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Statistical learning of adjacent and nonadjacent dependencies among nonlinguistic sounds

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Previous work has demonstrated that adults are capable of learning patterned relationships among adjacent syllables or tones in continuous sequences but not among nonadjacent syllables. However, adults are capable of learning patterned relationships among nonadjacent elements (segments or tones) if those elements are perceptually similar. The present study significantly broadens the scope of this previous work by demonstrating that adults are capable of encoding the same types of structure among unfamiliar nonlinguistic and nonmusical elements but only after much more extensive exposure. We presented participants with continuous streams of nonlinguistic noises and tested their ability to recognize patterned relationships. Participants learned the patterns among noises within adjacent groups but not within nonadjacent groups unless a perceptual similarity cue was added. This result provides evidence both that statistical learning mechanisms empower adults to extract structure from nonlinguistic and nonmusical elements and that perceptual similarity eases constraints on nonadjacent pattern learning. Supplemental materials for this article can be downloaded from pbr.psychonomic-journals.org/content/supplemental.

Statistical learning studies have demonstrated that adults, young children, and infants are capable of rapidly learning consistent relationships among temporally adjacent speech sounds or musical tones and of grouping these elements into larger coherent units, such as words or melodies (Aslin, Saffran, & Newport, 1998; Perruchet & Pacton, 2006; Saffran, Aslin, & Newport, 1996; Saffran, Johnson, Aslin, & Newport, 1999; Saffran, Newport, & Aslin, 1996; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). Similarly, adults and infants are capable of grouping temporally adjacent patterned visual elements into coherent units (Fiser & Aslin, 2002; Kirkham, Slemmer, & Johnson, 2002).

In contrast, however, the ability to learn dependencies among nonadjacent elements is more selective. Natural languages exhibit only certain limited nonadjacent dependencies among sounds and word classes (Chomsky, 1957). In artificial language experiments, only certain types of nonadjacent patterns are readily learned (Cleeremans & McClelland, 1991; Gómez, 2002; Newport & Aslin, 2004; Onnis, Monaghan, Richmond, & Chater, 2005) and are particularly difficult to learn when the materials are complex or are presented in lengthy or continuous streams. Newport and Aslin showed that statistical learning of patterns between nonadjacent syllables is difficult[1] but that similar relationships between nonadjacent *segments* (consonants or vowels), which are common in natural languages, can be learned quite easily. They suggested that, although nonadjacent relationships are more difficult to acquire than adjacent ones, this difficulty could be ameliorated when the nonadjacent elements are perceptually similar to one another (e.g., all consonants) and distinct from the intervening elements (e.g., vowels). Creel, Newport, and Aslin (2004) showed that patterns among nonadjacent tones could be learned if the nonadjacent elements are of a similar pitch range or timbre.

The results of the present experiments significantly broaden previous results through the examination of the same questions for patterns composed of nonlinguistic and nonmusical elements. We used nonlinguistic noises that have no names and that do not fall along a single dimension (e.g., pitch for tones). We asked whether such unfamiliar noises show the same signature properties of statistical learning that have been demonstrated for familiar speech materials—in particular, whether adults readily learn adjacent groupings and whether nonadjacent groupings are more selectively learned on the basis of whether the related elements are perceptually similar.

The materials and procedures were analogous to those used in previous studies of speech and tonal melodies. Adults were exposed to a continuous familiarization stream of nonlinguistic noises and were tested for their ability to recognize patterns that they had heard. In each experiment, we constructed the familiarization stream by creating four strings of three nonlinguistic sounds (*noise triplets*) and then sequencing tokens of these noise triplets in random order (excluding immediate repeats). In Experiment 1, in which the regularities are among adjacent noises, we show that these patterns of unfamiliar noises can be learned. In Experiments 2 and 3, in which the regularities are among nonadjacent noises, we demonstrate that these patterns *cannot* be learned, unless a perceptual similarity cue links the nonadjacent elements to one another.

We originally planned for the present series of experiments to be completely analogous to previous experiments

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of statistical learning in speech streams (Newport & Aslin, 2004; Saffran, Newport, & Aslin, 1996). However, extensive piloting demonstrated that two important experimental design parameters required modification in the present study.

First, 150 msec of silence was inserted between each noise in the familiarization streams, both within and across noise triplets. Although participants could not perceive the silences, this slight spacing between sounds improved performance, likely because this helped participants encode the distinct, unfamiliar noises.

