In all groups, the second interleaved subpattern encountered was formally simple. Evidence from the study suggests that rats chunked their interleaved patterns into component subpatterns, that is, they cognitively sorted pattern elements to form chunks based on nonadjacent structural relationships that can be characterized as rules. They also learned interitem associations via traditional discrimination learning to use adjacent elements as compound or configural cues for later events in the sequence. Thus, the evidence suggests that rats used chunking, rule learning, and interitem association learning concurrently to master these complex patterns.

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One question of significance for animal learning research is whether or not animals are constrained to learn about sequences of events on the basis of pair-wise associations

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between the successive elements (“interitem associations”), as in the classical notion of
“chaining” in sequence learning (Hull, 1931; Skinner, 1934). Some years ago, Terrace
(1987) indicated that little evidence existed that animals are able to spontaneously reorganize sequentially presented items into chunks not presented by the experimenter though, as
Terrace noted, such processes are readily observed in human free-recall (Tulving, 1962). A
significant body of evidence now suggests that animals are able to be more flexible in repre-
senting sequential events by coding hierarchical representations characterized by relations
for nonadjacent events (Fountain & Annau, 1984; Fountain, Rowan, & Benson, 1999;
Roitblat, Bever, Helweg, & Harley, 1991; Roitblat, Scopatz, & Bever, 1987).

One early study by Menzel (1973) allowed chimpanzees to observe him disperse food
rewards in caches about a field. One prediction based on the chaining view was that once
the animal was released into the field to recover the food rewards, the chimps would have
to report to caches in the order they observed the caches filled. However, it was observed
that the chimpanzees first reported to caches containing fruit, a preferred reward over vege-
tables. Once the fruit was collected, they then recovered the rest of the available food. This
experiment was perhaps the first to demonstrate chunking of nonadjacent stimuli by similar
qualitative relationships between stimuli. Similarly, Dallal and Meck (1990) and
Macuda and Roberts (1995) both found strong evidence that rats chunked food rewards
on a radial arm maze by food type, and Capaldi and Miller (1988) showed that rats can
keep count of different kinds of rewards by chunking nonadjacent items in series into
different food categories. However, the mechanisms involved in learning about nonadja-
cent events are not well understood.

More recent work on this problem has focused on how rats learn about other types of
relationships between nonadjacent events, such as the abstract organization of those
events. Nonhuman animals, like humans, appear to be sensitive to the organization of
stimuli presented in serial fashion. For example, several early experiments demonstrated
that structurally simpler patterns of rewards were easier for rats to learn than structurally
more complex patterns (Hulse & Dorsky, 1977, 1979), and other studies demonstrated
other putative rule-learning phenomena such as pattern generalization (Hulse & Dorsky,
1979) and extrapolation (Fountain & Hulse, 1981). However, we recently showed that a
simple associative computational model without separate rule-learning processes could
account for the foregoing data (Wallace & Fountain, 2001) and other features of serial pat-
tern learning as well (Wallace & Fountain, 2003). Although this outcome does not exclude
the possibility that rats were using rule-learning processes as originally claimed, the fact
that a simpler model could account for the phenomena implies that stronger empirical evi-
dence for rule learning is needed to support the claim that rats use rule-learning processes
in serial pattern learning.

Evidence indicating that rats use rule-learning processes in serial pattern learning has
come from two types of studies, those examining how rats represent patterns that have
multiple levels of hierarchical structure (Fountain, 1990; Fountain & Rowan, 1995a,
1995b) and those examining how rats cognitively sort elements of patterns composed of
interleaved subpatterns (Fountain & Annau, 1984; Fountain, Krauchunas, & Rowan,
1999). In recent studies where rats were required to learn to produce long and elaborate
response patterns on a circular array of 8 levers, the 2-, 3-, and 4-level hierarchical struc-
tures of training patterns predicted the relative difficulty of pattern acquisition and the
kinds of errors rats made on the most difficult elements of the patterns (Fountain &
Rowan, 1995a, 1995b). Similarly, elements and chunks that “violated” overall pattern
structure were especially difficult for rats to learn, and errors on these elements and chunks conformed to the expected pattern structure (Fountain & Rowan, 1995a, 1995b, 2000; Fountain, Wallace, & Rowan, 2002). Comparable effects have been observed in CF1 mice (Fountain et al., 1999).

Until recently, less evidence has been available to support the claim that animals, like humans, are able to detect rules relating nonadjacent stimuli. Human subjects, on the other hand, can extrapolate the missing element of an interleaved pattern such as AMBNCODPE__ based on the subpattern structures that are readily apparent to most people. By recognizing that the pattern is composed of the interleaved subpatterns, ABCDE and MNOP__, human subjects readily respond “Q” when asked to provide the missing element. In one early study with rats, we showed that rats, when presented a sequence of reward quantities, could spontaneously sort quantities from nonadjacent serial positions into chunks based on similar relationships between them to facilitate learning (Fountain & Annau, 1984). A comparable strategy in humans would be to learn the pattern 255455565558 by sorting pattern elements into 555 chunks and a 2468 chunk. Other work also supports the view that rats have this capacity (Fountain et al., 1999).

