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Abstract Rule Learning for Visual Sequences in 8- and 11-Month-Olds

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The experiments reported here investigated the development of a fundamental component of cognition: to recognize and generalize abstract relations. Infants were presented with simple rule-governed patterned sequences of visual shapes (ABB, AAB, and ABA) that could be discriminated from differences in the position of the repeated

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element (late, early, or nonadjacent, respectively). Eight-month-olds were found to distinguish patterns on the basis of the repetition, but appeared insensitive to its position in the sequence; 11-month-olds distinguished patterns over the position of the repetition, but appeared insensitive to the nonadjacent repetition. These results suggest that abstract pattern detection may develop incrementally in a process of constructing complex relations from more primitive components.

Detection and generalization of patterns is a fundamental, core component of cognition, central to object and face recognition (Biederman, 1987; Hummel & Biederman, 1992), categorization (Kruschke, 1992), inference (Tenenbaum & Griffiths, 2001), reasoning (Murphy, 2002), word segmentation (Swingley, 2005), language acquisition (Brown, 1973; Pinker, 1994), and other developmental achievements. A central question often posed by developmental researchers, therefore, concerns the ability of infants and children to learn patterns and structure. The environment contains an immeasurable variety of objects and events, and an infinite number of relations between them, most of which are not useful for the developing child. It is essential, then, to understand the types of patterns that children are and are not able to learn.

One common approach in investigations of early pattern perception is to examine infants' sensitivity to structured relations among stimulus features in visual or auditory input. Experiments on statistical learning, for example, have explored the extent to which infants detect and use distributional information in auditory or visual sequences to combine individual features into larger units. Typically in these experiments, infants are presented with a stream of input consisting of repeating multi-element units with randomized order, but fixed internal structure. Saffran, Aslin, and Newport (1996) used this approach to investigate 8-month-old infants' word segmentation in a corpus of artificial speech. Noting that adjacent sounds in natural speech that are likely to cooccur are usually found within words, whereas low-probability sound pairs tend to span word boundaries, Saffran et al. asked whether this difference in probability of cooccurrence provides potential information for word boundaries. Infants' discrimination of high- and low-probability sound pairs was explored with a synthesized speech stream; the only cues to word boundaries were the transitional probabilities between syllable pairs. Following exposure, the infants heard isolated repeated instances of familiar words, alternating with novel combinations of syllables. The infants showed a reliably greater interest in the novel syllable combinations than in the words, implying that they distinguished between the stimuli based on the transitional probabilities defining word boundaries. Similar evidence comes from experiments with nonspeech stimuli: tones (Saffran, Johnson, Aslin, & Newport, 1999), streams of colored shapes in a single location (Kirkham, Slemmer, & Johnson, 2002) or multiple locations (Kirkham, Slemmer, Richardson, & Johnson, 2007), and multielement scenes (Fiser & Aslin, 2002). In all these studies, infants provided evidence of sensitivity to the one-to-one correspondence in the familiarized stimuli between an element and its successor in sequence or location, or the grouping of elements in the spatial layout.

A second approach to pattern learning has been to explore infants' ability to detect and generalize higher order, abstract relations to new exemplars that may have no surface features in common with those presented in training (cf. Bruner, Goodnow, & Austin, 1956; Mervis, 1980). For example, 7-month-old infants can identify ABB, AAB, and ABA patterns in sequences of synthesized speech such as *la ta ta, gai mu mu,* and so on (Marcus, Vijayan, Bandi Rao, & Vishton, 1999). Given 2 min of exposure, infants were able to systematically discriminate between novel sequences following the same pattern (e.g., *wo fe fe*) and novel sequences following a different pattern (e.g., *wo fe wo*). Because both test sequences consisted of novel syllables, infants could not rely on specific memories for particular learned sequences or features. Instead, infants appeared to detect a higher order pattern or rule that governed the sequence order during familiarization. (Older infants have demonstrated similar abilities with more complex strings of words generated by a finite-state grammar; Gómez & Gerken, 1999.)

Relative to statistical learning, development of infants' ability to acquire rules is poorly understood. There are no data pertaining to how rule learning develops over time, and relatively few data pertaining to the scope of rule learning in infancy. Some work suggests that infants may be better at learning rules from speech than other domains of auditory stimulus, such as musical tones, timbres, and natural animal sounds (Marcus, Fernandes, & Johnson, 2007), and other studies suggest that infants may be able to acquire rules from visual images of everyday stimuli when the materials were presented simultaneously (Saffran, Pollak, Seibel, & Shkolnik, 2007; Tyrell, Stauffer, & Snowman, 1991; Tyrell, Zingardo, & Minard, 1993). In contrast, little is known about how infants acquire rules from temporally presented sequences of arbitrary stimuli—stimuli with which infants have no experience, unlike the auditory materials used in previous studies, which may confer an advantage when learning higher order sequential patterns.

