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Authors

Schonberg, Christina
Marcus, Gary F
Johnson, Scott P

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The roles of item repetition and position in infants' abstract rule learning

Christina Schonberg[1], **Gary F. Marcus**[2], and **Scott P. Johnson**[1]

[1]UCLA

[2]NYU

Abstract

We asked whether 11- and 14- month-old infants' abstract rule learning, an early form of analogical reasoning, is susceptible to processing constraints imposed by limits in attention and memory for sequence position. We examined 11- and 14- month-old infants' learning and generalization of abstract repetition rules ("repetition anywhere," Experiment 1 or "medial repetition," Experiment 2) and ordering of specific items (edge positions, Experiment 3) in 4-item sequences. Infants were habituated to sequences containing repetition- and/or position-based structure and then tested with "familiar" vs. "novel" (random) sequences composed of new items. Eleven-month-olds (N = 40) failed to learn abstract repetition rules, but 14-month-olds (N = 40) learned rules under both conditions. In Experiment 3, 11-month-olds (N = 20) learned item edge positions in sequences identical to those in Experiment 2. We conclude that infant sequence learning is constrained by item position in similar ways as in adults.

Keywords

sequence learning; abstract rule learning; infant learning; analogical reasoning; perceptual primitives

In the present paper, we examine mechanisms underlying infants' ability to learn and generalize sequential patterns. Sequence learning is essential for processes ranging from the acquisition of language to everyday activities such as preparing for bed, learning to count, learning to read, and getting ready for school. Insights into development of sequence learning in infancy, therefore, are vital for theories of developmental and cognitive function across a variety of domains. Our particular focus in this paper is on "abstract rule" learning, a kind of pattern learning involving identification of simple reduplicative patterns and generalization of the pattern to new items (e.g., Gerken, 2006; Marcus, Vijayan, Bandi Rao, & Vishton, 1999). Abstract rule learning is a form of analogical reasoning, the ability to learn correspondences and relations between objects (Gentner, 1983). Analogical reasoning

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Corresponding author: Scott P. Johnson, Department of Psychology, UCLA, Los Angeles, CA 90095, USA, scott.johnson@ucla.edu.

is central to learning, thought, and language (Namy & Gentner, 2002; Holyoak & Thagard, 1995), and the development, scope, and limits of abstract rule learning have been investigated in infants and children due to their considerable theoretical importance for understanding cognitive development (Gómez & Gerken, 2000; Marcus, 2000; Whitaker, Vendetti, Wendelken, & Bunge, 2018).

Our understanding of infant cognitive development has seen significant progress since suggestions that the newborn’s sensory world was a “blooming, buzzing confusion” (James, 1890) and that infants lack the capacity for abstract thought (Piaget, 1954). In recent years, evidence has accumulated that infant cognition rests on a foundation of basic systems of attention, learning, and memory, working in tandem to represent and reason about speech, people, objects, and events (Bremner, Slater, & Johnson, 2015; Johnson & Hannon, 2015; Rakison & Lupyan, 2008; Smith & Gasser, 2005). A vital question concerns how these basic systems interact, with development, to yield the capacity for abstract thought. Language, for example, requires a system of abstract syntactic relations, allowing us to produce and interpret limitless combinations of spoken words (Marcus, 2000). Abstract combinatorial thought, however, consists in more than language, and it extends to items other than words. At issue in the present paper is how domain-general abstract thought is constrained by limits in attention, learning, and memory during infancy.

An important case study is the representation of simple abstract rules, such as “same” (e.g., AA) and “different” (e.g., AB). Such rules can be instantiated in any sensory domain—say, as a repeating stimulus—and in principle should be independent of presentation format: A visual pattern such as DUCK DUCK GOOSE, for instance, might be as readily learned as the auditory pattern *duck duck goose*. As we recount subsequently, however, this prediction does not have firm support and the conditions under which infant rule learning operates best remain poorly understood. Studies of abstract rule learning in infancy, therefore, can shed light on the origins of analogical reasoning by elucidating the mechanisms that support successful abstract pattern recognition. In the present paper, we test rule learning in infancy by varying pattern structure, with a goal of examining conditions under which abstract relations are discovered.

Infants’ learning and generalization of simple abstract rules in sequential patterns was first investigated by Marcus et al. (1999), who exposed 7-month-old infants to strings consisting of computer-generated speech. In their first experiment, strings followed either an “ABA” pattern (e.g., *gah tee gah*, *nee lah nee*) or an “ABB” pattern (e.g., *gah tee tee, nee lah lah*). A and B items were separated by 250 ms of silence, strings by 1 s of silence. The speech stream was accompanied by a flashing light, mounted centrally in the testing chamber. After 2 minutes of continuous repetitions of one of these two familiarization patterns, the infants received trials of the same (familiar) pattern instantiated by different phonemes (e.g., *woh fei woh*, *dee koh dee*), and the second (novel) pattern on alternating trial, from a speaker located either to the left or right of the infant. Each kind of test stimulus was also accompanied by a flashing light, located either left or right, and learning was operationalized in terms of differences in looking time toward the light when the word or part-word was heard. The infants exhibited a reliable preference for the novel pattern, a result that extended to a test of ABB vs. AAB. The balance of phonetic features across familiarization and test stimuli ruled out the possibility that performance was based on learning sequences of low-level cues (such as voiced vs. unvoiced consonants). Importantly, the positive outcome of the ABB/AAB comparison obviated an account based on learning a simple reduplication pattern (i.e., adjacent repetition) without respect to its place in sequence (i.e., initial/final position).

Studies of infant rule learning have produced mixed results with respect to the learnability of a simple abstract repetition rule, either adjacent, as in AAB or ABB, or nonadjacent, as in ABA (see Table 1). In experiments that examined auditory rule learning, for example, 7-month-olds familiarized with ABA sequences of syllables generalized to new ABA patterns when contrasted with ABB, and vice-versa; that is, infants who learned ABA appeared to recognize this pattern when it was instantiated in new items, and identified ABB as a novel pattern (Marcus et al., 1999; Marcus et al., 2007). These results replicated with tests of ABB vs. AAB, and AAB vs. ABB. Likewise, in studies examining visual rule learning with 3-item arrays, 7-month-olds who were habituated to ABA arrays of human faces, dogs, or cats generalized to new ABA patterns when contrasted with ABB, and vice-versa (Bulf, Brenna, Valenza, Johnson, & Turati, 2015; Saffran, Pollak, Seibel, & Shkolnik, 2007). Infants also learned AAB and ABB patterns when tested against each other (Saffran et al., 2007).

In contrast, experiments that examined visual rule learning with 3-item sequences of colored looming shapes, presented one at a time, revealed sharp limits in 8- and 11-month-old infants' ability to learn and generalize abstract repetition rules (Johnson et al., 2009). Eight-month-olds succeeded in learning ABB vs. ABA; that is, infants who were habituated to ABB patterns looked longer at ABA test sequences than ABB sequences when both were composed of new items, providing evidence of retention and generalization of the original pattern. In contrast, 8-month-olds failed to learn ABB vs. AAB, AAB vs. ABA, or ABA vs. ABB. Eleven-month-old infants, however, learned ABB vs. AAB, AAB vs. ABA, and AAB vs. ABB, yet, like the 8month-olds, failed to learn ABA vs. ABB. In other words, 8-month-olds succeeded in learning an abstract "late repetition" rule (repetition in the final position, ABB) when tested against a "nonadjacent repetition" rule (ABA), and failed to learn late vs. early repetition, early vs. nonadjacent repetition, and nonadjacent vs. late repetition. Eleven-month-olds learned all these abstract rules except nonadjacent vs. late repetition.

In the visual abstract rule learning tasks, therefore, learning and generalization of an abstract repetition rule was constrained by both its *kind* and its *position*: Nonadjacent repetitions (ABA) were not learned in visual sequences, and adjacent repetitions (i.e., the only rule learned by 8-month-olds; Johnson et al., 2009; cf. Thiessen, 2012, Exp. 3) were learned best when they occurred at the final position in sequence and when contrasted against ABA at test. (Similarly, Ferry et al., 2016 used functional near-infrared spectroscopy to examine neonates' ability to track syllable position, and found that changes in syllables at the edge of a sequence were detected better than internal items.) By 11 months, infants appeared to learn adjacent repetition rules regardless of initial or final placement, and regardless of the structure of the comparison test sequence.

Adults' acquisition of a repetition-based structure appears to be constrained by position as well (Endress, Scholl, & Mehler; 2005): Adults discriminated seven-syllable sequences from new items in sequence based on differences in *internal* vs. *edge* repetitions, differentiating, for example, sequence ABCDDEF (with an internal repetition—DD) vs. sequence ABCDEFF (with an edge repetition—FF). (The *edge* of a sequence is its beginning or end.) However, the repetition-based structure was only generalized when given edge repetitions. That is, adults could recognize sequences ABCDEFF and GHIJKLL as sharing the same abstract pattern (edge repetition), but could not recognize the abstract correspondence between ABCDDEF and GHIJJKL (internal repetition).