In two recent studies in our laboratory (Fountain et al., 1999), rats learned either a structured (ST) or unstructured (UNST) subpattern interleaved with elements of a repeating (R) subpattern in one experiment or an alternation (A) subpattern in another experiment. The question was whether rats would show sensitivity to the structure of nonadjacent pattern elements by learning the interleaved subpatterns at different rates as a function of subpattern complexity. The prediction was that if rats use rule-learning processes to encode serial interleaved patterns, rats should learn subpatterns with simpler structure faster than those with more complex structure.

The first experiment sought to determine whether rats would show signs of being sensitive to the organization of nonadjacent elements from interleaved subpatterns when one subpattern was composed of a simple, repeating element and the second subpattern was either highly structured or not. Rats learned to press levers in an 8-lever circular array in the proper sequential order determined by the prescribed serial pattern (Fountain & Rowan, 1995a, 1995b; Rowan, Fountain, Kundey, & Miner, 2001). The levers were designated Levers 1 through 8 in clockwise order with Lever 8 adjacent to Lever 1. Correct responses were reinforced by hypothalamic brain-stimulation reward (BSR) and incorrect responses were corrected. For rats in the structured (ST) subpattern condition, a 123 234 345 456 567 subpattern was interleaved with a repeating (R) subpattern, 888 888 888 888 888, resulting in the ST–R pattern that rats were required to learn:

182838 283848 384858 485868 586878.

For rats in the unstructured (UNST) subpattern condition, a 153 236 345 426 547 subpattern was interleaved with the same R subpattern to create the UNST-R pattern in the same manner. For both patterns, integers represent the clockwise position of correct levers in the array on successive trials and spaces represent pauses that served as phrasing cues. As predicted by rule-learning theory, acquisition of the interleaved structured pattern (i.e., ST–R) was significantly faster than for the interleaved unstructured pattern (i.e., UNST–R).

In the second experiment, rats learned two interleaved sequences where both were created from sets composed of more than one element. As before, longer patterns were composed of two interleaved subpatterns; either a structured or unstructured subpattern was interleaved
with a subpattern of two alternating elements. For one group of rats, the structured (ST) sub-
pattern, 123456, was interleaved with the alternating (A) subpattern, 787878 to create the ST-
A pattern. For another group of rats, the unstructured (UNST) subpattern, 153426, was like-
wise interleaved with the same alternating subpattern to produce the UNST-A pattern. Note
that the unstructured subpattern was generated by exchanging two elements of the structured
subpattern. Rats learned the subpatterns of their interleaved patterns at different rates both
within and between pattern groups. As predicted based on subpattern structure, in the case of
the UNST-A pattern, the A subpattern was acquired faster than the UNST subpattern. The
A subpattern would be expected to be acquired faster because it is formally simple whereas
the UNST subpattern has little structure (Hulse, 1978; Hulse & Dorsky, 1977; Jones, 1974).
Based on similar reasoning, it was expected that the ST subpattern should be easier to learn
than the UNST subpattern, and this result was obtained. In the case of the ST–A pattern,
since both subpatterns were structured, it might be difficult to predict in advance based on
subpattern structure alone whether rats should find either the ST or A subpattern easier to
learn than the other. However, if structural complexity is equated (i.e., if the same number of
rules are needed to describe subpattern structure), rats might show the same predisposition
that humans do (Kotovsky & Simon, 1973) to detect repeating elements before other struc-
tural features of patterns. In fact, evidence for the latter assertion was obtained in this exper-
iment. Rats in the ST–A pattern group showed better acquisition for A with its repeating “7”
and “8” elements than ST subpatterns of their interleaved pattern despite the fact that both
ST and A subpatterns have simple structure that can be described by a single rule (viz., a
“+1” rule for the 123456 ST subpattern versus an “alternate” rule for the 787878 A subpat-
ttern). The results of differential acquisition of ST and UNST subpatterns support the notion
that accurate performance on these interleaved subpatterns was dependent on a mnemonic
representation characterized by relations for nonadjacent events (Roitblat et al., 1991;
Roitblat et al., 1987). The results indicate that rats are sensitive to the organization of nonad-
jacent elements in serial patterns and that they can detect and sort structural relationships in
interleaved patterns.