Our goal in this article is to elucidate the learning mechanisms that might be involved in infant rule learning. In the experiments reported here, we investigate infants' capacity to acquire rules from arbitrary sequences of visual stimuli, and we examine how those abilities change over the course of development. As noted previously, rule learning is likely facilitated by materials with which infants are commonly familiar, and we reasoned that the use of unfamiliar stimuli might challenge the rule learning skills of infants, perhaps producing a pattern of both successes and failures to learn and discriminate specific rules. In particular, we hypothesized that *repetition* of elements—an identity relation—might be an early-learned rule, such as the BB repetition in an ABB sequence. An early emerging capacity to recognize temporally contiguous relations, such as a repetition of elements, might stem from the capacity of infants to segment and detect units in sequential stimuli on the basis of paired associates. By 2 months, for instance, infants can identify differences in transitional probabilities that define stimulus pairs in sequences of looming visual shapes, when stimulus pairs are adjacent in the sequence (Kirkham et al., 2002), and similar outcomes have been observed with auditory sequences in older infants (e.g., Saffran et al., 1996; Saffran et al., 1999). Although discovery of abstract patterns cannot be performed on the basis of statistical information per se, early sensitivity to statistical structure might provide a foundation for acquisition of more complex relations, perhaps by directing infants' attention toward potential patterns on the basis of proximity in space and time (Diamond, Churchland, Cruess, & Kirkham, 1999; Quinn, in press).

We adopted the general method used by Kirkham et al. (2002): Infants were exposed to sequences of looming colored shapes in a visual preference procedure. Infants were first habituated to ABB, ABA, or AAB patterns, presented one shape at a time in the center of a computer monitor (see Figure 1). Following habituation, a new set of colored shapes was shown, instantiating either the familiar rule or a novel rule on alternating trials. Discrimination of the familiar and novel patterns was expected to effect a novelty preference for the new rule (Bornstein, 1985). On the other hand, familiarity preferences have been observed in sequence learning experiments that tested infants' responses to complex relations, such as detection of pairs of spatially arranged visual shapes among distracters (Fiser & Aslin, 2002, used an infant-controlled habituation design), and segmentation of streams of artificial speech when stress and statistical cues were placed in conflict (Thiessen & Saffran, 2003, used a fixed-duration familiarization design). We reasoned that our paradigm might affect familiarity preferences for some of the more complex comparisons we tested, because infants often prefer familiar to novel stimuli when the familiar might require additional processing (Hunter & Ames, 1988).

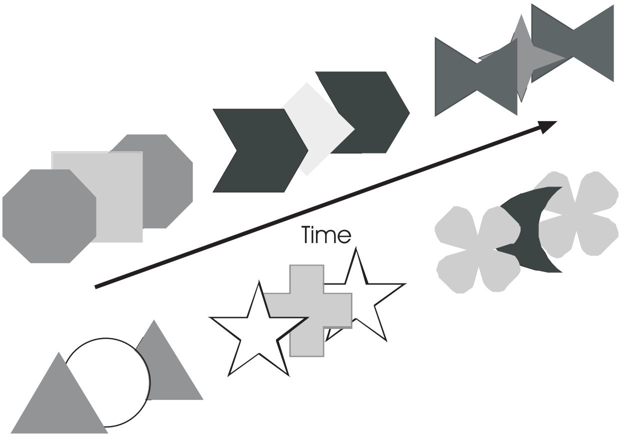

FIGURE 1 Schematic examples of stimulus sequences (in this case, ABA) shown to infants in the six experiments.

In previous experiments on infant rule learning (Marcus et al., 1999; Saffran et al., 2007), 7-month-olds succeeded in learning rule-bound patterns "symmetrically"; that is, infants who were trained with ABA discriminated this pattern from ABB, and vice versa (and also for AAB vs. ABB). We found, in contrast, that learning sequential rule-bound visual patterns was largely asymmetrical (see Table 1). Our experiments, therefore, are organized by the kinds of discrimination required of infants to learn each pattern. The data can be explained by the ability of infants to detect identity relations—the repeating elements in the patterns—and their positions within the sequences: ABB contains a late repetition (i.e., the repeating elements occur late in the sequences), AAB contains an early repetition, and ABA contains a nonadjacent repetition. Our study provides evidence that these relations are not all learned under the conditions we provide, and clarify some of the possible reasons for the learning asymmetries we observed.

