

Sequence Learning in 4 Month-Old Infants: Do Infants Represent Ordinal Information?

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We investigated how 4-month-old infants represent sequences: Do they track the statistical relations among specific sequence elements (e.g., AB, BC), or do they encode abstract ordinal positions (i.e., B is second)? Across three experiments, we habituated infants to sequences of four moving/sounding elements - three of the elements varied in their ordinal position whereas the position of one target element was invariant (e.g., ABCD, CBDA). We next tested whether infants detected a change in the target's position. Results showed that infants detected an ordinal change only when it disrupted the statistical co-occurrence of elements but not when statistical information was controlled. We conclude that 4-month-olds learn the order of sequence elements by tracking their statistical associations but not their invariant ordinal position.

Sequences are all around us and our ability to perceive and learn them is critical for the performance of many cognitive and motor skills (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Lashley, 1951; Zacks & Tversky, 2001). From a developmental perspective, sequences are particularly important because they provide infants with ready-made information regarding the structured nature of their world. For example, speech, language, music, and many other types of everyday events consist of temporally structured sequences of distinct elements whose overall meanings derive from their specific sequential position in the series of elements. A variety of empirical findings have demonstrated that infants are sensitive to

sequences. For example, studies have shown that starting at birth infants exhibit a sensitivity to the temporal patterning of unimodal and multimodal information (Lewkowicz, 2003; Lewkowicz & Marcovitch, 2006; Nazzi, Bertoni, & Mehler, 1998; Trehub & Thorpe, 1989), by three months of age they can detect serial order changes inherent in dynamic, multimodal sequences (Lewkowicz, 2004, 2008), and by the end of the first year of life they exhibit a sensitivity to the particular sequencing of naturally ordered everyday events (Baldwin, Baird, Saylor, & Clark, 2001).

Although findings such as these demonstrate that infants can perceive and learn sequences, they do not specify how they represent them. That is, they do not indicate whether infants encode abstract ordinal information or whether they only encode the statistical relations among specific sequence elements. To illustrate these possibilities, consider the case of an infant who begins to cry and then sees and hears her mother, father, and finally brother come running into her room, one after the other. There are two possible ways in which the infant might

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represent this type of sequential information. One is by representing ordinal information, namely, the fact that her mother entered the room first, father second, and brother third. Encoding such ordinal information requires a rather elaborate representational scheme. First, the infant needs to encode each event type by means of abstract placeholders (e.g., three events, X, Y, Z). Second, the infant must order those various placeholders (X=first, Y=second; Z=third). Finally, she must link each placeholder to the event-token that instantiates it. Specifically, in the *Mother-Father-Brother* sequence, the infant must possess (minimally) three placeholders for the three events, order them from first to third, and link each token to its appropriate placeholder (e.g., *Mother*→first placeholder). The other way in which the infant might represent this kind of sequential information is by only encoding the associations among specific tokens (i.e., their statistical relations). For example, the infant might represent the *Mother-Father-Brother* example by encoding pair-wise associative links between specific tokens (e.g., *Mother-Father*; *Father-Brother*). Such a scheme lacks a representation of ordinal information in that abstract placeholders are not specified for each event type, the placeholders are not ordered (e.g., “first vs. second”), and the placeholders are not linked to specific tokens (e.g., “*Father*” corresponds to the second placeholder).

Although these two representational schemes are quite different, in some cases they might support comparable generalizations. In particular, both representational schemes would allow infants to distinguish familiar from unfamiliar sequences. For example, an infant familiar with the *Mother-Father-Brother* sequence should be able to distinguish it from a *Father-Brother-Mother* permutation. Such a discrimination could be based either on detection of an unfamiliar token association (e.g., *Brother-Mother*) or on detection of a change in ordinal relations (e.g., *Father* now

occurs in first position). To distinguish between these two representational schemes, one could investigate generalization to sequences that include novel elements (Berent, Everett, & Shimron, 2001; Berent, Marcus, Shimron, & Gafos, 2002; Berent & Shimron, 1997; Marcus, 2001). If infants represent ordinal information then they should recognize the invariant ordinal position of a familiar sequence element in a novel context. For example, infants should be able to extract the ordinal consistency between the familiar *Mother-Father-Brother* sequence and a novel *Dog-Father-Bird* sequence. In both sequences, *Father* occupies the second position. It should be noted, however, that this invariance can be recognized only if an infant can extract the invariant ordinal position of *Father* despite changes in the associative relations between *Father* and adjacent sequence elements. The invariance cannot be recognized if infants only track token-associations. In this latter case, an infant would only be able to distinguish the familiar *Mother-Father-Brother* sequence from an unfamiliar one (e.g., *Father-Bird-Dog*), but fail to recognize the ordinal invariance in the *Mother-Father-Brother* sequence and a novel *Dog-Father-Bird* sequence.