The present research addresses potential criticisms of the Fountain and Rowan et al.
(1999) studies. First, perhaps 787878 was easier to learn in each case not because it is for-
mally simpler in structure but because Levers 7 and 8 are contiguous in the octagonal oper-
ant chamber. Perhaps 123456 and 153426 were more difficult than 787878 because in the
former case rats had to distribute their responses over a spatially broader array. Second,
although the length of each subpattern and the complete interleaved serial pattern used in
Fountain and Rowan et al. (1999) were the same, the “set size” of element sets from which
pattern elements were drawn varied between subpatterns. “Set size” refers to the number of
unique elements which compose a subpattern. For instance, the subpattern 123456 has a
set size of 6, whereas the subpattern 787878 has a set size of only 2. Perhaps this factor, not
subpattern structure, was the major determinant of the rate of acquisition for the alternat-
ing 78 subpattern relative to the simple 123456 and complex 153426, which would account
for a large part of the effects observed in acquisition. Third, the elements constituting each
respective subpattern in each interleaved serial pattern were mutually exclusive so that
arrays for each element set had spatial boundaries with the other set. In other words,
Levers 7 and 8 were only used in the alternating subpattern, never in the other subpattern,
so the boundaries between the 123456 set of levers and the 78 set might have been salient
cues for locating the four set-boundary levers (1, 6, 7, and 8) compared to locating other
levers.
The experiment we report examined how rats learned serial patterns composed of sub-patterns with or without violations of subpattern structure. The experiment was also designed to control for the concerns just discussed by creating interleaved serial patterns from subpatterns composed of elements drawn from two identical sets of elements so that the resulting subpatterns were the same length, were created from element sets with identical elements and, of necessity, equal set sizes. This approach allowed us to rule out the foregoing factors as determinants of differential subpattern acquisition to better evaluate the extent to which chunking, subpattern structure, and associations between elements (“inter-item associations”) are important determinants of interleaved pattern learning in rats.

Rats learned interleaved patterns based on two simple subpatterns, but for different groups of rats, pattern structure was manipulated by introducing 0, 2, or 4 violations into the first subpattern of the interleaved pattern. Rats were randomly assigned to three pattern conditions. One group learned an interleaved S–S serial pattern: 1526374851627384. This interleaved pattern is based on the two formally simple (S) subpatterns, 12345678 and 56781234. Both subpatterns are considered formally simple because they can be described by a single rule, namely, a “+1” rule that indicates that on successive trials the rat must choose the lever to the right of the last correct lever. In fact, the subpatterns are structurally the same, only differing in terms of where the pattern begins in the array (Lever 1 vs. Lever 5 as starting lever). This interleaved pattern was called “S–S,” to signify that it was composed of two subpatterns of simple structure. A second group learned an interleaved 2V–S serial pattern: 1526473851627384. This interleaved 2V–S pattern was composed of two subpatterns, one with 2 violation (2V) elements and the other with simple structure: 12435678 and 56781234. Note that the 2V subpattern contains two “violation” elements that break the +1 rule that describes the elements constituting the rest of this subpattern. The 2V subpattern was created by exchanging the “4” and “3” elements of the first subpattern of the S–S pattern. The second subpattern of 2V–S is identical to the second subpattern of the S–S pattern. A third group learned an interleaved 4V–S serial pattern: 1526473861527384. This interleaved 4V–S pattern was composed of two subpatterns, one with 4 violation (4V) elements and the other with simple structure: 12436578 and 56781234. The 4V subpattern was created by exchanging the “3” and “4” elements and the “5” and “6” elements of the first subpattern of the S–S pattern. The second subpattern of 4V–S is identical to the second subpattern of the S–S and 2V–S patterns.

The general goals of the study were to assess differential group and subpattern acquisition rates and to characterize the types of errors (intrusion responses) rats made in order to evaluate the extent to which chunking, subpattern structure, and interitem associations are important determinants of interleaved pattern learning in rats. One specific goal was to assess the extent to which rats show evidence of chunking interleaved patterns by sorting elements into component subpatterns, as suggested in earlier studies (Fountain & Annau, 1984; Fountain et al., 1999), when subpattern structure is made more ambiguous by introducing violations into subpattern structure. Evidence to support this idea would be differential learning rates for component subpatterns of the interleaved patterns. Another specific goal was to test the hypothesis that subpattern structure is an important determinant of interleaved pattern learning in rats, as suggested in earlier studies (Fountain et al., 1999). The rule-learning view predicts that the S–S interleaved serial pattern, composed of 2 simple subpatterns should be learned faster than the 2V–S and 4V–S interleaved patterns which both contained violation elements. According to this view, subpattern difficulty should increase in the order S, 2V, and 4V due to the greater number of structural flaws
produced by adding 2 and 4 violations to the formally simple S subpattern to create 2V
and 4V subpatterns, respectively. Another prediction of the rule-learning view is that intru-
sion errors generated by rats on violation elements should conform to the inherent struc-
ture of the sequence. A third specific goal was to evaluate the results for evidence that rats
learn serial patterns by developing associations between elements that make up the pat-
terns (Capaldi, 1967, 1971, 1994). Because elements are often termed “items” in both the
nonhuman animal and human literature, this latter view that rats and other animals learn
sequences by developing interitem associations has been termed the “item memory view.”
According to the item memory view, the type of intrusion errors observed on a given trial
should be determined by generalization of interitem associations learned elsewhere in the
pattern. Taken together, the results will help us evaluate whether rats learn patterns by
adopting a single strategy or, as suggested by recent work in our laboratory, by employing
multiple behavioral processes concurrently (Fountain et al., 2002).