GENERAL METHODS

Participants

Eighty 8-month-olds and 80 11-month-olds made up the final sample. Twelve additional infants were observed but excluded from the analyses due to fussiness (three 8-month-olds, five 11-month-olds), sleepiness (one 8-month-old), or experimenter error (one 8-month-old, two 11-month-olds). Infants were recruited by letter and telephone from hospital records and commercially available lists of new parents, and from birth announcements in the local newspaper. All infants were full term and had no known developmental difficulties. Parents were provided with a small gift (a toy or baby t-shirt) for participation.

TABLE 1
Possible Rule Learning Comparisons and Outcomes of the Experiments

	Outcomes	
Condition	*8-Month-Olds*	*11-Month-Olds*
ABB vs. AAB (late vs. early repetition)	Fail	Succeed
ABB vs. ABA (late vs. nonadjacent repetition)	Succeed	Not tested
AAB vs. ABA (early vs. nonadjacent repetition)	Fail	Succeed
AAB vs. ABB (early vs. late repetition)	Not tested	Succeed
ABA vs. ABB (nonadjacent vs. late repetition)	Fail	Fail
ABA vs. AAB (nonadjacent vs. early repetition)	Not tested	Not tested

Apparatus and Stimuli

A Macintosh computer and 53-cm color monitor were used to generate the stimuli. An observer, blind to the stimulus on the screen at any given time, recorded looking times by pressing a key as the infant looked and releasing when the infant looked away. The computer presented stimuli, stored the observer's data, calculated the habituation criterion for each infant, and changed displays after the criterion had been met.

Stimuli consisted of 12 colored shapes (gray octagon, red square, green chevron, cyan diamond, blue bowtie, magenta four-pointed star, orange triangle, yellow circle, white five-pointed star, turquoise cross, pink clover, purple crescent) presented one at a time against a black background (see Figure 2). Each shape was shown for 1 sec in the center of the monitor and loomed from 4 to 24 cm in height (2.4°–14.6° visual angle). The shapes were organized into ABA, ABB, or AAB sequences, each followed by a 1-sec blank screen. Six unique shapes were presented during habituation (e.g., octagon–square–octagon, chevron–diamond–chevron, bowtie–star–bowtie) and six unique shapes were presented during test (e.g., triangle–circle–triangle, star–cross–star, clover–crescent–clover). In both habituation and test trials, triplet sequences were randomly ordered with the single constraint that no two sequences successively would be the same.

Procedure

Infants were tested individually and sat on a parent's lap 95 cm from the computer monitor. The parent was instructed not to interact with the infant. The infants were habituated to an ABA, ABB, or AAB sequence until habituation of looking occurred or 12 trials had elapsed. The habituation criterion was defined as a decline in looking times across a block of four trials adding up to less than 50% of looking times during the first four trials. The stream of stimuli was shown as long as the infant attended to the monitor. A trial ended when the infant looked away for 2 sec, or when total trial length reached 90 sec. If the infant looked back within 2 sec, the trial resumed at the place where it had stopped (i.e., the loom of the shape resumed). Between trials, a beeping target was presented to return the infant's attention to the screen. After habituation, infants viewed three test sequences alternating between familiar and novel (four test trials total), both instantiated in new looming shapes. Two test trials consisted of the three possible three-shape sequences that had a familiar pattern, and two test trials with these same three-shape sequences were arranged in a novel pattern. This ensured that any looking time difference observed would necessarily be related to the structure of the sequence, not low-level stimulus attributes such as color or contour. Ordering of test trials was counterbalanced across infants so that half the infants saw a familiar trial first and half the infants saw a novel trial first.

EXPERIMENT 1A

In the first experiment, 8- and 11-month-old infants were exposed to ABB sequences during a training period, followed by new sequences instantiating either an ABB or an AAB pattern (see Tables 1 and 2). Experiment 1, therefore, asked whether infants can discriminate a late repetition from an early repetition, a discrimination that can be accomplished by infants when these rules are instantiated in speech (Marcus et al., 2007; Marcus et al., 1999). Twenty 8-month-olds (11 girls, 9 boys, *M* age = 245.0 days, *SD* = 8.9) and 20 11-month-olds (11 girls, 9 boys, *M* age = 336.0 days, *SD* = 6.74) were included in the final sample.