Thus one kind of abstract rule, adjacent repetition, appeared to be learned and generalized in 3-item sequences by infants at 8 months, but learning was constrained by edge position—the repetition was learned and generalized in final but not initial position (Johnson et al., 2009). In contrast, 11-month-olds' learning in 3-item sequences was not impaired by edge position constraints, raising the broader question of whether infants at this age can learn abstract repetition rules independent of position (cf. Ferry et al., 2016; Endress et al., 2005). Here, we address this question by testing 11-month-olds' ability to learn and generalize abstract rules in sequences that are a sufficient length (4 items) to disentangle repetition from sequence position. We also observed an older age group, 14-month-olds, given the possibility that they may be able to overcome position constraints to which 11-month-olds are susceptible. Even though 11month-olds appear to be abstract rule learners, we know from the other studies reviewed here that certain patterns and positions are salient to learners. It is possible, therefore, that 11-montholds' abstract rule learning is entirely constrained by position and abstract repetition patterns per se are not learned and generalized to new item sequences.

In Experiment 1, we asked whether 11- and 14-month-old infants can detect and generalize an abstract "repetition anywhere" rule (i.e., AABC, ABBC, ABCC). If repetition can be identified regardless of position, we would expect infants to generalize these sequences when instantiated in new items. However, it may be that consistent position information is a key part of infants' abstract rule learning (or that repetition is easiest to learn in final or initial position; Johnson et al., 2009). We addressed this question in Experiment 2 by testing whether 11- and 14month-olds can detect and generalize a "medial repetition" rule (i.e., internal position). We also completed Experiment 3, a control for the possibility that 11-month-olds are unable to learn any structures in 4-item sequences under tested circumstances.

We used a simple paradigm to establish learning and generalization of an abstract repetition rule. In Experiments 1 and 2, infants were habituated to 4-item sequences composed of 3 unique items, one of which repeated (see Figure 1). Following habituation, infants viewed 4item test sequences composed of all new items. One "familiar" test sequence instantiated the same abstract repetition rule as in habituation sequences, and in the other "novel" test sequence, items were ordered pseudorandomly (items were not allowed to repeat). (Both "familiar" and "novel" sequences were new, but were so termed because the same abstract rule governed both habituation and familiar test sequences.) We reasoned that infants would look longer at the novel sequence following habituation if they learned and generalized the abstract repetition rule, thus recognizing the correspondence across habituation and familiar test sequences. In Experiment 3, following evidence that 11-month-olds failed to learn and generalize abstract repetition rules independent from position (Experiment 1) or in the internal position (Experiment 2), we tested 11-month-olds' ability to learn non-abstract, "item-based" structure in 4-item sequences: specific items appearing consistently at initial and final edge positions (cf. Johnson et al., 2009).

The principal dependent measure of learning and generalization, therefore, was a difference in posthabituation looking at novel and familiar test sequences (Bornstein, 1985; Spelke, 1985). We report three complementary measures of performance: (a) mean *looking times* to familiar and novel test sequences, computed as the average score across three presentations of each sequence, (b) *novelty preferences*, computed as total looking to the novel test sequences divided by total looking to familiar and novel sequences combined, and (c) *recovery scores*, computed as looking time differences between the initial presentation of familiar and novel test sequences and the final presentation of the habituation sequence. Recovery of interest in both test displays might simply indicate responses to new items independent of the underlying pattern, but greater recovery toward the novel sequence would support the claims that (a) the abstract repetition rule itself was learned and generalized to new items in Experiments 1 and 2, and (b) that items at edge positions were learned and discriminated from sequences in which items appeared in other locations in Experiment 3. Note that this design helps to ensure that looking time preferences at test are not due to the specific items tested, but instead are due to sequence order (structured vs. random). We used standard parametric (analysis of variance and t-test) and nonparametric (sign test and Fisher's exact test) analyses for these measures.

In all experiments we employed an intermodal presentation method in which looming shapes were accompanied by spoken syllables (Frank, Slemmer, Marcus, & Johnson, 2009; Thiessen, 2012). Infants were first habituated to 4-item sequences (shapes + syllables) containing repetition- and/or position-based structure. They were then tested with 4-item sequences with familiar structure instantiated across new items or combinations of items vs. 4-item novel sequences composed of the same items but in pseudorandom order.

Experiment 1

Method

Participants.—Twenty 11-month-olds (M_{age} = 11.25 months; SD = .297; 8 girls) and 20 14-month-olds (M_{age} = 14.20 months; SD = .313; 9 girls) were recruited from a major metropolitan area to participate in this study. An additional three 11-month-olds were tested but excluded for fussiness (2) or preterm birth (1). An additional four 14-month-olds were tested but excluded for fussiness. Participants were recruited using lists provided by a third-party company based on their demographic characteristics and were compensated for travel expenses and given a small gift of appreciation (a t-shirt or toy for the infant).

Materials and Apparatus.—Visual stimuli were drawn from an inventory of 18 colored shapes: red square, cyan diamond, gray octagon, blue bow tie, green chevron, purple star, light blue cross, orange triangle, yellow circle, pink clover, indigo moon, lavender heart, light green sun, tan pinwheel, maroon ring, white star, violet parallelogram, and ruby X (see Figure 1). Auditory stimuli consisted of 18 spoken syllables: *bah, bei, boh, dee, doo, gei,* *gah, jai, jah, jee, koh, kei, poh, pai, too, tai, woh, and wai,* drawn from the pool of stimuli created originally for the Marcus et al. (1999) study.

Stimuli were presented using Macromedia Director on a Macintosh computer and were displayed on a 53 cm color screen. Each shape was presented on a black background, increasing in size from 4 cm to 24 cm high (2.4–14.6˚ visual angle) over a period of 667 ms, accompanied by a spoken syllable. In a separate room, the experimenter viewed the infant on a monitor and recorded looking times during the experiment; the experimenter was blind to what was being presented on the screen.

Procedure.—Infants were seated in a quiet, dark room on a caregiver’s lap approximately 95 cm from the screen. Infants were habituated to 4-item sequences of looming shapes, and each shape was accompanied by a unique syllable. Shape-syllable pairings were determined randomly; the same pairings were used for each infant (see Figure 1). Sequences were assembled from a randomly chosen set of nine (out of the total 18) shape-syllable combinations (hereafter called “items” for simplicity), such that three unique items (e.g., A, B, C) composed each 4-item sequence. One of the three items was randomly chosen to repeat, which yielded a repetition in the initial (e.g., AABC), medial (e.g., ABBC), or final (e.g., ABCC) position.

Before each habituation trial, a visual attention-getter appeared in the center of the screen to draw the infant’s attention; when the experimenter determined that the infant was looking at the screen, he or she pressed a button to begin the trial. Each shape loomed for 667 ms, and there was a 667 ms pause between each sequence. At the onset of each shape, an auditory syllable (268–489 ms) was also played; the pattern of syllables matched the pattern of shapes being displayed. For example, in an ABBC pattern, both the middle shape and syllable repeated. In each habituation trial, the 4-item sequences were randomly displayed one after another with no immediate repetition of any specific sequence. Each trial ended when the infant looked away for two consecutive s or when a maximum looking time of 90 s was reached. An infant-controlled habituation paradigm was used, such that the habituation criterion was defined as a 50% decline in mean looking time over four consecutive trials, compared to the mean looking time of the first four habituation trials.

At test, infants viewed familiar and novel 4-item sequences with items drawn from the remaining nine in the total inventory that were not shown during habituation. Familiar test sequences followed the same constraints as those described previously for the habituation sequences: Each sequence was composed of 3 unique items that always appeared in the same order within the sequence, one item repeated (producing an initial, medial, or final repetition), and sequence order was random with no immediate repeats. Novel test sequences were composed of the same nine items, presented in sequences of four items whose ordering was randomized with no constraints except no items repeated in any single sequence. Infants viewed six alternating familiar and novel trials (three each), and viewing order was counterbalanced such that half the infants viewed a familiar trial first and half the infants viewed a novel trial first. Preliminary analyses examining sex differences in performance (i.e., looking times toward familiar vs. novel test sequences) revealed no reliable effects in any of the experiments in this report, and so this variable was dropped from subsequent analyses.

Results and Discussion

In Experiment 1, we asked whether 11- and 14-month-olds could learn an abstract repetition rule anywhere in a 4-item sequence (i.e., AABC, ABBC, or ABCC) and could generalize the “repetition anywhere” rule to sequences of new items. If so, we expected infants to look longer on novel vs. familiar test trials (i.e., show a novelty preference), and recover interest more to the novel vs. the familiar test sequence, relative to the habituation stimulus.