Methods

Subjects

The subjects were 18 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 BSR (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 U 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. Both food and water were freely available in
the home cage.

Apparatus

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 BSR. Each box was con-
structed from clear Plexiglas with a floor of stainless steel rods. Each was enclosed in a
sound-attenuating shell made of particleboard (20 × 60 × 65 cm). These shaping chambers
were housed in a room separate from those of the test chambers.

The training 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
ever 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 centrally
located in the ceiling of the chamber. Two such operant chambers were each located in sep-
arate testing rooms (approximately 2.0 × 2.6 m) illuminated throughout testing by fluo-
rescent lighting. The only major distal cues in the rooms were wall-mounted electrical outlet
panels on two walls and a door on a third wall. 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 by a microcomputer and interface (interface and Med-State Software, Med Associates, Fairfield, VT).

**Procedure**

Throughout all phases of the experiment, rats received reinforcement consisting of a single 200-ms BSR “pulse” of a 60-Hz sinusoidal pulse train from a constant current source of 30–85 μA. In all procedures, rats received one such pulse for each correct response.

After at least 1 week’s recovery from surgery, rats were shaped to lever press for BSR in a shaping chamber. At the beginning of the session, the lever was inserted into the chamber and remained inserted throughout the 30-min session. Rats were required to make at least 1000 lever press responses within a 30-min session and received up to 2 sessions to meet criterion. Rats that failed to meet the criterion were excluded from the study.

After 18 adult male hooded rats were shaped to lever press for BSR pulses, they were randomly divided into 3 groups and trained daily in the octagonal operant chamber. In a discrete-trial 8-choice procedure with correction, all 8 levers were inserted into the chamber at the beginning of each trial. If a correct choice was made, all levers were retracted and BSR was administered. For incorrect choices, all levers but the correct lever were withdrawn and the rat was required to produce the correct response to obtain BSR before continuing to the next trial. On each trial, the lever chosen and the latency to the first response were recorded.

Rats were randomly assigned to three pattern conditions:

- **Structured/Structured (S–S) Pattern**
  
- **Two Violation/Structured (2V–S) Pattern**
  
- **Four Violation/Structured (4V–S) Pattern**

Integers refer to the clockwise position of the levers in the octagonal chamber. Underlined integers indicate where pattern elements were interchanged to produce the 2V–S or 4V–S pattern from the S–S pattern. All ITIs and inter-pattern intervals were 1 s in duration. Rats received 20 patterns without interruption each day for 35 days.

**Results**

**Acquisition curves**

On each trial, rats’ first choice of lever was recorded and scored as correct or incorrect, with incorrect responses immediately followed by the correction procedure. Fig. 1 shows acquisition curves for the three interleaved pattern groups over the 35 days of the experiment. The results show that the S–S pattern was significantly easier to learn than the 2V–S and 4V–S patterns. In all reported analyses, main effects and interactions were considered significant if \( p < .05 \). An analysis of variance (ANOVA) was conducted on rats’ daily mean
percent errors by subpatterns (pooled across elements of subpatterns). The ANOVA indicated significant main effects for groups, $F(2,15) = 5.39$, subpatterns, $F(1,15) = 36.63$, and days, $F(34,510) = 105.72$. Significant interactions included Groups $\times$ Days, $F(68,510) = 1.533$, Subpatterns $\times$ Days, $F(34,510) = 6.51$, and Groups $\times$ Subpatterns $\times$ Days, $F(68,510) = 1.59$. Planned comparisons based on the appropriate error term from the ANOVA demonstrated that rats in S–S learned their pattern significantly faster than rats in the 2V–S and 4V–S. Specifically, S–S rats made significantly fewer errors than rats in 2V–S on Days 2–25, excluding Days 5, 16, 17, and 24. S–S rats also made significantly fewer errors than rats in 4V–S on Days 3–32, excluding Day 17. Differences in group mean errors between 2V–S and 4V–S were never significant ($p > .05$).

Fig. 2 shows acquisition curves for the component first and second subpatterns of S–S, 2V–S, and 4V–S (top to bottom panels, respectively) over the 35 days of the experiment. The results show that for each group the first subpattern was easier to learn than the second subpattern. That is, the first S subpattern of S–S was learned faster than the second S subpattern (Fig. 2, top panel), the 2V subpattern of 2V–S was learned faster than its interleaved S subpattern (Fig. 2, middle panel), and the 4V subpattern of 4V–S was learned faster than its interleaved S subpattern (Fig. 2, bottom panel). These conclusions were supported by planned comparisons based on the ANOVA that showed that S–S rats made significantly fewer errors on their first S subpattern than on their second S subpattern on Days 2–14, 16, 19, 22, 27, and 33. Rats in 2V–S made significantly fewer errors on their 2V subpattern than on their S subpattern on Days 3–28, excluding Days 26 and 27. Rats in 4V–S made significantly fewer errors on their 4V subpattern than on their S subpattern on Days 3–17, 20, and 23.