Results and Discussion

Table 2 shows posthabituation looking times from Experiment 1A. (Preliminary analyses incorporating test trial order and sex revealed no effects involving these variables; therefore the principal analyses in all three experiments collapsed across order and sex.) A 2 (age: 8 vs. 11 months) × 2 (test sequence: novel vs. familiar) × 2 (test trial block) mixed analysis of variance (ANOVA) yielded a significant main effect of test trial block, $F(1, 38) = 5.90, p < .05$, partial $\eta^2 = .134$, resulting from an overall decline in looking times across trial blocks. There was also a significant interaction between age and test sequence, $F(1, 38) = 5.38, p < .05$, partial $\eta^2 = .124$. Post-hoc analyses (simple effects tests) on data from each age group revealed no reliable looking time differences for novel versus familiar sequences in the 8-month-olds, $F(1, 38) = .58$, *ns,* partial $\eta^2 = .015$. In contrast, 11-month-olds exhib-

TABLE 2
Data From Experiments 1 to 3

			Looking Times in Sec (SEM)			
			Novel		*Familiar*	
Experiment	*Age*	*Contrast*	*M*	*SD*	*M*	*SD*
1A	8 months	ABB vs. AAB	12.25	2.25	13.95	3.05
	11 months	ABB vs. AAB	15.65	1.95	12.09	1.80*
1B	8 months	ABB vs. ABA	16.78	2.38	8.70	1.06**
2A	8 months	AAB vs. ABA	9.75	1.29	9.04	1.07
	11 months	AAB vs. ABA	11.08	1.53	14.96	2.07*
2B	11 months	AAB vs. ABB	8.35	0.75	12.26	1.95*
3	8 months	ABA vs. ABB	17.43	3.37	18.07	4.75
	11 months	ABA vs. ABB	10.82	1.50	10.91	1.38

Note. The first pattern in each contrast refers to both the habituation sequence and the familiar test sequence; the second pattern refers to the novel test sequence.

*$p < .05$. **$p < .01$.

ited a reliable novelty preference, $F(1, 38) = 6.36, p < .05$ partial $\eta^2 = .143$. Novelty preferences, computed as the sum of looking times to the novel sequence divided by total looking times to both test sequences, were also compared to chance-level performance. Performance was not reliably different than chance for 8-month-olds, $t(19) = -.09$, *ns,* Cohen's $d = -.029$, but this difference was statistically significant for 11-month-olds, $t(19) = 2.72, p < .05$, Cohen's $d = .861$.

To examine the possibility that this outcome might be due to an inherent preference for AAB versus ABB sequences, a separate control group of 16 11-month-olds (5 girls, 11 boys, *M* age = 331.1 days, *SD* = 11.9) was shown the test sequences with no prior habituation experience. There was no reliable preference for either pattern, $t(15) = .64$, *ns,* Cohen's $d = -.220$. A between-groups *t* test comparing preference for AAB by 11-month-olds in the habituation and control groups was marginally significant, $t(34) = 1.83, p < .08$, Cohen's $d = .597$. We asked next if test sequence preferences might have resulted from differences in encoding of the sequences during the habituation phase of the experiment. One 8-month-old failed to habituate after 12 trials; six 11-month-olds failed to habituate. There were no reliable differences in test display preference between the 11-month-old habituators and the nonhabituators, $t(18) = 1.57$, *ns,* Cohen's $d = .761$. There were no significant differences in total habituation looking times between 8- and 11-month-olds, $t(31) = -1.72$, *ns,* Cohen's $d = -.597$ (8-month-olds' looking times during habituation: $M = 141.79$ sec, $SD = 75.14$; 11-month-olds' looking times: $M = 190.39$ sec, $SD = 87.21$).

In summary, after habituation to ABB, 11-month-old infants showed a novelty preference for AAB at test, but this effect was not observed in 8-month-olds, nor was there a spontaneous preference for AAB in a control group. These data suggest that 11-month-olds extracted the ABB pattern during habituation and discriminated it from AAB.

EXPERIMENT 1B

In the next experiment, we asked if 8-month-olds' failure to acquire the ABB rule, when placed against AAB at test, might stem from confusing a feature in common across both sequences: the repetition of elements. It is possible that the repetition was recognized in both ABB and AAB across specific stimulus elements, yet no discrimination between the rules due to a failure to notice that the repetition was late in ABB and early in AAB. Successful discrimination of ABB from AAB therefore requires that the infant detect the position of the repetition within the sequences. In Experiment 1B, we tested 8-month-olds' discrimination of ABB versus ABA, a contrast that can be made on the basis of the immediately adjacent repetition. Twenty infants (8 girls, 12 boys, *M* age = 247.4 days, *SD* = 6.5) made up the final sample.