Looking times.—A 2 (age group) x 2 (trial type – novel or familiar) x 2 (order – novel or familiar first) x 3 (test trial block) mixed ANOVA on posthabituation looking times with repeated measures on the second and fourth factors revealed a significant main effect of test trial block, $F(2, 36) = 4.79$, $p = .011$, $\eta 2_p = .12$, the result of a decline in looking across trials, and a significant age group x trial type interaction, $F(1, 36) = 8.03$, $p = .008$, $\eta 2_p = .182$. There were no other significant effects. To explore the age group x trial type interaction we computed follow-up t-tests on mean looking to novel vs. familiar test sequences. These analyses indicated that 11-month-olds did not look differently to the novel and familiar test stimuli, $t(19) = -.92$, $p = .371$, *ns*, whereas 14-month-olds looked reliably longer at novel vs. familiar test sequences, $t(19) = 3.06$, $p = .006$ (see Figure 2, top left and bottom left).

Novelty preferences.—The *M* novelty preference for 11-month-olds was .47 ($SD = .13$), which was not different than chance, $t(19) = -.76$, $p = .459$, *ns*. Nine of the 20 11-month-olds looked longer at the novel sequence, sign test $p = .83$. In contrast, the *M* novelty preference for 14-month-olds was .61 ($SD = .14$), which was greater than chance, $t(19) = 3.65$, $p = .002$. Seventeen of the 20 14-month-olds looked longer at the novel sequence, sign test $p = .003$. More of the 14-month-olds showed a novelty preference than the 11-month-olds, Fisher’s exact test $p = .019$, and the novelty preference for the older infants was greater than that of the younger infants, $t(38) = 3.13$, $p = .003$ (see Figure 2, top center and bottom center).

Recovery scores.—Eleven-month-olds recovered interest in both the novel and familiar sequences relative to the last habituation trial, $ts(19) = 3.15$ and 2.02, $ps = .005$ and .057, respectively ($M_{\text{novel}} = 18.45$ s, $SD = 15.83$, $M_{\text{familiar}} = 17.64$ s, $SD = 19.35$, $M_{\text{habituation}} = 8.90$ s, $SD = 7.18$). Recovery to the first novel vs. familiar test trial was not significantly different, $t(19) = .16$, $p = .875$, *ns*. Fourteen-month-olds also recovered interest in both the novel and familiar sequences, $ts(19) = 4.31$ and 3.16, $p < .001$ and $p = .005$, respectively ($M_{\text{novel}} = 21.60$ s, $SD = 15.67$, $M_{\text{familiar}} = 12.31$ s, $SD = 8.56$, $M_{\text{habituation}} = 5.75$ s, $SD = 3.41$). Unlike 11-month-olds, however, the older infants’ recovery scores to novel vs. familiar sequences were significantly higher, $t(19) = 3.26$, $p = .004$ (see Figure 2, top right and bottom right).

Taken together, results from looking times, novelty preferences, and recovery scores provide evidence that 14-month-olds, but not 11-month-olds, learned and generalized a “repetition anywhere” rule. Eleven-month-olds, however, did recover interest in the new items.

Experiment 2

In Experiment 1, 14-month-olds, but not 11-month-olds, appeared to learn and generalize an abstract repetition rule that was independent of its position in sequence. In Experiment 2, again testing 11- and 14-month-olds, we used sequences with a "medial repetition" rule to examine the possibility that consistency of the items' position in sequence would facilitate abstract repetition learning in 11-month-olds (see Figure 3). As in Experiment 1, we reasoned that rule learning would be reflected in longer looking during novel vs. familiar test trials.

Method

Participants.—Twenty 11-month-olds (M_{age} = 11.15 months, SD = .34; 14 girls) and 20 14-month-olds (M_{age} = 14.14 months, SD = .39; 9 girls) participated in Experiment 2. An additional six 11-month-olds were tested but excluded due to technical error (2) or fussiness (4), and an additional two 14-month-olds were tested but excluded for fussiness. Participants were recruited and compensated in the same manner as in Experiment 1.

Materials and Apparatus.—The item stimuli and presentation apparatus were the same as in Experiment 1.

Procedure.—The procedure was the same as in Experiment 1, with the exception of the structure of the habituation and familiar test sequences. Infants were habituated to sequences that contained a medial repetition as well as consistent items in the the first and fourth positions of each sequence (two different sets of items). Sequences were assembled from a randomly chosen set of ten from the inventory of 18. Again, three shapes composed each 4-item sequence, but the second item was always repeated, instantiating a medial repetition rule. Four items were selected (from the ten) for first and fourth positions in two unique sequences, and 3 items were selected for the medial positions in each sequence (e.g., ABBC, DEEF, AGGC, DHHF, etc.). The two types of medial repetition sequence were presented in alternation during habituation.

The familiar test sequences tested for generalization of the medial repetition rule without consistent shape/syllable items in the first and fourth positions. Familiar sequences were composed of items drawn from the entire inventory, with the constraints that the second item always repeated, and the first and fourth items in sequence could not be one of the four items that occupied those positions in the habituation sequences. The novel sequences followed the same constraints described in Experiment 1.

Results and Discussion

In Experiment 2, we asked if 11- and 14-month-olds could learn and generalize an abstract repetition rule appearing in medial position in a 4-item sequence (e.g., ABBC). If so, we again expected infants to look longer on novel vs. familiar test trials, and to recover interest more in novel vs. familiar sequences relative to habituation.

Looking times.—A 2 (age group) x 2 (trial type) x 2 (order) x 3 (test trial block) mixed ANOVA yielded a main effect of test trial block, $F(2, 35) = 12.68$, $p < .001$, $\eta^2_p = .42$, the result of a decline in looking across trials, a significant trial type x order interaction, $F(1, 36) = 9.86$, $p = .003$, $\eta^2_p = .22$, due to a tendency for infants in both order conditions to look longer at the trial type that was presented first, and a significant age group x trial type interaction, $F(1, 36) = 8.61$, $p = .006$, $\eta^2_p = .19$, due to differences in looking at novel and familiar test sequences between 11- and 14-month-olds. There were no other significant effects. Follow-up *t*-tests on *M* looking to novel vs. familiar test sequences indicated that 11-month-olds did not look differently to the novel and familiar test stimuli, $t(19) = -.60$, $p = .555$, *ns*, whereas 14-month-olds looked reliably longer at novel vs. familiar test sequences, $t(19) = 2.84$, $p = .011$ (see Figure 4, top left and bottom left).

Novelty preferences.—The *M* novelty preference for 11-month-olds was .50 ($SD = .12$), which was not different than chance, $t(19) = -.11$, $p = .913$, *ns*. Nine of the 20 11-month-olds looked longer at the novel sequence, sign test $p = .83$. In contrast, the *M* novelty preference for 14-month-olds was .59 ($SD = .14$), which was greater than chance, $t(19) = 2.70$, $p = .014$. Seventeen of the 20 14-month-olds looked longer at the novel sequence, sign test $p = .003$, and thus more of the 14-month-olds showed a novelty preference than the 11-month-olds, Fisher's exact test $p = .019$, and the novelty preference for the older infants was greater than that of the younger infants, $t(38) = 2.11$, $p = .041$ (see Figure 4, top center and bottom center).

Recovery scores.—Eleven-month-olds recovered interest in both the novel and familiar sequences, *t*s(19) = 2.22 and 2.77, *p*s = .039 and .012, respectively ($M_{\text{novel}} = 18.78$ s, $SD = 17.34$, $M_{\text{familiar}} = 24.10$ s, $SD = 18.28$, $M_{\text{habituation}} = 11.05$ s, $SD = 9.05$). Recovery to the first novel vs. familiar test trial was not significantly different, $t(19) = 1.08$, *ns*. Fourteen-month-olds recovered interest in the novel sequence, $t(19) = 3.47$, $p = .003$, but not the familiar sequence, $t(19) = 1.73$, $p = .10$ ($M_{\text{novel}} = 36.05$ s, $SD = 25.36$, $M_{\text{familiar}} = 22.23$ s, $SD = 14.74$, $M_{\text{habituation}} = 17.21$ s, $SD = 12.68$). Recovery scores were significantly higher to novel vs. familiar sequences, $t(19) = 2.77$, $p = .012$ (see Figure 4, top right and bottom right).

Taken together, looking times, novelty preferences, and recovery scores provide evidence that 14-month-olds, but not 11-month-olds, learned and generalized a "medial repetition" rule. As in Experiment 1, however, 11-month-olds did recover interest in the new items.

Experiment 3

Experiment 3 was designed to control the possibility that sequences used in Experiments 1 and 2 were too complex or lengthy for 11-month-olds to detect patterns or structure, perhaps due to limits in working memory for items (Feigenson, Carey, & Hauser, 2002; Moher, Tuerk, & Feigenson, 2012) or sequences (Ross-Sheehy, Oakes, & Luck, 2003). Habituation sequences in Experiment 3 were identical to those used in Experiment 2 (see Figure 3), and we tested for learning the consistent positions of the first and last items in sequence; that is, the edge positions of items A and C, and D and F, in ABBC and DEEF patterns, respectively. As in Experiments 1 and 2, we reasoned that edge position learning would be reflected in longer looking during novel vs. familiar test trials, and greater recovery to novel sequences after habituation.