Rats in the three groups learned the first subpatterns of the three interleaved patterns at different rates. As shown in the top panel of Fig. 3, the first S subpattern of S–S was significantly easier to learn than the 2V subpattern, and the 2V pattern was easier to learn than the 4V subpattern. These conclusions were supported by planned comparisons based on
the appropriate error term from the foregoing ANOVA that showed that S–S rats made significantly fewer errors on their first S subpattern than rats did on the 2V subpattern on Days 2–3, 6–11, 19–24, 25–29, 31, 33, and 35. Rats made significantly fewer errors on the 2V subpattern than on the 4V subpattern on Days 8–13, 16, 18, 21, 27, and 32.

Rats in the three groups also learned the second subpatterns of the three interleaved patterns at different rates. As shown in the bottom panel of Fig. 3, the second S subpattern
of S–S was significantly easier to learn than the S subpattern of 2V–S, and the S subpattern of 2V–S was easier to learn than the S subpattern of 4V–S. These conclusions were supported by planned comparisons based on the appropriate error term from the foregoing ANOVA that showed that S–S rats made significantly fewer errors on their second S subpattern than 2V–S rats did on their S subpattern on Days 4–29, excluding Day 27. S–S rats also made significantly fewer errors on their second S subpattern than 4V–S rats did on their S subpattern on Days 4–33. Rats in 2V–S made significantly fewer errors on their S subpattern than rats in 4V–S did on their S subpattern on Days 11–15, excluding Day 14.

Fig. 3. Acquisition curves for the component first and second subpatterns (top and bottom panels, respectively) of S–S, 2V–S, and 4V–S over the 35 days of the experiment. The top panel shows acquisition for the first subpattern of each interleaved pattern and the bottom panel shows acquisition for the second subpattern. Percentages of daily mean errors were averaged across all elements of the patterns. Error bars: ±SEM.
Error profiles and intrusions

Fig. 4 shows rats’ group mean element-by-element percent error rates collapsed across all 5 weeks of the experiment. The top and bottom panels parse the data by first and second subpatterns of the interleaved patterns, respectively. For the first subpatterns (top panel), the results show that increased error rates in 2V and 4V violation subpatterns compared to the first S of S–S were associated with violation elements and the element following violation elements in the same subpattern. That is, 2V–S rats had increased error rates on the “4” and “3” violation element plus the succeeding “5” element, whereas 4V–S rats had increased errors on the “4,” “3,” “6,” and “5” violation elements plus the succeeding “7” element.
element. Error rates on other elements of 2V and 4V were no different than on the corresponding elements of S. For the second subpatterns (bottom panel), error rates were generally higher throughout the S subpatterns of 2V–S and 4V–S compared to the second S of S–S, as indicated by the analysis of acquisition curves above, with the exception that rats in both 2V–S and 4V–S made no more errors than S–S on the “8” element of their S subpattern, and rats in 4V–S did the same on the “2” element. Additionally, rats in both 2V–S and 4V–S made more errors than on other elements of their S subpattern on the “4” element of their S subpattern, and rats in 4V–S did the same on the “6” element. An ANOVA on element-by-element means for the data pooled for the entire experiment indicated significant main effects for groups, $F(2,15)=4.74$, subpatterns, $F(1,15)=24.14$, and elements, $F(7,105)=11.68$. Significant interactions included Groups $\times$ Elements, $F(14,105)=5.20$, and Groups $\times$ Subpatterns $\times$ Elements, $F(14,105)=9.39$. The foregoing conclusions were drawn from planned comparisons based on the appropriate error term from the ANOVA.

We conducted analyses of the types of errors rats committed, termed intrusion errors, on an element-by-element basis. To simplify presentation of the results, in the next two sections the results are grouped into those demonstrating chunking and rule learning and those demonstrating interitem associations.

**Intrusion errors attributable to subpattern chunking and rule learning**

In the 2V subpattern of the 2V–S pattern (Fig. 4, top panel), error rates were particularly inflated on the “435” elements. On these elements, rats’ most frequent intrusion errors obeyed the subpattern “+1” rule, that is, they fit the pattern of one-to-the-right of the last correct element of the subpattern (that is, ignoring interleaved elements of the S subpattern). Thus, in the 2V subpattern, 12435678, the “2” element was most frequently followed by a “3” intrusion error on the next subpattern element, “4” (57% of the errors committed on that element), the “4” element was most frequently followed by a “5” intrusion error on the “3” element (38%), and the “3” element was most frequently followed by a “4” intrusion error on the “5” element (84%).