Results and Discussion

A 2 (test sequence: novel vs. familiar) × 2 (test trial block) mixed ANOVA yielded a significant main effect of test sequence, $F(1, 19) = 15.40$, $p < .01$, partial $\eta^2 = .448$, due to a novelty preference for the ABA sequence, and no other reliable effects (see Table 1). The novelty preference was reliably different than chance, $t(19) = 4.45$, $p < .01$, Cohen's $d = .980$. To examine the possibility that this outcome might be due to an inherent preference for ABA versus ABB sequences, a separate control group of 16 8-month-olds (10 girls, 6 boys, *M* age = 224.4 days, *SD* = 17.1) was shown the test sequences with no prior habituation experience. There was no reliable preference for either grammar, $t(15) = .36$, *ns,* Cohen's $d = .123$. A between-groups *t* test comparing preference for ABA by 8-month-olds in the habituation and control groups was statistically significant, $t(34) = 2.19$, $p < .05$, Cohen's $d = .724$. Four infants failed to habituate; their novelty preferences were not reliably different relative to those of the habituators, $t(18) = .70$, *ns,* Cohen's $d = .488$. Habituation times for 8-month-olds in Experiment 1B (who learned ABB when contrasted with ABA at test) were not reliably different than those for 8-month-olds in Experiment 1A (who failed to learn ABB when contrasted with AAB), $t(33) = –1.52$, *ns,* Cohen's $d = –.506$ (Experiment 1B 8-month-olds' looking times: $M = 190.34$ sec, $SD = 112.78$; Experiment 1A looking times: $M = 141.79$ sec, $SD = 75.14$).

In contrast to Experiment 1A, in which we obtained no evidence for 8-month-olds' discrimination of ABB when placed against AAB at test, in Experiment 1B we found that ABB was learned during habituation when the task was to discriminate this sequence from ABA. The ABB rule might be easier to discriminate within an ABB–ABA contrast because infants detected the repetition during habituation, but were not required to detect its position (early or late) within the sequence.

EXPERIMENT 2A

The next experiment examined 8- and 11-month-old infants' acquisition of an AAB rule when placed against ABA. Recall from Experiment 1B that 8-month-olds who were habituated to ABB discriminated this pattern against ABA, presumably on the basis of the repetition learned during training. We reasoned that acquisition of a late repetition (ABB) might be facilitated by greater salience relative to an early repetition (AAB), due to recency effects, previously reported in experiments on adult and infant learning of sequential information (Conway & Christiansen, 2005; Endress, Scholl, & Mehler, 2005; Rose, Feldman, & Jankowski, 2001; Ross-Sheehy, Oakes, & Luck, 2003). Twenty 8-month-old infants (8 girls, 12 boys, *M* age = 237.6 days, *SD* = 9.6) and 20 11-month-olds (10 girls, 10 boys, *M* age = 335.2 days, *SD* = 8.76) were included in the final sample.

Results and Discussion

A 2 (age: 8 vs. 11 months) × 2 (test sequence: novel vs. familiar) × 2 (test trial block) mixed ANOVA yielded a significant interaction between age and test trial block, $F(1, 38) = 4.82$, $p < .05$, partial $\eta^2 = .113$, resulting from an overall decline in looking times across trial blocks for 8-month-olds; there was no decline for 11-month-olds. There was also a significant interaction between age and test sequence, $F(1, 38) = 4.34$, $p < .05$, partial $\eta^2 = .103$. Post-hoc analyses (simple effects tests) on each age group revealed no reliable looking time differences for novel versus familiar sequences in the 8-month-olds, $F(1, 38) = .21$, *ns,* partial $\eta^2 = .005$. In contrast, 11-month-olds exhibited a reliable familiarity preference, $F(1, 38) = 6.21$, $p < .05$, partial $\eta^2 = .140$. Test sequence preference was not reliably different than chance for 8-month-olds, $t(19) = .64$, *ns,* Cohen's $d = .200$. The familiarity preference was marginally significant for 11-month-olds when compared to chance, $t(19) = -1.90$, $p = .072$, Cohen's $d = -.601$. Three 8-month-olds failed to habituate; their novelty preferences were not reliably different relative to habituators, $t(18) = -.57$, *ns,* Cohen's $d = -.481$. Four 11-month-olds failed to habituate; their novelty preferences, too, were not reliably different relative to habituators, $t(18) = 1.09$, *ns,* Cohen's $d = .774$. There were no significant differences in total habituation looking times between 8- and 11-month-olds, $t(31) = .44$, *ns,* Cohen's $d = .155$ (8-month-olds' looking times during habituation: $M = 151.98$ sec, $SD = 69.26$; 11-month-olds' looking times: $M = 141.44$ sec, $SD = 66.72$).