Method

Participants.—Twenty 11-month-olds (M_{age} = 11.16 months, SD = .32; 6 girls) participated in Experiment 3. One additional infant was tested but excluded due to fussiness. Participants were recruited and compensated as in Experiments 1 and 2.

Materials and Apparatus.—The item stimuli and presentation apparatus were the same as in Experiments 1 and 2.

Procedure.—The procedure was the same as in Experiment 2, with the exception of the structure of the test sequences. Here, familiar test trials maintained the first and fourth items across two sequences but had no repetitions (i.e., each familiar sequence was composed of four unique items; see Figure 3). Novel test trials followed the same constraints described previously.

Results and Discussion

Looking times.—A 2 (trial type) x 2 (order) x 3 (test trial block) mixed ANOVA yielded a reliable main effect of trial type, $F(1, 18) = 7.86$, $p = .012$, $\eta^2_{\text{p}} = .30$, due to longer looking overall at novel vs. familiar test sequences (see Figure 5, left). There was also a main effect of trial block, $F(2, 17) = 3.87$, $p = .041$, $\eta^2_{\text{p}} = .31$, due to a decline in looking across trials, and a significant interaction between trial block and trial type, $F(2, 17) = 5.86$, $p = .012$, $\eta^2_{\text{p}} = .41$. Follow-up t-tests revealed that infants looked more toward the novel sequence than the familiar in the first block, $t(19) = 2.75$, $p = .013$, and in the second block, $t(19) = 2.80$, $p = .011$, but not in the third block, $t(19) = .22$, ns. The novelty preference suggests that infants learned edge positions of the first item in sequence, the last item, or both, from the habituation phase.

Novelty preferences.—The M novelty preference was .63 (SD = .11), which was different than chance, $t(19) = 5.24$, $p < .001$. Seventeen of the 20 infants looked longer at the novel sequence, sign test $p = .003$ (see Figure 5, center).

Recovery scores.—Infants recovered interest in the novel pattern, $t(19) = 2.70$, $p = .014$, but not the familiar, $t(19) = -.62$, $p = .540$, ns (M_{novel} = 19.10 s, SD = 19.18, M_{familiar} = 8.72 s, SD = 5.80, $M_{\text{habituation}}$ = 9.48 s, SD = 7.01), and recovery was greater to the novel, $t(19) = 2.75$, $p = .013$ (see Figure 5, right).

Recovery scores.—Infants recovered interest in the novel pattern, $t(19) = 2.70$, $p = .014$, but not the familiar, $t(19) = -.62$, $p = .540$, ns (M_{novel} = 19.10 s, SD = 19.18, M_{familiar} = 8.72 s, SD = 5.80, $M_{\text{habituation}}$ = 9.48 s, SD = 7.01), and recovery was greater to the novel, $t(19) = 2.75$, $p = .013$ (see Figure 5, right).

Finally, we compared performance of 11-month-olds in Experiments 2 and 3 with a 2 (experiment) x 2 (trial type) x 3 (test trial block) mixed ANOVA. This analysis revealed a significant main effect of test trial block, $F(2, 76) = 11.44$, $p < .001$, $\eta^2_{\text{p}} = .23$, due to a decline in looking times across trials, and an experiment x trial type interaction, $F(1, 38) = 6.83$, $p = .013$, $\eta^2_{\text{p}} = .15$, due to differences in looking at novel and familiar test sequences, as noted earlier. Significantly more infants showed a novelty preference in Experiment 3 than in Experiment 2 (17 vs. 9), Fisher's exact test $p = .019$, and the novelty preference was significantly stronger in Experiment 3 than in Experiment 2, $t(38) = 3.55$, $p = .001$.

Taken together, therefore, the results of Experiments 2 and 3 suggest that when both an abstract repetition rule *and* item-specific, edge position information were available in habituation sequences, 11-month-olds learned item-specific information—violations of ordinal positions of one or both edge items—across habituation and test, but not an abstract repetition rule.

General Discussion

Cognitive operations have been characterized in terms of general-purpose statistical learning mechanisms to acquire probabilistic associations among features and items (e.g., Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996; McClelland & Rumelhart, 1986; Seidenberg, 1997) and rule learning mechanisms to identify similarity and correspondence of inputs that do not share specific features or items (e.g., Gobet et al., 2001; Marcus, 2001; Marcus et al., 1999). This question is particularly important for understanding cognitive development, because it constrains the forms that theories of infant learning can take.

We tested for infants' learning and generalization of an abstract repetition rule in 4-item sequences of shape-syllable stimuli. In a departure from past studies showing that 11-month-olds learn an abstract repetition rule when the repetition appears in the initial or final positions in sequence (Johnson et al., 2009), we found that 11-month-olds failed to learn this rule when the repetition appeared in variable positions (initial, medial, or final, Experiment 1), or in an internal position (Experiment 2). Fourteen-month-olds, however, appeared to learn repetition rules under both conditions, and 11-month-olds in Experiment 3 succeeded in learning edge positions of items in sequences identical to those used to test repetition learning in Experiment 2. We conclude that infants' abstract repetition rule learning and generalization are mediated in part by the positions in sequence in which regularities appear. That is, mechanisms for identifying simple abstract repetition rules, perhaps an early form of analogical reasoning (Gentner & Markman, 1997) are susceptible to processing constraints imposed by limits in attention and memory for sequence position. Items at edge positions in sequence appear to be distinctly salient. (Similar findings for adults were reported by Endress et al., 2005, 2010.)

Objections to this interpretation may be raised. For example, it may be that infants preferred novel to familiar sequences due to a spontaneous propensity to prefer random over structured sequences (Addyman & Mareschal, 2013), or that infants preferred novel sequences because they comprised 4 unique items vs. 3 in familiar sequences. Such explanations, however, would have to account for the age differences in performance we observed, in particular why 11month-olds in Experiments 1 and 2 did not exhibit the same preferences as 14-month-olds. A second objection could be brought against our design, which did not test for infants' discrimination of distinct abstract rules (e.g., AABC vs. ABCC, or AABC vs. ABCA) in like fashion to previous abstract rule learning studies using 3-item sequences (see Table 1). Yet our questions did not require such a design. A more complex design testing for generalization of an abstract rule from habituation to test *and* discrimination of the learned rule from another at test might reveal limits in 14-month-olds' learning, but this remains an open question. A third objection could be levied against our use of looming shapes as stimuli, as opposed, for example, to human faces or other more familiar stimuli, which may facilitate infants' abstract rule learning (Saffran et al., 2007; Bulf et al., 2015). The goal of the current investigation, however, was not to facilitate abstract rule learning, but rather to examine its limits and development, which can shed light on abstract rule learning mechanisms (cf. Johnson et al., 2009), as we elaborate below.

Repetition and Position as Perceptual Primitives

Previous studies of statistical and rule learning in infancy have obtained evidence for sensitivity to item repetition and item position in infants as young as newborns. Studies using functional neuroimaging, for example, revealed differences in newborns' cortical activity to ABB vs. ABC patterns instantiated in computer-synthesized speech (Gervain, Macagno, Cogoi, Peña, & Mehler, 2008), as well as AAB vs. ABC patterns (Gervain, Berent, & Werker, 2012), implying that infants can distinguish between distinct rule-governed patterns at birth. These findings are consistent with the possibility of an innate perceptual "repetition detector" capable of discriminating patterns with repetition from those without repetition. It seems plausible that a repetition detector is functional earlier in development than other, more broad mechanisms for abstract rule learning, but this question remains open.

Gervain and colleagues also reported that newborns discriminated AAB vs. ABB, implying sensitivity to position as well as repetition, but failed to discriminate ABA vs. ABC, perhaps from difficulties in identifying nonadjacent repetition. Additional evidence for sensitivity to item position at birth comes from a study on visual statistical learning in neonates (Bulf et al., 2011): Infants were habituated to sequences of 4 looming shapes organized into 3 pairs, and at test looked longer at random sequences vs. the same structured sequences seen during habituation (cf. Kirkham et al., 2002).

These studies tested for infants' detection of repetition and position by contrasting structured vs. random test sequences (with the exception of the AAB vs. ABB comparison reported by Gervain et al., 2012), thus demonstrating discrimination of different rule-bound patterns. None of these studies tested for *learning*, however, and none tested for *generalization* of learned structures to new contexts (see Table 1). The possibility of learning and generalization of abstract rules in neonates remains unknown; to our knowledge there has never been a proper test.

Studies that have tested for rule learning and generalization in postnatal infants have revealed that these processes can be observed as early as 3 months (Anderson et al., 2018): Infants who were initially familiarized with single objects, and subsequently habituated to pairs of objects (either the same, AA, or different, AB), looked longer at test at object pairs with the opposite pattern (AB and AA, respectively), providing evidence for generalization of learned abstract structure from familiarization to test. Moreover, 4-month-old infants who were familiarized with AAB or ABA patterns instantiated in musical chords or tones subsequently showed increased interest toward the novel pattern in new items (Dawson &

Gerken, 2009). Rule learning and generalization in 5-month-olds from 3-item shape-syllable sequences has also been reported (Frank et al., 2009). To our knowledge, there are no published reports demonstrating rule learning and generalization under any conditions in infants younger than 3 months.