Second, the total exposure duration to the streams needed to be significantly lengthened relative to that in previous studies with speech and tones (Creel et al., 2004; Newport & Aslin, 2004; Saffran, Aslin, & Newport, 1996; Saffran et al., 1999; Saffran, Newport, & Aslin, 1996). In previous studies in the speech domain, infants (Saffran, Aslin, & Newport, 1996) and adults (Newport & Aslin, 2004, and unpublished data) learned adjacent syllable dependencies and nonadjacent segment dependencies with familiarization periods of 2–20 min. However, our piloting in the noise domain showed that adults failed to learn adjacent dependencies when the total familiarization was 20, 35, or 40 min. It took 100 min of exposure, across three familiarization sessions, for participants to learn the adjacent statistical regularities. We then used this same 100-min exposure in testing nonadjacent dependency learning.

Thus, in the present series of experiments, we extend our previous results of statistical learning to nonlinguistic and nonmusical items. We show that the learning process is much more difficult and requires a much longer familiarization exposure than when the elements are speech sounds or tones; but, nonetheless, the same type of selective learning occurs for these patterns. In the General Discussion section, we consider what these findings tell us about the mechanisms involved in statistical pattern learning.

EXPERIMENT 1
Adjacent Dependency Learning

The structure of the patterned regularities in the present experiment was identical to that in the easiest of our previous languages, designed for infants (Saffran, Aslin, & Newport, 1996). Four nonlinguistic noise triplets were constructed, each of which contained three unique noises; these triplets were then sequenced in a constrained random order with no immediate repetitions to form a familiarization stream. Over the familiarization stream, the transitional probabilities between noises within a triplet were all 1.0; the transitional probabilities at the triplet boundaries were all .33. Each individual noise was of the same duration, loudness, and frequency, with the same interval from one noise to another. The only available information for segmenting the nonlinguistic noise triplets was the greater statistical regularity of adjacent noise sequences within a triplet than of adjacent noise sequences that spanned a triplet boundary.

Method

Participants. Sixteen University of Rochester undergraduates participated, for a payment of $30 each. In this and in the following experiments, participants were monolingual English speakers with normal hearing and no diagnosed learning disabilities or attention disorders. None had previously participated in a statistical learning experiment.

Stimulus materials. An inventory of 12 nonlinguistic sounds, composed of Macintosh Operating System 9 alert sounds and iMovie sounds (from www.apple.com), was used in this experiment.[2] SoundEdit 16 Version 2 (Macromedia, Inc.) was used to edit each individual sound to a duration of 0.22–0.25 sec, to standardize volume across sounds, and to fade each sound in and out (10-msec ramp).

Four different nonlinguistic noise triplets were created for each of two different phonetic instantiations (Language 1 and Language 2) to guard against participants' idiosyncratic preferences for particular individual sounds or their combinations. Each noise triplet consisted of three unique sounds from the sound inventory (Table 1). In this and in the following experiments, a 150-msec silent interval was inserted between each sound within and between each noise triplet, using SoundEdit. Eight participants were tested in each of the two language conditions.

For each condition, 24 tokens of each of the four noise triplets were sequenced in random order (excluding immediate repeats) to create a continuous sound stream. The stream was then looped 21 times to create a familiarization stream of approximately 40 min (with two 1-min silent rest periods at equally spaced intervals), which participants heard during each of the first two testing sessions. The stream was also looped 10 times to create a familiarization stream of approximately 20 min (with a 1-min silent rest period at the halfway point), which participants heard during the third session. The participants were thus exposed to a total of 4,992 noise triplet tokens during the three-session familiarization period.

For the two-alternative forced choice test (see the Procedure section), four *noise part-triplets* were created for each language (see Table 1 and the Appendix).

Procedure. All of the participants were tested individually in a quiet room while listening to the recordings on a Sony minidisk player through Sennheiser Symphony HD 570 headphones. The participants were instructed to listen attentively to the continuous sound stream, that they might begin to recognize some patterns, and that, at the end of the third session, they would be tested to determine how well they recognized the patterns.

The experiment consisted of two phases: familiarization and test. There were three sessions on consecutive days. During each of the first two sessions, the participants heard the 40-min familiarization stream; during the third, the participants heard the 20-min familiarization stream and then completed the test.

Test trials were constructed by pairing each noise triplet with each noise part-triplet to determine whether the participants could recognize the more statistically consistent patterns (the noise triplets). Each noise triplet/noise part-triplet combination occurred twice (in counterbalanced order) during the test, resulting in a total of 32 trials. In this and in the following experiments, two different randomized presentation orders were used for the trials (counterbalanced across participants).