In summary, 11-month-old infants provided evidence of learning AAB during habituation when tested with an AAB–ABA contrast, but there is no evidence that the 8-month-olds in this experiment learned AAB and discriminated it from ABA, unlike Experiment 1B, in which we obtained evidence for learning ABB when placed against ABA. Thus under these conditions rule learning appears to be vulnerable to a recency effect for younger infants. Eleven-month-olds detected the repetition even without the advantage conferred by recency of the repetition, although this detection led to a familiarity rather than a novelty preference during test.

EXPERIMENT 2B

Next, we asked if 11-month-olds would acquire AAB if placed within a contrast we reasoned might be more difficult: AAB–ABB. Success at this task requires detection of the repetition and discrimination of its position within the sequence (evidence for both of which was obtained in Experiment 1A); in addition, infants must learn the sequence without the advantage of the sequence-final position of the repetition during habituation. Twenty infants (9 girls, 11 boys, M age = 333.1 days, $SD = 8.9$) were included in the final sample.

Results and Discussion

A 2 (test sequence: novel vs. familiar) × 2 (test trial block) mixed ANOVA yielded a significant main effect of test sequence, $F(1, 19) = 4.78$, $p < .05$, partial $\eta^2 = .201$, due to a familiarity preference for the AAB sequence, and no other reliable effects (see Table 1). The familiarity preference was reliably different than chance, $t(19) = -2.22$, $p < .05$, Cohen's $d = -.712$. Two infants failed to habituate; their familiarity preferences were not reliably different relative to habituators, $t(18) = .70$, *ns,* Cohen's $d = .628$. Habituation times for 11-month-olds in Experiment 2B (who learned AAB when contrasted with ABB at test) were not reliably different relative to times for 11-month-olds in Experiment 2A (who learned AAB when contrasted with ABA), $t(32) = -.47$, *ns,* Cohen's $d = -.162$ (Experiment 2B looking times: $M = 153.13$ sec, $SD = 76.67$; Experiment 2a looking times: $M = 141.44$ sec, $SD = 66.72$).

In summary, 11-month-olds acquired AAB under conditions we reasoned were more stringent than those imposed by the contrast in Experiment 2A, that is, when the repetition was in the sequence-initial position. Discrimination of AAB from ABB again would appear to rely on sensitivity to the position of the repetition in both test patterns.

EXPERIMENT 3

In the final experiment, we asked whether infants would acquire an ABA rule when pitted against ABB at test. Recall from Experiment 1B that 8-month-olds provided evidence of discrimination of these two patterns when habituated to ABB. Twenty 8-month-old infants (8 girls, 12 boys, *M* age = 243.4 days, *SD* = 9.5) and 20 11-month-olds (12 girls, 8 boys, *M* age = 338.0, *SD* = 14.2) were included in the final sample.

Results and Discussion

A 2 (age: 8 vs. 11 months) × 2 (test sequence: novel vs. familiar) × 2 (test trial block) mixed ANOVA yielded a reliable main effect of test trial block, $F(1, 38) = 7.09$, $p < .05$, partial $\eta^2 = .157$, the result of an overall decline in looking times across trials, and no other reliable effects. There is no evidence from this analysis for either a novelty or a familiarity preference (see Table 1), a suggestion confirmed by *t* tests to compare test preferences to chance, *t*s < 1.5, *ns,* Cohen's *d*s < .48. Two 8-month-olds failed to habituate; their novelty preferences were not reliably different relative to habituators, $t(18) = -1.66$, *ns,* Cohen's $d = -1.30$. One 11-month-old failed to habituate. There were no significant differences in total habituation looking times between 8- and 11-month-olds, $t(35) = .22$, *ns,* Cohen's $d = .071$ (8-month-olds' looking times during habituation: $M = 150.27$ sec, $SD = 64.79$; 11-month-olds' looking times: $M = 144.52$ sec, $SD = 93.82$).

In summary, there is no evidence from Experiment 3 that infants at either age could learn the ABA sequence during habituation when tested with an ABA–ABB contrast. It may be, therefore, that a nonadjacent repetition rule is especially difficult to acquire under tested circumstances, a possibility consistent with earlier work documenting the difficulty of learning a nonadjacent dependency in linguistic sequences (e.g., Gómez, Bootzin, & Nadel, 2006).