Likewise, studies of item-based sequence learning, requiring no generalization, have reported early sensitivity to item orders in sequence. For example, newborns' cortical responses (measured with fNIRS) to 6-syllable sequences revealed sensitivity to order violations at edge positions (but not internal positions; Ferry et al., 2016), and 3-month-olds appeared to recognize violations of serial order in 3-item shape-sound sequences, relative to habituation sequences (Lewkowicz, 2008). Furthermore, there is evidence that 5-month-olds (but not younger infants) can use differences in transitional probability to segment shape sequences, recognizing frequent vs. infrequent shape pairings relative to habituation sequences (Marcovitch & Lewkowicz, 2009; Slone & Johnson, 2015). By 8 months, infants seem to use a "chunking" mechanism, as well as transitional probabilities, to segment shape sequences when tested for learning of "illusory" sequences or "embedded" units in streams of looming shapes (Slone & Johnson, 2018; cf. Endress & Mehler, 2009; Giroux & Rey, 2009). To our knowledge, however, there are no published reports of transitional probability sensitivity in infants younger than 5 months.

Taken together, then, extant literature and the current experiments provide little support for infant learning of abstract rules or transitional probabilities among items until the first several months after birth, and furthermore imply that what we might consider "perceptual primitives" such as repetition (Endress et al., 2009; cf. Mandler, 1988, 1992) are detected and learned most effectively only in context. The context, which we consider next, includes the perceptual and cognitive capacities of infants, which change with development, and task conditions.

Infant Sequence Learning in Context

Results of our experiments can be interpreted in light of recent theories proposing that statistical and rule learning are both constrained by saliency and consistency of information (and as such might not represent distinct learning mechanisms) as well as general limits in attention and memory (Aslin & Newport, 2012, 2014). Some of these constraints are specific to modality (e.g., prosodic groupings and other speech cues; Johnson & Jusczyk, 2001; Thiessen & Saffran, 2003) or the experimental setting (e.g., gaze or action cues that direct attention to particular items or relations; Baldwin, Andersson, Saffran, & Meyer, 2008; Yu, Ballard, & Aslin, 2005), but others, such as identification and learning of repetition and position, are domain-general and may operate similarly across many contexts.

For example, the differences in performance we observed in the 11-month-olds in Experiments 2 and 3 of the present study are consistent with findings from younger infants (7month-olds), who were able to learn differences in 5-item sequences from switched initial and final items, but not internal items (Benavides-Varela & Mehler, 2015; cf. Marchetto & Bonatti, 2015), and from adults, who generalized a repetition to new items when it appeared in final position, but not a medial position, in 7-item syllable sequences (Endress et al., 2005). More broadly, the results are consistent with the serial position curve (Ebbinghaus,

1885) and the recency effect (Baddeley & Hitch, 1974). These studies suggest that item position, most notably final position, is more salient than item repetition, relatively speaking. Thus in spoken language, repetition (heard anywhere in an utterance) may be surprising and therefore “deserving of an explanation” (Gerken, Dawson, Chatila, & Tenenbaum, 2015, p. 82), but in visual (or intermodal) sequences it may not necessarily recruit attention to the same degree.

Because any particular set of items in a group potentially supports an infinite number of possible structures and generalizations thereof, a learner must determine the most likely pattern given a limited amount of experience with it. One way in which this problem may be constrained is by a “gradient of generalization” in both statistical and rule learning. If multiple patterns are possible across a set of inputs yet vary in their consistency, the most consistent information over the distribution should produce the best learning (Aslin & Newport, 2014). Evidence compatible with this notion comes from a study with 9-month-old infants; stimuli were designed such that multiple patterns were present in a single 3-syllable sequence, and the consistency of each pattern—based on either a rule or position (AAB vs. ABA or variability of the final item in position, respectively)—determined which was learned (Gerken, 2006; see Table 1).

Yet information must be detected to be learned (cf. Endress et al., 2005). In Experiments 2 and 3 of the current paper, information for both medial repetition and edge position was equally consistent across habituation exemplars, yet 11-month-olds learned only about specific items in edge positions. Notably, 14-month-olds appeared to learn a repetition rule both when it was restricted to the medial position (Experiment 2) and when it was free to appear in initial, medial, or final position (Experiment 1). These results imply that important developments in rule learning consist of the “separation” of perceptual primitives such that they become less interdependent and perhaps more salient on their own.

Does this interpretation turn on the details of our paradigm? Different choices in stimulus parameters, exposure time, test comparisons, and so forth may yield different outcomes, and inspection of Table 1 reveals appreciable variability in approaches to questions of infants’ abstract rule learning. There is much to be gained from additional studies of the conditions that support learning, given that we lack important baselines of performance.

Finally, consider the findings (from Experiments 2 and 3) that 11-month-olds extracted position-based but not rule-based structures from identical sequences. In a previous test of multiple pattern learning from a single set of input, adults listened to speech streams that could be interpreted in terms of rules or statistical relations (Endress & Bonatti, 2007). With briefer listening times, participants learned the rule-bound structure, but did not identify the statistical structure without substantially longer exposure durations. This result led to the claim that there is a fast-working mechanism for extracting rule-governed patterns, and a second slower mechanism that requires additional time to learn associations among items; this second mechanism then may join or take over the representations contributed by the first. Unlike the adults in the Endress and Bonatti study, the 11-month-old infants we observed appeared to learn about items, but not rules, during a relatively brief period of habituation. The reasons for this effect are unclear, but they are not likely to stem from differences in consistency, as noted previously. Recently, 8-month-old infants were found to learn different statistical structures (transitional probabilities and “chunks” of items) as a function of exposure time (Slone & Johnson, 2018), and it may be that 11-montholds would learn rule structure in the current stimulus set if they accumulated more looking times than allowed for by the infant-controlled habituation method. Additionally, neither the current studies nor the larger literature can speak to whether, in general, the abstract rule learning system might come “on line” earlier during development than the item-specific learning system (e.g., ordinal position, transitional probabilities) or vice-versa. These questions await future study.

Conclusions

Infants’ identification of an abstract rule in sequential input appears to be constrained by non-abstract information such as sequence length, consistency, and position. Learning about specific items as well as abstract relations among items is facilitated when materials to be learned occur at edge positions (perhaps increasing saliency), a finding which is consistent with well-known limits on adults’ memory such as the serial position effect. Although infants at birth can discriminate certain rule-governed when compared to unstructured input (Table 1), the extant literature and current studies provide evidence that learning and generalization of abstract rules develop across the first year after birth and beyond. On this account, perceptual primitives such as repetition and position may serve as initial building blocks, and development of abstract rule learning, and perhaps analogical reasoning more broadly, resides in the ability to discover and remember abstract structure across increasingly complex inputs.

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Highlights

- We examined how limits in attention and memory constrain infants' learning of abstract rules, an early form of analogical reasoning.
- Fourteen-month-olds were able to learn an abstract repetition rule regardless of position in sequence, but 11-month-olds failed to learn abstract repetition rules, in 4-item sequences.
- Infant sequence learning may be constrained by item position in similar ways as in adults.
- Results help clarify infants' abilities to discover, learn, and generalize abstract patterns, and how these abilities develop.

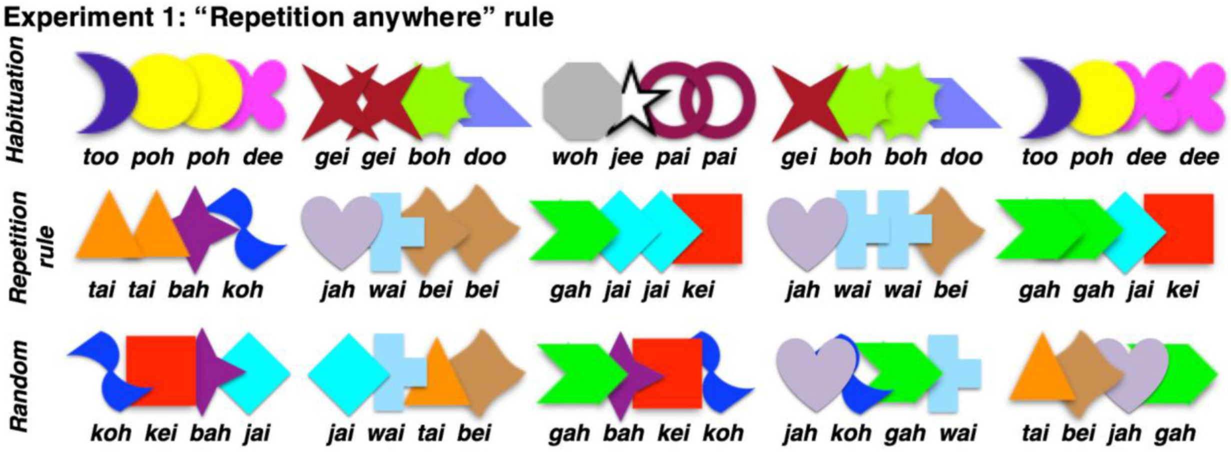

Figure 1:

Schematic depiction of habituation and test sequences for Experiment 1. The top row represents the habituation sequence, the middle row represents the familiar test sequence, and the bottom row represents the novel (random) test sequence. See text for details.