In the 4V subpattern of the 4V–S pattern (Fig. 4, top panel), error rates were particularly inflated on the “43657” elements. On these elements, as in the 2V subpattern, rats’ most frequent intrusion errors obeyed the subpattern “+1” rule, that is, they fit the pattern of one-to-the-right of the last correct element of the subpattern (that is, ignoring interleaved elements of the S subpattern). Thus, in the 4V subpattern, 12436578, the “2” element was most frequently followed by a “3” intrusion error on the “4” element (73% of the errors committed on that element), the “4” element was most frequently followed by a “5” intrusion error on the “3” element (44%), the “3” element was most frequently followed by a “4” intrusion error on the “6” element (77%), the “6” element was most frequently followed by a “7” intrusion error on the “5” element (24%, though “6” perseveration errors accounted for 56% of intrusions), and the “5” element was most frequently followed by a “6” intrusion error on the “7” element (63%).

Finally, one intrusion error provides particularly strong evidence that rats chunked subpatterns and encoded “+1” rules. In both 2V–S and 4V–S, daily patterns ran together with no interruption. Except on the first pattern of the day, the result was that in both violation patterns the first violation element “4” was preceded by at least 9 rule-consistent trials (i.e., without violations): 516273841526 → 4 in 2V–S and 273841526 → 4 in 4V–S. In both violation patterns, the element before the violation element, “4,” was “6.” It should be noted that “6” never preceded “3” in either pattern. Yet, “3,” the response predicted by
extrapolation of the subpattern “+1” rule in the sequence leading up to it, was the most frequent response on the “4” violation element (accounting for 57 and 73% of errors committed on that element in 2V–S and 4V–S, respectively).

Intrusion errors attributable to interitem associations

Whereas evidence for chunking and rule learning involves data supporting the idea that rats learned rules relating nonadjacent elements from the S subpatterns, evidence that rats also acquired interitem associations relies on evidence of adjacent-item associations, remote associations, and compound cues that ignore subpattern membership of items. Several examples of these types of associations are evident in the data. For example, in the S subpatterns of 2V–S and 4V–S (Fig. 4, bottom panel), three data points stand out as indicating two unusually difficult elements in the subpattern and three other data points stand out as unusually easy. All of these can be accounted for by the notion of interitem associations acquired via traditional discrimination learning.

In the S subpatterns of the 2V–S and 4V–S conditions (Fig. 4, bottom panel), the error rate was particularly inflated on the “4” element despite the fact that this element was consistent with the “+1” rule that relates all elements of the S subpatterns. For 2V–S, the most frequent intrusion error on this element was “5” (accounting for 90% of the errors on this element), whereas in 4V-S the most frequent error was “6” (54%). The “4” element was cued in both cases by 738 (ignoring subpattern membership). Earlier in the 2V–S sequence, 1526473851627384, 738 was followed by “5,” the response observed as the prominent intrusion error on the later “4” element. Not surprisingly, the most frequent intrusion error on “5” after 738 was “4,” which was the correct response after 738 later in the sequence.

The same pattern was observed in the 4V–S sequence, 1526473861527384, where 738 was followed by “6” earlier in the sequence and “4” later in the sequence; the most prominent errors in both cases were confusions between the two locations. Similarly, in both 2V–S and 4V–S, “8” always immediately follows a 73 sequence (ignoring subpattern membership), and “3” never cues a different response. The result is low error rates whenever an “8” response is required. Why is “6” difficult and “2” easy in S of 4V–S? A 152 sequence cues “6” early in the pattern and “7” later in the pattern. The result is high rates of “7” intrusion errors (90%) after 152 early in the pattern and high rates of “6” errors (63%) later in the pattern. There is no consistent compound cue that could serve as the basis for this confusion in 2V–S, so intrusion error rates are not inflated in the same way in 2V-S. Finally, in 4V–S, a 15 sequence always cues “2”, so low rates of errors are observed whenever a “2” response is required. This is not true in 2V–S, so this benefit is not observed in 2V–S.

Discussion

Rats learned serial patterns composed of two interleaved subpatterns. In one group, the first subpattern was a formally simple sequence, whereas in two other groups the first subpattern was formally more complex, containing 2 or 4 violation elements, respectively. In all groups, the second subpattern encountered was formally simple. These S–S, 2V–S, and 4V–S pattern conditions were expected to assess the relative extent to which rat interleaved serial pattern learning involved cognitive chunking, rule learning, adjacent-item associative learning, and learning of remote associations (stimulus compounds of multiple elements preceding the target element). The study was designed to control for such factors as subpattern and pattern length, the spatial extent of the array from which the pattern elements
were drawn, the number of elements used to create each subpattern (i.e., set size), and the specific elements in the array that were used to create patterns. Evidence from the study suggests that rats chunked elements by subpattern structure, that is, they chunked elements by nonadjacent relationships that can be characterized as rules. They also learned via traditional discrimination learning to use adjacent elements individually and in compounds as cues for later events in the sequence. Thus, the evidence suggests that rats used chunking, rule learning, and interitem association learning concurrently to master this complex task.