GENERAL DISCUSSION

Our experiments present evidence concerning development of a fundamental cognitive capacity: the detection of abstract relations across sets of unfamiliar stimuli (in this case, a set of looming shapes) that share no surface features in common. Our focus was on the abstract relation of identity between two elements in a series of three-element sequences (ABB, AAB, and ABA), or a repetition, and on the position of the repetition in the strings. In ABB and AAB sequences, the identical elements were adjacent, instantiating late and early repetition, respectively; ABB and AAB were discriminable via the position of the repetition within the sequence. In ABA sequences, there was a nonadjacent repetition.

The results from the 11-month-olds we observed can be summarized as follows (see also Tables 1 and 2). Outcomes of ABB versus AAB and AAB versus ABB contrasts (Experiments 1A and 2B) tell us that they can encode and discriminate repetitions in both early and late positions. Results from the AAB versus ABA contrast (Experiment 2A) tell us they can encode an early repetition and discriminate it from a nonrepetition. We did not test an ABB versus ABA contrast, but presumably 11-month-olds would also be able to encode a late repetition and discriminate it from a nonrepetition, as 8-month-olds did (Experiment 1B). Results from the ABA versus ABB contrast (Experiment 3) suggest that they cannot encode a nonadjacent repetition, although we know they can detect both early and late repetitions during test as described previously. We do not know whether an early repetition during test (viz. ABA vs. AAB) would make this easier than the failure we observed in the ABA versus ABB contrast, although this seems unlikely. The pattern of novelty and familiarity preferences implies that learning ABB and discriminating it from AAB is relatively easy (a novelty preference) and that learning AAB and discriminating it from ABB and ABA is relatively difficult (a familiarity preference). Learning ABA appears to be harder still. It is possible that ABA as tested here fell between a novelty and a familiarity preference, implying an intermediate level of difficulty, but this would be inconsistent with the larger literature on learning nonadjacent relations (e.g., Gómez, 2002).

The results from the 8-month-olds provide evidence for a more limited capacity to learn and discriminate rule-bound visual sequences. The failure of 8-month-olds to learn ABB versus AAB (Experiment 1A) cannot stem from an inability to encode a late repetition, because they succeeded with ABB versus ABA (Experiment 1B). This failure, therefore, might be a "confusion" of the late repetition during encoding (ABB) with the early repetition during test (AAB), implying furthermore that the repetition was learned during habituation but its position was not encoded (and hence ABB and AAB were not discriminated). Alternatively, it might be that the 8-month-olds acquired the rule "identity anywhere" or "there is a repetition" and saw both ABB and AAB as both being instantiations of this rule (although extracting the rule was easier from the end of the string than from the beginning). The failure with AAB versus ABA (Experiment 2A) cannot be due to the inability to recognize a nonadjacent repetition during test (ABA) because they succeeded at ABB versus ABA (Experiment 1B). Failure at ABA versus ABB (Experiment 3) could be due to the inability to encode a nonadjacent repetition (like the 11-month-olds) or the inability to recognize a repetition during test. (We did not test ABA vs. AAB with either age group, reasoning that it would be even more difficult than ABA vs. ABB.) A final consideration is the possibility that the null result for the AAB versus ABB contrast fell between a novelty and a familiarity preference (see the preceding discussion of ABA learning by 11-month-olds), reflecting an intermediate level of difficulty.

Based on these results, it appears that one abstract relation that is acquired relatively early is that of repetition, and one that is acquired soon thereafter is that of position in sequence. Infants' failure (under tested circumstances) to discriminate ABA and ABB is consistent with prior work suggesting the difficulty for both infants (Gómez, 2002; Gómez & Maye, 2005), and adults (Newport & Aslin, 2004) to detect relations of nonadjacent dependency. Although in principle one might encode ABA as, say, a pair of difference relations, a more natural encoding might require the detection of nonadjacent repetition, evidently a cognitively demanding task. Infants may have perceived ABA sequences as little more than randomly ordered different elements; hence no specific relation was learned and transferred to the test stimuli. (When difference per se as an abstract relation may be acquired is unknown.)

Sensitivity to position information in visual event sequences is also available early in life, but evidence to date suggests that it might be delayed relative to repetition. Eight-month-old infants, for example, detected violations of the sequential order of three objects, introduced one at a time, after learning the sequence during habituation (Lewkowicz, 2004). The three objects were dropped into the scene and a unique sound was played as each hit the floor. Order violations were specified in test stimuli either by audio information (reordering of sounds, but not objects), by visual information (reordering of objects, but not sounds), or by both, and infants responded to all three. Four-month-old infants also detected sequence violations but only under more limited circumstances—when attention was directed toward global stimulus properties, accomplished by concealing a particularly salient local feature (the impact of objects against a surface), and when serial order was specified multimodally (i.e., visual and auditory cues jointly). There is evidence of sensitivity to serial order in causal sequences by 6-month-olds, who show recovery of interest when viewing a reversal of a previously habituated causal event (Leslie & Keeble, 1987), but little is known at present about how younger infants would respond to such events (Cohen & Amsel, 1998).