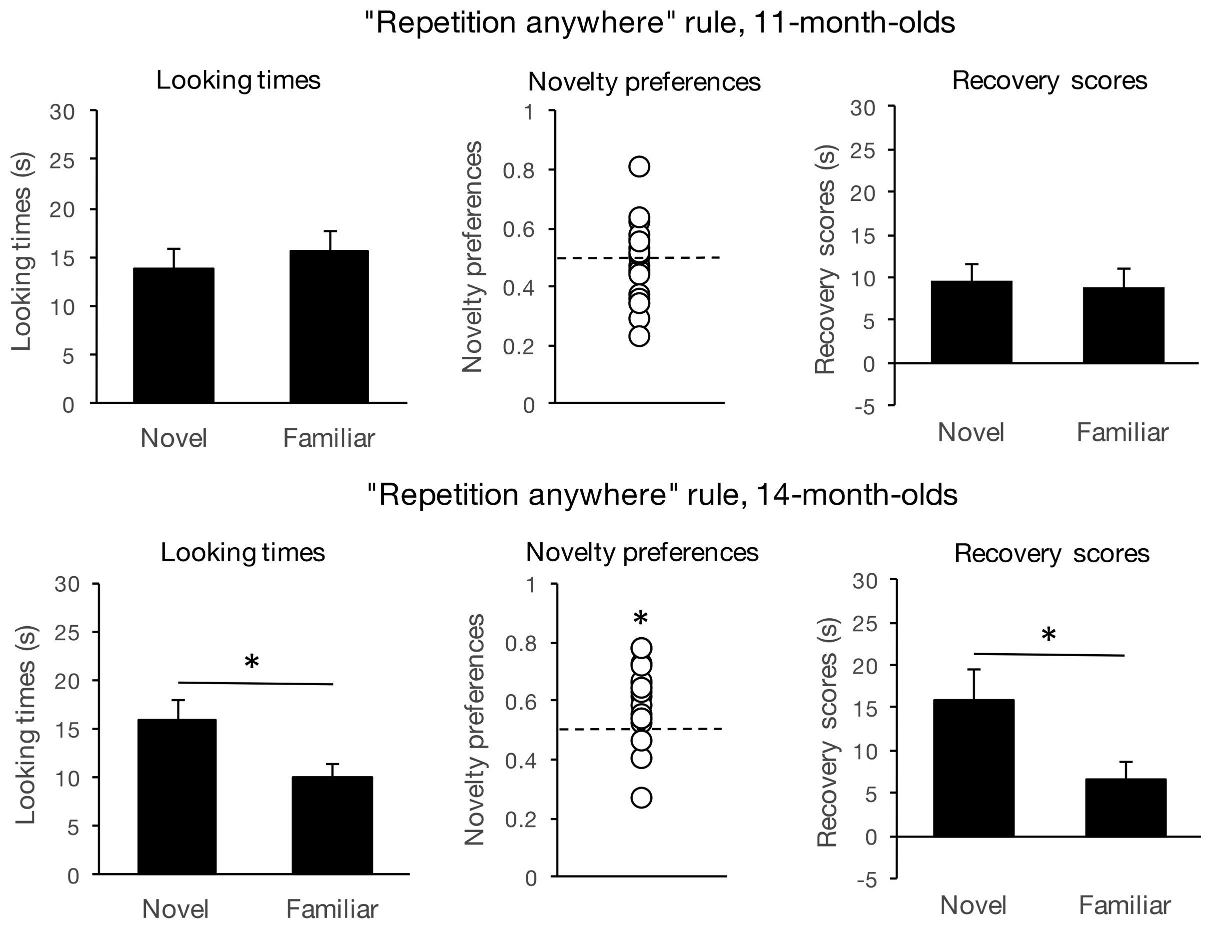

Figure 2:

Looking times, novelty preferences, and recovery scores for Experiment 1 to test for a “repetition anywhere” rule. Top: 11-month-olds. Bottom: 14-month-olds. * $p < .05$. Error bars = *SEM.*

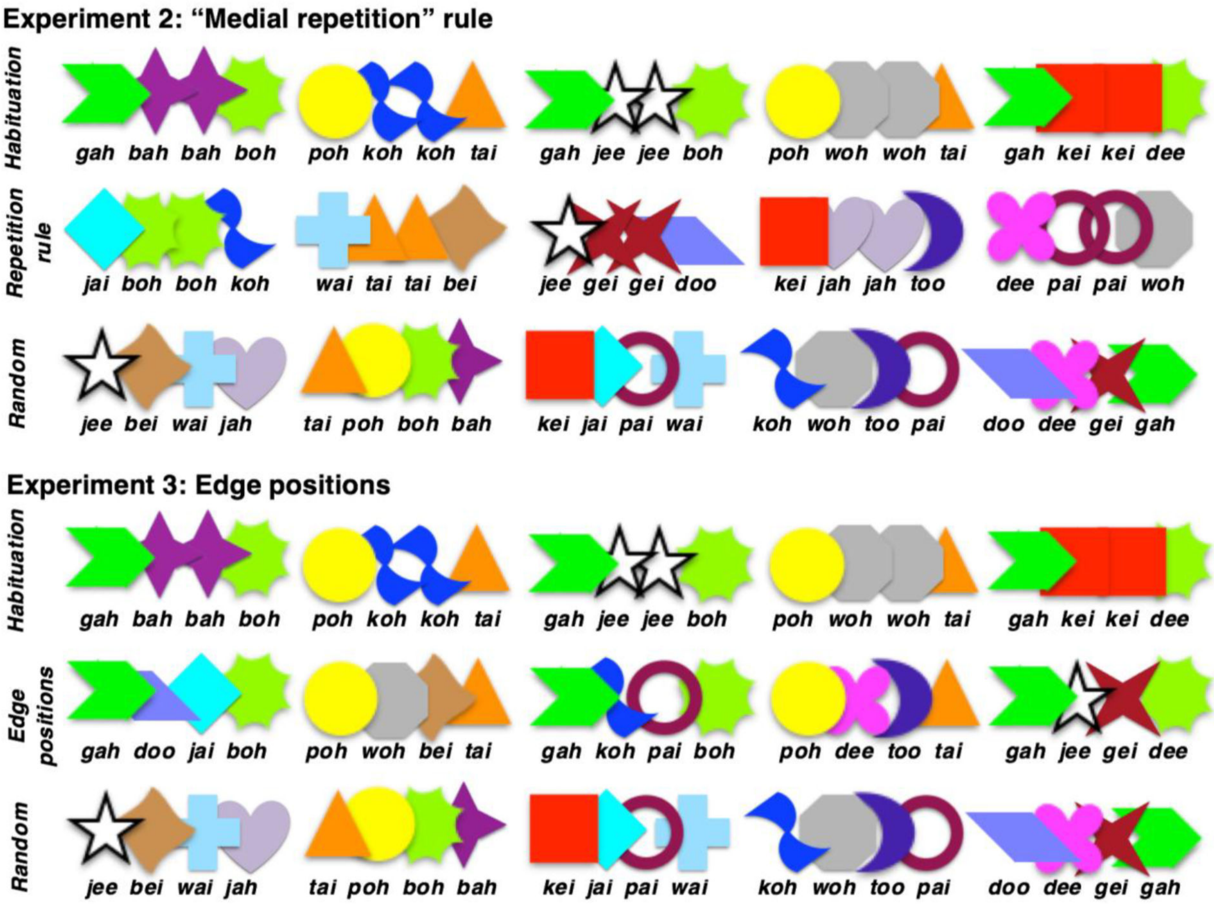

Figure 3:

Schematic depiction of habituation and test sequences for Experiments 2 (top section) and 3 (bottom section). Within each section, the top row represents the habituation sequence, the middle row represents the familiar test sequence, and the bottom row represents the novel (random) test sequence. See text for details.