For each test trial, the participants heard a noise triplet and a noise part-triplet, separated by a 1-sec silent interval. The participants were instructed to indicate which was more familiar, on the basis of the recording they had heard, by circling either "1" or "2" on a preprinted answer sheet. A 5-sec silent interval followed each trial to allow the participants time to record their response.

Results

We report the pooled data for Languages 1 and 2, since there was no significant difference between the participants' performances on the two languages [$t(14) = 1.24$, $p = .23$]. The first bar in Figure 1 shows the pooled test results. Participants *did* readily acquire the regularities within the languages. Overall, test performance significantly exceeded chance [$M = 67.58\%$ correct; $t(15) = 4.58$, $p = .0004$].

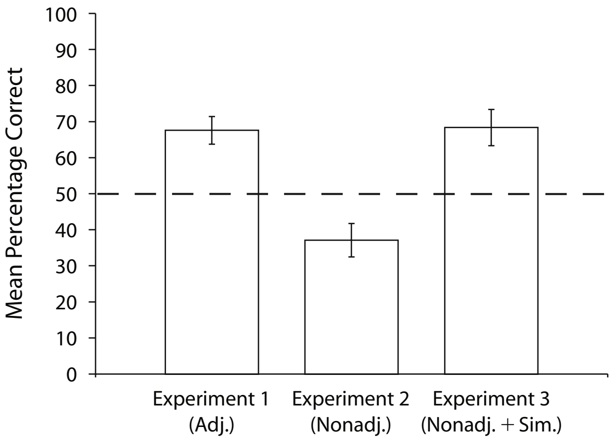

Figure 1. Participants' mean percentage correct (± one standard error of the mean) on test items in Experiments 1–3. Adj., adjacent; nonadj., nonadjacent; nonadj. + sim., nonadjacent with perceptual similarity.

EXPERIMENT 2
Nonadjacent Dependency Learning Without Perceptual Similarity Cues

In this experiment, we asked whether participants would be able to learn a set of statistics in a nonlinguistic sound stream in which the statistical regularities occur among nonadjacent elements that were *not* selected to be perceptually similar. We created a continuous sound stream that contained a pattern in which the only available information for segmenting the noise triplets was the greater statistical regularity of nonadjacent noises forming triplets than of any of the adjacent noises. The transitional probabilities between nonadjacent noises within each triplet were all 1.0; those between adjacent noises within each triplet were all .5; those between adjacent noises that spanned a triplet boundary were all .5.

Method

Participants. A new set of 16 University of Rochester undergraduates participated for a payment of $30 each.

Stimulus materials. An inventory of six sounds was used to create four noise triplets for each of two languages. This inventory was a subset of that from Experiment 1 (see Table 1 and the Appendix). The nonadjacent patterned relationships occurred between the first and third sounds of each noise triplet (e.g., between Sounds A and B), skipping over the intervening sound element (e.g., *x*). As is shown in Table 1, there were two nonadjacent frames for the participants to detect: A[*x* or *y*]B and C[*x* or *y*]D.

The randomization and looping schemes for creating the streams were similar to those in Experiment 1. Noise triplets were sequenced in a constrained random order (excluding immediate repeats) to create a continuous sound stream. Words 1 and 4 could be followed only by Words 2 and 3; Words 2 and 3 could be followed only by Words 1 and 4 (see Table 1; words are listed in consecutive order). Each word and each juncture occurred equally often. Eight participants were tested in each of the language conditions.

As in Experiment 1, for the test, four noise part-triplets were created (see Table 1 and the Appendix).

Procedure. The procedure was identical to that of Experiment 1, except for the use of different stimuli and test materials.

Table 1
Noise Triplet Structure for Experiments 1–3

Experiment	Noise Triplet Structure	Noise Part-Triplet Structure
1	ABC	FJK
	DEF	LDE
	GHI	BCG
	JKL	HIA
2 and 3	A*x*B	*x*DA
	A*y*B	*y*DA
	C*x*D	BC*x*
	C*y*D	BC*y*

Results

We report the pooled data for Languages 1 and 2, since there was no significant difference between the participants' performances on the two languages [$t(14) = -0.081$, $p = .94$]. The second bar in Figure 1 shows the pooled test results. The participants did *not* acquire the patterned relationships. Overall, test performances were significantly below chance [$M = 37.11\%$ correct; $t(15) = -2.78$, $p = .014$].