Evidence for chunking and rule learning

Earlier studies have provided evidence that rats can learn patterns by encoding rules that describe pattern structure (Fountain & Rowan, 1995a, 1995b) and that they can chunk interleaved serial patterns into their component subpatterns based on the structural properties of the subpatterns (Fountain & Annau, 1984; Fountain et al., 1999). However, recent computer modeling and behavioral studies have shown that some phenomena previously taken as evidence for chunking and rule learning in rats may be accounted for by discrimination learning processes, specifically, formation of associations between pattern elements, generalization, and overshadowing (Fountain, Benson, & Wallace, 2000; Stempowski, Carman, & Fountain, 1999; Wallace & Fountain, 2001, 2003). In light of this recent evidence, we need strong evidence to support a rule-learning interpretation of serial pattern learning results.

Our new evidence supports the claim that rats were sensitive to the relationships between elements of interleaved patterns even though the elements were not adjacent in series. Rats chunked patterns into component subpatterns, learned the “+1” rule relating nonadjacent elements of simple (S) subpatterns, and treated violation elements as structural imperfections. Evidence to support these claims for chunking and rule learning comes from (1) comparisons of pattern and subpattern acquisition rates and (2) intrusion error analyses, particularly for violation elements. Acquisition results showed that the interleaved serial pattern, S–S, composed of two subpatterns of simple structure, was learned faster than interleaved serial patterns containing violation elements, as predicted by rule-learning theory. Further, in each interleaved pattern, subpatterns were acquired at different rates. Even though the two S subpatterns in the interleaved serial pattern S–S were essentially identical, rats nonetheless chunked elements with respect to constituent subpattern, learning the first S subpattern faster than the second S subpattern. Similarly, with reference to the 2V–S and 4V–S interleaved patterns, the first subpatterns, which contained violation elements, were acquired faster than the second subpatterns, S in both cases. When first subpatterns are considered, the formally simple S subpattern was easier to learn than formally complex 2V and 4V subpatterns that contained violations, as predicted by rule-learning theory. Taken together, these results strongly support the notion that rats were chunking patterns into their constituent subpatterns and that subpattern structure was a determinant of subpattern difficulty.

Evidence for chunking and rule learning also came from results of the intrusion error analysis. Errors on violation elements were frequently responses consistent with the +1 rule describing simple subpattern structure. As we indicated in the results above, some of the strongest evidence for chunking and rule learning comes from high-frequency responses on violation elements that are natural extensions of subpattern rules but were never reinforced. In fact, some of these responses clearly violated adjacent-item associations that might have been
learned through reinforcement. Such responses fit well with predictions of rule-learning theory, but are not easily explained by common associative mechanisms of discrimination learning.

One reasonable question is: How do we know rats learned rules relating nonadjacent elements rather than remote associations? We argue that the foregoing results indicate that rats learned rules that related nonadjacent elements of subpatterns. It should be noted that one reasonable alternative hypothesis is that the errors we observed could be attributed to nonadjacent-item associations, rather than to rule learning. That is, it is possible that rats chunked patterns into their constituent subpatterns, but learned to anticipate subpattern elements based on remote associations rather than rules. For example, by ignoring intervening elements, rats in the 2V–S group learned the pattern, 152647385127384, where the violation elements are underlined. Rather than learning rules about nonadjacent subpattern elements, rats could have learned a \(2 \rightarrow 3\) remote association (ignoring the intervening “7” element of the other subpattern) in the S subpattern that generalized to the 2V subpattern, say, rather than a “+1” rule. This would result in high rates of “3” errors on “4,” the first violation element, as we observed. However, the prediction that should also follow would be that at the point of the violation in the 2V subpattern the rat should have also learned a 2 \(\rightarrow 4\) association that would be expected to generalize as well. That should have produced symmetrically high rates of “4” errors on the later “3” element, but no accompanying increase in these types of errors in the S subpatterns was observed. This result indicates that there was a bias for “+1” rules learned within S subpatterns (as a result of chunking subpatterns) to readily transfer as default responses to the violation subpatterns.

Thus, although rats apparently used chunking to learn the rules relating elements in S subpatterns and generalized them to violation subpatterns, they treated learning about violation elements as a separate problem to be solved. This result is consistent with rule learning but not with an associative learning interpretation.

**Evidence for associative learning: Item memory**

Some features of the data strongly support the view that rats encoded a representation of subpattern structure, but other features of the results show that rats also learned adjacent-item and remote associations in this paradigm. If we ignore subpattern structure and treat the patterns as an undifferentiated series of events, we find strong evidence that sequential adjacent-element associations and remote associations controlled rats’ sequential choices. As we indicated in the analysis of intrusion responses, several of the easiest and most difficult elements for rats to learn could be accounted for by multiple-item associations. When multiple cues consistently signaled the same outcome, the target elements were among the easiest to learn. In contrast, when multiple cues signaled different outcomes at different points in the sequence, creating a difficulty “branching” problem (Restle & Brown, 1970a, 1970b), the target elements were among the most difficult to learn due to generalization of errors across instances where the same cues predicted different outcomes.