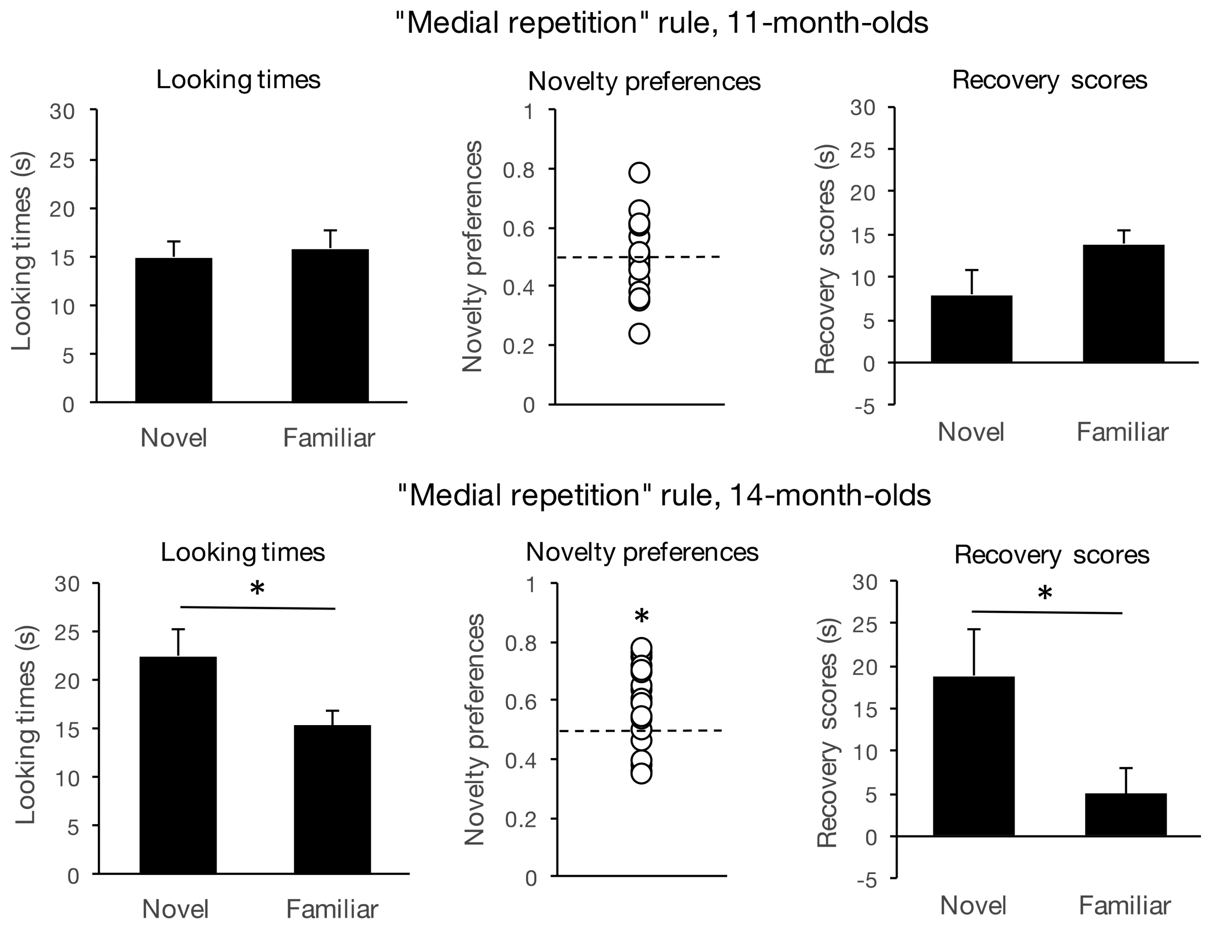

Figure 4:

Looking times, novelty preferences, and recovery scores for Experiment 2 to test for a “medial repetition” rule. Top: 11-month-olds. Bottom: 14-month-olds. * $p < .05$. Error bars = *SEM*.

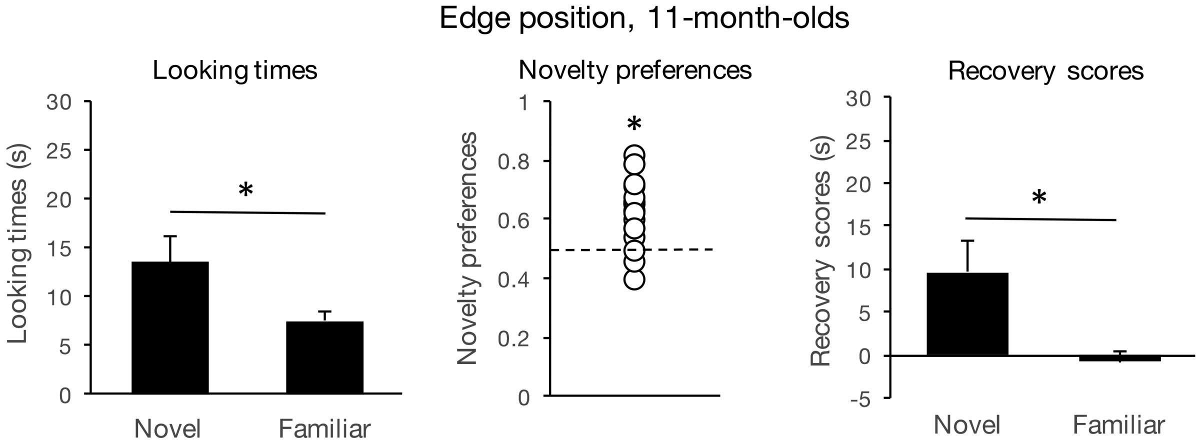

Figure 5:

Looking times, novelty preferences, and recovery scores for Experiment 3 to test for 11-montholds' sensitivity to items at edge positions in sequence. * *p* < .05. Error bars = *SEM.*

Table 1

Summary of extant literature on infant abstract rule discrimination, learning, and generalization

Authors	**Ns, ages**	**Stimuli**	**Exposure/test**	***Tested for….**	****Tokens/types**	*****Results**
Addyman & Mareschal, 2010, Exp. 1	15 4-mo 15 8-mo	Arrays of objects	• Infantcontrolled habituation • 4 test trials	AA vs. AB AB vs. AA	Learning: 19/19 Test: 6/6	AA vs. AB 4-mo R̂ AB vs. AA 4-mo + AA vs. AB 8-mo + AB vs. AA 8-mo
Exp. 2	9 4-mo 10 8-mo	Arrays of geometric shapes	• 48 training trials, AA & AB predict an event in one of two locations • 12 test trials	Correct anticipatory eye movements to AA or AB location during test trials	Learning: 2/2 Test: 4/4	+ AB 4-mo AA 4-mo + AB 8-mo AA 8-mo
Anderson et al., 2018, Exp. 1	31 3-mo	3D arrays of toys	• Infantcontrolled habituation • 8 test trials	AA vs. AB AB vs. AA	Pretraining with individual objects Learning: 6/6 Test: 12/8	R̂ AA vs. AB R̂ AB vs. AA
Exp. 2	32 3-mo	3D arrays of toys	• Infantcontrolled habituation • 6 test trials	AA vs. AB AB vs. AA	Pretraining with individual objects Learning: 4/4 Test: 9/6	+ AA vs. AB + AB vs. AA
Bulf et al., 2015	71 7-mo	Arrays of upright or inverted faces	• Infantcontrolled habituation • 6 test trials	ABB vs. ABA ABA vs. ABB	Learning: 8/8 Test: 4/4	+ ABB vs. ABA upright + ABA vs. ABB upright ABB vs. ABA inverted ABA vs. ABB inverted
Dawson & Gerken, 2009	36 4-mo 36 7-mo	Musical tones or chords	• 2 min familiarization • Head turn • 2 test trials	AAB vs. ABA ABA vs. AAB	Learning: 8/16 Test: 4/4	+ AAB vs. ABA 4-mo + ABA vs. AAB 4-mo − AAB vs. ABA 7-mo −ABA vs. AAB 7-mo
Ferguson & Lew-Williams, 2016	64 7-mo	Musical tones; syllables at test in two conditions	• 2.5 min familiarization • Head turn • 12 test trials	(Not described)	Learning: 4/16 Test: 4/4	+ pre-exposure (to tones as communicative signals) − no exposure − no exposure, tones to speech + pre-exposure, tones to speech
Ferry et al., 2015, Exp. 1	10 7-mo 16 9-mo	3D arrays of toys	• 40 sfamiliarization • 2 test trials	AA vs. AB AB vs. AA	Learning: 1/1 (AA), 2/1 (AB) Test: 6/4	− AA vs. AB 7-mo − AB vs. AA 7-mo − AA vs. AB 9-mo −AB vs. AA 9-mo
Exp. 2	32 7-mo 32 9-mo	3D arrays of toys	• Pre-exposure to a subset of 7 toys • Infantcontrolled habituation • 3 test trials	AA vs. AB AB vs. AA	Learning: 4/4 Test: 9/3	+ AA vs. AB 7-mo + AB vs. AA 7-mo + AA vs. AB 9-mo + AB vs. AA 9-mo
Frank et al., 2009	96 5-mo	Multimodal geometric shape/ syllable sequences	• Infantcontrolled habituation • 4 test trials	ABB vs. ABA ABA vs. ABB	Learning: 6/3 Test: 6/6	+ ABB vs. ABA multimodal + ABA vs. ABB multimodal