It is unclear why the participants scored below chance on the test. However, we have previously observed similar performance levels in tests of statistical learning among nonadjacent speech syllables (Newport & Aslin, 2004). Importantly, performances in Experiment 2 were significantly worse than performances in Experiment 1 [$F(1,30) = 25.59$, $p < .0001$]. The failure to learn these nonadjacent relationships occurred despite the fact that the number of different noise triplets (four) was the same across the two experiments, and there were fewer patterns to be learned in Experiment 2 (two) than in Experiment 1 (eight). (See Table 1.)[3]

EXPERIMENT 3
Nonadjacent Dependency Learning With Perceptual Similarity Cues

Previous studies have provided evidence that the learning of nonadjacent patterned relationships is highly selective (Creel et al., 2004; Newport & Aslin, 2004; Onnis et al., 2005). With speech materials, learners readily acquire nonadjacent relationships among consonants (with the intervening vowels unrelated) or among vowels (with the intervening consonants unrelated), but not among nonadjacent syllables. One hypothesis is that these results are particular to speech and arise from differences in learning segments versus learning syllables. But another hypothesis is that these results are not domain-specific and, rather, reflect the greater ease of pattern learning among perceptually similar elements. If the latter hypothesis is correct, comparable results should appear in the learning of patterns in nonlinguistic materials.

In the present experiment, we investigated whether perceptual similarity among nonadjacent, nonlinguistic sounds facilitates participants' pattern learning. We added four new sounds to our inventory, which were perceptually similar to one another (*tonal*) but perceptually different from other (*raspy*) sounds in our inventory. Although the same type of A*x*B nonadjacent patterns were used here as were used in Experiment 2, the nonadjacent patterned relationships in the present experiment occurred among the raspy sounds, with intervening tonal sounds.

As in Experiment 2, the continuous sound stream contained a pattern in which the only available information for segmenting the noise triplets was the greater statistical regularity of nonadjacent noises than of any of the adjacent noise sequences. The transitional probability structure was identical to that in Experiment 2.

Method

Participants. A new set of 16 University of Rochester undergraduates participated for a payment of $30 each.

Stimulus materials. An inventory of 10 sounds was used to create four noise triplets for each of two languages. This inventory included 6 sounds from Experiment 2 and 4 new sounds from www.partnersinrhyme.com (see Table 1 and the Appendix). As in Experiments 1 and 2, each sound was edited to a duration of 0.22–0.25 sec, normalized to standardize volume across sounds, and faded in and out. Five naive adults rated each individual sound on a scale of 1–7 (with 1 being *not tonal at all* and 7 being *very tonal*). The mean of the participants' ratings for the atonal (raspy) sounds ($M = 2.97$) that had been preselected for the experiment was significantly different from the mean of the participants' ratings for the tonal sounds ($M = 4.50$) that had been preselected for the experiment [$t(4) = 7.19, p = .002$].

In each noise triplet, the nonadjacent raspy elements (e.g., A and B from Table 1) were perceptually similar to one another but perceptually different from the intervening tonal element (e.g., *x*).

The randomization and looping schemes were identical to those in Experiment 2. Eight participants were tested in each of the two language conditions.

As in Experiments 1 and 2, for the test, four noise part-triplets were created (see Table 1 and the Appendix).

Procedure. The procedure was identical to those of Experiments 1 and 2, except for the use of different stimuli and test materials.

For the test, the structure of the noise part-triplets was identical to that of those in Experiments 1 and 2. Test trials were constructed by pairing each noise triplet with each noise part-triplet. Each noise triplet/noise part-triplet combination occurred once (in counterbalanced order) during the test, resulting in a total of 16 trials. The test structure was otherwise identical to those in Experiments 1 and 2.

Results

We report the pooled data for Languages 1 and 2, since there was no significant difference between the participants' performances on the two languages [$t(14) = 1.74, p = .10$]. The third bar in Figure 1 shows the pooled test results. Participants *did* readily acquire the regularities within these languages. Overall, test performances significantly exceeded chance [$M = 68.36\%$ correct; $t(15) = 3.66, p = .0023$]. Thus, the participants learned the nonadjacent relationships when the nonadjacent elements were perceptually similar to one another but perceptually different from the intervening elements.[4] Performances in Experiment 3 significantly exceeded performances in Experiment 2 [$F(1,30) = 20.88, p < .0001$].