The ability to detect simple reordering of familiar objects would seem to be a requirement for sensitivity to positions of abstract relations, and the Lewkowicz (2004) study demonstrates that the foundations of this ability may become established by 8 months when tested with a visual preference method, and when orderings of objects and sounds learned during habituation are tested with identical stimuli. Yet in the experiments reported here, 8-month-olds did not respond to variations in position, implying that at this age, sensitivity to ordering of specific elements does not, on its own, suffice for recognizing the ordering of abstract elements. Eleven-month-olds did respond to position, discriminating ABB from AAB and vice versa, and we found an asymmetry in test display preferences depending on which of these two patterns was viewed during habituation. Infants habituated to ABB showed a novelty preference, but infants habituated to AAB showed a familiarity preference (control data revealed no inherent preference for either sequence). It seems likely that having a sequence-final repetition improved performance due to a recency effect, but it is unknown how 8-month-old infants would deal with an AAB versus ABB contrast with visual sequences; a positive result would cast doubt on this explanation. Discovering a repetition early in the sequence may be especially challenging, leading to a preference for familiarity rather than novelty at test in 11-month-olds; this explanation also accounts for the failure of younger infants to learn AAB. A familiarity preference might obtain when its match with a memory representation is not yet firmly in place, as would be the case when the representation is still being actively processed (Hunter & Ames, 1988; Roder, Bushnell, & Sasseville, 2000), implying an increased processing load imposed by an especially difficult abstract pattern.

Of course, many questions inevitably remain open. We have not, for example, tried to address the earliest age at which rules can be acquired, and establishing the lower bound for rule learning may require experimentation from multiple methods. It might be, for example, that performance can be facilitated with an operant paradigm, such as conjugate reinforcement, which has shown to be more sensitive than visual preference paradigms when testing sensitivity to correlated visual attributes (e.g., Bhatt & Rovee-Collier, 1994, vs. Younger & Cohen, 1983, 1986) and when testing serial order learning (e.g., Gulya, Rovee-Collier, Galluccio, & Wilk, 1998, vs. Lewkowicz, 2004). Other procedural differences across studies, such as rate of presentation and training method (fixed-trial familiarization vs. infant-controlled habituation) also merit further investigation.

Our goal, however, was not to discover the earliest possible evidence of rule learning, but rather to challenge the rule learning system, to better understand how it copes with arbitrary materials, and how it develops with age. The piecemeal learning of arbitrary rules that we observed contrasts with earlier work in two intriguing ways. First, statistical and associative learning are observable in very young infants. Kirkham et al. (2002), for example, reported that performance in 2-month-olds, the youngest infants tested, was as strong as that of 8-month-olds, the oldest tested, in a visual statistical learning task using stimulus elements similar to those in the experiments reported here. Similarly, even newborn infants have been shown to learn associations among stimulus features and retain them for short intervals (Slater, Quinn, Brown, & Hayes, 1999); by 3 months, memory for such associations can last considerably longer (Bhatt & Rovee-Collier, 1994). Second, the rulewise differences that we observed with arbitrary visual materials contrast with the uniformity of learning of different rules when infants are exposed to speech (Marcus et al., 1999); by 7 months infants are already able to recognize and generalize a broad range of rules including even the ABA versus ABB comparison that eluded the 11-month-olds we observed. This possibility is consistent with the observation that 7-month-olds are better able to acquire rules from speech than from sequences of musical tones, timbres, and natural animal sounds (Marcus et al., 2007), and can acquire rules in visual patterns that comprise familiar objects when they are presented simultaneously (Saffran et al., 2007; Tyrell et al., 1991; Tyrell et al., 1993). Results of the experiments reported here highlight the need to better understand other aspects of cognitive development in infancy, such as the role of attention and working memory, likely involved in identifying and discriminating sequential patterns, and perhaps responsible for apparent discrepancies across findings in the literature.

Finally, to the extent that our tasks require noticing a pattern and extending it to analogous cases, our results may also have implications for the development of analogy (cf. Gentner, Holyoak, & Kokinov, 2001; Goswami, 2001), suggesting that it too might develop incrementally, broadening as a child's capacity to perceive abstract relations expands.

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