This associative view, however, cannot account for the foregoing phenomena implicating chunking and rule learning. Instead, the results taken together fit better with the idea that rats used rule learning and associative learning concurrently. Rats appeared to learn about the formally simple rules that described the underlying interleaved structures of the sequences and governed long strings of elements. They also used associative memory of multiple items as compound cues to anticipate specific pattern elements where those cues were particularly distinctive.
Conclusions

This paper presents evidence for concurrent chunking, rule learning, and interitem association learning in rat serial pattern learning. In so doing, it extends earlier work on rats’ ability to chunk noninterleaved sequences (Capaldi, Nawrocki, Miller, & Verry, 1986; Fountain, 1990; Fountain, Henne, & Hulse, 1984) and interleaved sequences (Fountain & Annau, 1984; Fountain et al., 1999). Several comments are in order. First, although the foregoing results indicate that rats were chunking by subpatterns, evidence indicated that chunking was incomplete. Intrusion data showed that rats generalized violation responses they were required to perform in 2V and 4V to corresponding locations in their S subpatterns. An important goal for future work should be to identify the factors that determine the ease or difficulty of chunking. For example, it is likely that creating component subpatterns from two identical sets of eight spatial locations contributed to the difficulty of chunking the interleaved patterns in this study.

Second, in addition to employing chunking and rule-learning processes, rats used sequential interitem associations and compound cues involving remote associations to help anticipate some, if not all, elements in their sequence. This conclusion suggests that information about interitem associations can co-exist with rule-based representations of the sequence. Whether this occurs in separate stores or a common representation is not clear, though some recent work from our laboratory suggests that storage and retrieval of associations and rules may depend on separate processes for the two types of information (Fountain & Rowan, 2000; Fountain et al., 2002).

Third, rats in each condition learned the first subpattern of their interleaved patterns faster than the second. We have no explanation for this first-subpattern advantage; it is not apparent that it can be explained by interitem association theory or rule-learning theory. The interitem association or item memory viewpoint (Capaldi, 1967, 1971, 1994) suggests that rats learn serial patterns by associating successive elements, such that, when learning the serial pattern ABCDE, rats come to learn “A predicts B,” “B predicts C,” and so forth. In other words, no sensitivity to rules is implied by this view. This explanation cannot account for the differential acquisition rates observed between interleaved patterns and subpatterns and, particularly, the first-subpattern advantage we observed. If rats were simply chaining responses together in sequential fashion, one would not expect patterns of equal length, identical elements, uniform set sizes, and equivalent spatial distributions to be learned at different rates. Rule-learning theory likewise cannot explain the first-subpattern advantage; rule-learning theory predicts that formally simpler patterns or subpatterns (such as S subpatterns) should be easier to learn than formally more complex patterns or subpatterns such as those containing violation elements (2V and 4V, in this case). Thus, rule-learning theory predicts that S subpatterns should be learned before 2V or 4V subpatterns in the same interleaved pattern. In fact, rats learned the first subpattern of each interleaved pattern before the second even when the first subpattern was 2V or 4V and the second subpattern was S. In addition, rule-learning theory does not necessarily predict a first-subpattern advantage in S–S where the component subpatterns were both formally simple. The first-subpattern advantage also does not fit with earlier studies where the second subpatterns of interleaved patterns were learned before the first (Fountain et al., 1999), though it must be noted that subpatterns in those patterns were not matched for length, identical elements, uniform set sizes, and equivalent spatial distributions as they were here. Clearly, more work is needed to identify the factors responsible for the first-subpattern
advantage that was such a prominent feature of the interleaved pattern learning we observed. 

Interleaved serial patterns in this study were created from subpatterns composed of elements drawn from two identical sets of elements so that the resulting subpatterns were the same length, were created from element sets with identical elements and, of necessity, equal set sizes. By holding these factors and pattern length constant, only the order of pattern elements was varied in the present experiment. Yet, rats learned their interleaved serial patterns and constituent subpatterns at different rates. Rats presented with interleaved serial patterns in each case were able to chunk elements into constituent subpatterns of varying degrees of structural organization. The results clearly demonstrated that rats’ memorial representations included information about the rules that described simple structures in nonadjacent elements of their interleaved patterns. However, rats’ memorial representations also included multiple item memory, that is, interitem associations and remote associations acquired via traditional discrimination learning. More research needs to be conducted to determine whether rule-based information and interitem associations are stored in a common representation or multiple representations and to characterize the processes involved in managing information from multiple sources to anticipate future events (cf. Fountain, 2005).

References