Authors	Ns, ages	Stimuli	Exposure/test	*Tested for….	**Tokens/types	***Results
						− ABB vs. ABA unimodal − ABA vs. ABB unimodal (visual or auditory)
Gerken, 2006	48 9-mo	Syllables	• 2 min familiarization • head turn • 4 test trials	AAB vs. ABA ABA vs. AAB AA*di* vs. ABA A*di*A vs. AAB	Learning: 5/4 Test: 4/4 Learning: 5/4 Test: 3/4	+ AAB vs. ABA + ABA vs. AAB − AA*di* vs. ABA − A*di*A vs. AAB
Gerken et al., 2015	80 9-mo	Syllables	• 21 s familiarization • head turn • 12 test trials	*leledi* vs. ABA *ledile* vs. ABB *lelezhi* vs. ABA *lezhile* vs. AAB *lelezhi* vs. A*zhi*A *lezhile* vs. AA*zhi* *leledi* vs. A*di*A *ledile* vs. AA*di*	Learning: 2/1 Test: 4/6 Learning: 2/1 Test: 4/6 Learning: 2/1 Test: 3/6 Learning: 2/1 Test: 3/6	+ AAB vs. ABA + ABA vs. AAB − AAB vs. ABA − ABA vs. AAB + AA*zhi* vs. A*zhi*A *+* A*zhi*A vs. AA*zh* + AA*di* vs. A*di*A + A*di*A vs. AA*di*
Gervain et al., 2008	44 neonates	Syllables	4.2 min exposure to each pattern, continuous fNIRS recording	Discrimination of ABB/ABC Discrimination of ABA/ABC	20/140	+ ABB vs. ABC − ABA vs. ABC
Gervain et al., 2012	66 neonates	Syllables	4.2 min exposure to each pattern, continuous fNIRS recording	Discrimination of AAB/ABC Discrimination of AAB/ABB	20/140	+ AAB/ABC + AAB/ABB
Hochmann et al., 2011, Exp. 2	24 12-mo	Syllables	• 32 training trials, vowel AA & consonant AA predict an event in one of two locations • 8 test trials	Correct anticipatory eye movements to vowel AA & consonant AA location during test trials	Learning: 9/12 Test: 4/4	+ AA vowel repetitions − AA consonant repetitions
Hochmann et al., 2016, Exp. 1	36 14-mo	Geometric shapes on cards	• 36 trials (no test trials), exposure to match or nonmatch relative to a standard	Correct anticipatory eye movements to match or nonmatch location during test trials	18 unique items	+ match-to-sample + nonmatch-to-sample
Exp. 2	50 14-mo	Geometric shapes on cards	• 24 training trials, exposure to match or nonmatch relative to a standard • 12 test trials	Correct anticipatory eye movements to match or nonmatch location during test trials	Learning: 12 unique items Test: 6 unique items	+ match-to-sample + nonmatch-to-sample (when standard matches card just seen) match-to-sample nonmatch-to-sample (when standard is different than card just seen)
Hochmann et al., 2018, Exp. 1	18 7-mo	Geometric shape pairs	• 32 training trials, two rulebased patterns predict an event in one of two locations • 8 test trials	Correct anticipatory eye movements to correct location during test trials	Learning: 6/12 Test: 2/4 (shape and color varied)	+ AA − AB

Authors	Ns, ages	Stimuli	Exposure/test	*Tested for….	**Tokens/types	***Results
Exp. 2	25 12-mo	Geometric shape pairs	• 32 training trials, two rulebased patterns predict an event in one of two locations • 8 test trials	Correct anticipatory eye movements to correct location during test trials	Learning: 9/6 Test: 4/4 (shape only varied)	+ AA − AB
Johnson et al., 2009	80 8-mo 80 11-mo	Geometric shape sequences	• Infantcontrolled habituation • 4 test trials	ABB vs. AAB ABB vs. ABA AAB vs. ABA AAB vs. ABB ABA vs. ABB	Learning: 6/3 Test: 6/3	− ABB vs. AAB 8-mo + ABB vs. AAB 11-mo + AAB vs. ABA 8-mo − AAB vs. ABA 8-mo + AAB vs. ABA 11-mo + AAB vs. ABB 11-mo − ABA vs. ABB 8-mo − ABA vs. ABB 11-mo
Kovács, 2014	64 7-mo 16 12-mo	Syllables	• 36 training trials, two rulebased patterns predict an event in one of two locations • 8 test trials	Correct anticipatory eye movements to correct location during test trials	Learning: 6/12 Test: 2/4	+ AA (vs. AB) 7-mo − AB (vs. AA) 7-mo + AA (vs. AB) 12-mo − AB (vs. AA) 12-mo + AAB (vs. ABA) 7-mo − ABA (vs. AAB) 7-mo + ABA (vs. ABC) 7-mo − ABC (vs. ABA) 7-mo
Kovács & Endress, 2014	28 7-mo	Syllables concatenated into hierarchical patterns	• 4.5 min familiarization • Head turn • 12 test trials	ABB vs. AAB (repeating item = aba, other item = abb) ABB vs. AAB (repeating item = abb, other item = aba)	Learning: 6 syllables (a or b), 18 words (ABB or AAB) Test: 6 syllables, 12 words	− AAB vs. ABB (repeating item = aba) − ABB vs. AAB (repeating item = aba) +-AAB vs. ABB (repeating item = abb) + ABB vs. AAB (repeating item = abb)
Kovács & Mehler, 2009	22 12-mo bilingual 22 12-mo monolingual	Syllables	• 36 training trials, two rulebased patterns predict an event in one of two locations • 8 test trials	Correct anticipatory eye movements to correct location during test trials	Learning: 6/12 Test: 2/4	+ ABA (vs. ABB) bilinguals + AAB (vs. ABA) bilinguals − ABA (vs. AAB) monolinguals + AAB (vs. ABA) monolinguals
Marcus et al., 2007	128 7.5-mo	Musical tones, animal sounds, timbres, syllables	• 2–2.4 min familiarization • head turn • 12 test trials	ABB vs. ABA ABB vs. AAB	Learning: 8/16 Test: 4/4	+ ABB vs. ABA + ABB vs. AAB tones to tones animal sounds to animal sounds timbres to timbres + syllables to syllables + syllables to tones + syllables to animal sounds + syllables to timbres
Marcus et al., 1999	48 7-mo	Syllables	• 2 min familiarization • head turn	ABA vs. ABB ABB vs. ABA ABB vs. AAB	Learning: 8/16 Test: 4/4	+ ABA vs. ABB + ABB vs. ABA + ABB vs. AAB

Authors	Ns, ages	Stimuli	Exposure/test	*Tested for….	**Tokens/types	***Results
			• 12 test trials			
Rabagliati et al., 2012	24 7.5-mo	Gesture sequences	• Infant-controlled habituation • 8 test trials	ABB vs. AAB AAB vs. ABB	Learning: 8/16 Test: 4/4	+ ABB vs. AAB − AAB vs. ABB
Saffran et al., 2007	44 7-mo	Arrays of dogs or cats	• Infant-controlled habituation • 8 test trials	ABA vs. ABB ABB vs. ABA AAB vs. ABB ABB vs. AAB ABA vs. ABB ABB vs. ABA	Learning: 8/16 Test: 4/4	+ ABA vs. ABB + ABB vs. ABA + AAB vs. ABB + ABB vs. AAB + ABA vs. ABB + ABB vs. ABA
Thiessen, 2012	128 7-mo	Multi-modal geometric shape/tone sequences	• Infant-controlled habituation • 6 test trials	ABA vs. ABB ABB vs. ABA ABA vs. ABB ABB vs. ABA	Learning: 6/9 (multimodal) Test: 2/2 (visual) Learning: 6/9 (visual/auditory) Test: 2/2 (visual)	+ ABA vs. ABB + ABB vs. ABA + ABA vs. ABB + ABB vs. ABA
Tyrell et al., 1991	22 7-mo	3D arrays of toys	• 40 sfamiliarization • 2 test trials	AA vs. AB AB vs. AA	Learning: 1/1 (AA), 2/1 (AB) Test: 3/2	+ AA vs. AB + AB vs. AA
Tyrell et al., 1993	40 7-mo	3D arrays of toys	• 80 s exposure • Infants conditioned to look at either AA or AB	AA vs. AB AB vs. AA	9/6	+ AA vs. AB + AB vs. AA

Note: All studies included an exposure phase (e.g., habituation or familiarization) and a test phase to examine generalization of the learned rule to new items except Gervain et al. (2008, 2012), Hochmann et al. (2016, Exp. 1; 2018), Kovács (2014), and Tyrell et al. (1993), who tested for discrimination of two rule-based structures, but not learning or generalization.

[*] The first pattern refers to the structure(s) presented during the exposure phase. For generalization studies, this same pattern and a new (second) pattern, both instantiated in new items, were presented during the test phase.

[**] Tokens = the number of unique items presented during the learning and test phases.

Types = the number of unique array or sequence types presented during the learning and test phases.

[***] + denotes positive evidence for generalization (or discrimination) of tested rule. – denotes null results for tested rule.