GENERAL DISCUSSION

The results of the present series of three experiments provide important new information about how adults learn patterned relations among elements in continuous streams. First, the ability to extract statistical patterns between temporally adjacent elements is rendered much more difficult when the elements are unfamiliar, complex, unlabeled noises than when the elements are familiar speech syllables. Minimum exposure duration required for successful learning of adjacent patterns differed by a factor of five from that found in previous studies of statistical learning with speech or simple tones. Second, the pattern of results—superior learning of adjacent statistics and successful learning of nonadjacent statistics only when they were defined by a correlated acoustic cue—replicated findings from studies of both speech and tones. Thus, although the efficiency of statistical learning was reduced by element unfamiliarity, the overall pattern of statistical learning remained invariant.

One question that arises from the much greater exposure duration required for learning in the present experiments is whether the rapidity of statistical learning with speech materials benefits from extensive prior exposure to speech (thereby rendering its elements highly familiar) or from a natural, more efficient encoding of speech sounds and tones by adults and infants. Marcus, Fernandes, and Johnson (2007) argued for the special status of speech, whereas Johnson et al. (2009) softened that claim on the basis of finding comparable patterns in studies of visual statistical learning (see also Saffran, Pollak, Seibel, & Shkolnik, 2007). At minimum, we know that rapid statistical learning of patterns across speech syllables does not require a species-specific mechanism unique to humans, since both tamarin monkeys (Hauser, Newport, & Aslin, 2001) and rats (Toro & Trobalón, 2005) learn statistical relations between adjacent syllables. Future research with nonspeech sounds will be required to test whether infants are predisposed to process speech in a particularly efficient manner or whether any initially unfamiliar and complex set of nonspeech sounds could be learned efficiently, given sufficiently extensive prior exposure.

Most significant, however, is the finding that, even with materials that are highly unfamiliar and that require much greater exposure for successful statistical learning, the same findings obtain regarding the types of patterns that are relatively easy and relatively hard to learn. Statistically consistent patterns among arbitrarily chosen adjacent elements are easier to learn than those among arbitrarily chosen nonadjacent elements, and this advantage for adjacent over nonadjacent patterns holds even when there are many fewer nonadjacent patterns to be learned. However, when the nonadjacent elements are perceptually similar to one another, and distinct from the intervening elements, learning is successful. Our results support the view that perceptual similarity is one of several contributing constraints on learning. Taken together, these findings suggest that temporal proximity and perceptual similarity can each support statistical learning across a wide range of materials.

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NOTES

1. See Peña, Bonatti, Nespor, & Mehler (2002) for counterevidence.

2. Each individual sound from Experiments 1–3 is included as a .wav file in the supplementary material at pbr.psychonomic-journals.org/content/supplemental.

3. One possible reason for the significantly below-chance performance is that frames (i.e., A_B or C_D) were allowed to repeat in the constrained randomization. Thus, an A*x*BA*y*B sequence may have heightened attention to the bigram (BA) at a triplet boundary.

4. Endress and Mehler (2009) claimed that learners might not learn three-syllable words as units but, rather, become sensitive to co-occurrences of syllable pairs (enabling them to distinguish words from part-words on a two-alternative forced choice test). We are agnostic about whether noise triplets have been learned as a chunk in this sense; we argue only for stream segmentation, which could be based on sets of bigram groupings.

SUPPLEMENTAL MATERIALS

The sound files used in these experiments can be obtained from pbr.psychonomic-journals.org/content/supplemental.

APPENDIX
Sound Inventory for Experiments 1–3

Sound	Experiment 1		Experiment 2		Experiment 3	
	Language 1	Language 2	Language 1	Language 2	Language 1	Language 2
SimpleBeep	A	H	–	–	–	–
ChuToy	B	J	B	*x*	B	A
HighSproing	C	B	A	D	–	C
Bell	D	E	–	–	–	–
DigitalLand	E	G	–	–	–	–
Purr	F	L	–	–	–	–
Indigo	G	C	*x*	B	A	D
MagicMorph	H	D	C	*y*	–	B
Sosumi	I	F	–	–	–	–
Chirp	J	K	–	–	–	–
Voltage	K	I	D	A	D	–
Temple	L	A	*y*	C	C	–
Button	–	–	–	–	*x*	–
Spo	–	–	–	–	*y*	–
BeepFM	–	–	–	–	–	*x*
BeepPure	–	–	–	–	–	*y*

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