Lewkowicz (2004; 2008) has shown that infants as young as three months of age can distinguish between different audiovisual, dynamic sequences based on the sequencing of their elements. For example, infants who were habituated to an ABC sequence of moving/sounding objects exhibited response recovery when presented with a CAB sequence of the same set of elements. Although these findings demonstrate that infants are sensitive to the sequencing of elements, it is difficult to determine whether infants detected sequence differences based on token-association information or on ordinal position information because both types of information was available in those studies. Moreover, other evidence indicates that infants

are sensitive to both types of information. Thus, studies have shown that starting as early as two months of life infants are very good at extracting and learning adjacent sequence-element associations in sequences composed of visual as well as auditory elements (Fiser & Aslin, 2002; Jusczyk, Luce, & Charles-Luce, 1994; Kirkham, Slemmer, & Johnson, 2002; Richardson & Kirkham, 2004; Saffran, Aslin, & Newport, 1996; Saffran, Johnson, Aslin, & Newport, 1999) and that by the second year of life they can learn non-adjacent sequence-element associations (Gómez, 2002; Gómez & Maye, 2005). In addition, in the latter part of the first year of life, infants can learn grammatical rules (e.g., ABB vs. ABA) specifying the ordering of distinct syllables (Marcus, Vijayan, Rao, & Vishton, 1999) and can track the ordinal position of a particular syllable (Gerken, 2006) suggesting that older infants are sensitive to ordinal information as well.

The findings of rule-learning in older infants are particularly interesting. Although they suggest that sensitivity to ordinal information is present in infancy, they do not necessarily demonstrate that infants can broadly represent ordinal relations. That is, the existing evidence of rule-learning only comes from older infants and from studies utilizing linguistic stimuli. Moreover, a recent study has shown that the ability to learn rules from linguistic stimuli does not necessarily extend to other auditory stimuli (Marcus, Fernandes, & Johnson, 2007). Specifically, this study demonstrated that 7.5 month-old infants can extract rules from sequences of speech sounds but that they do not from nonspeech sound sequences. These results cast doubt on the ability of young infants to acquire rules representing the ordering of nonlinguistic events and bolster the concerns that young infants' sensitivity to sequential information (Lewkowicz, 2004) reflects the representation of specific token-associations, rather than ordinal information per se.

To date, no studies have attempted to dissociate responsiveness to ordinal information from responsiveness to token-association. The present research was designed to do so in three separate experiments. Experiment 1 investigated whether infants can learn the invariant ordinal position of a target sequence element in the context of three other elements and whether they can then detect a change in its ordinal position during test trials. To do so, we first habituated infants to a series of 4-element sequences consisting of the same elements where three of them changed their ordinal position across the different sequences while the fourth one - the target - remained in an invariant ordinal position (e.g., B in ABCD, CBDA, DBAC). Following habituation, we administered two sets of test trials. One set tested whether infants encoded the target's invariant position and, if so, whether this knowledge was tied to the specific sequence elements making up the habituation sequences. We did this by contrasting responsiveness to the target element in its familiar versus novel ordinal position in the context of the already familiar sequence elements (e.g., ABCD vs. ACBD). The other test set examined whether infants also encoded the more abstract concept of "second" or "third" by contrasting responsiveness to the target in its familiar versus novel ordinal position but this time when the target was presented in the context of novel sequence elements (e.g., EBFG vs. EFBG). Experiment 2 investigated whether infants can extract ordinal position information when processing load is reduced. To this end, we repeated Experiment 1 except that this time we reduced the overall processing load during the test phase by administering only the novel-context test trials (e.g., EBFG vs. EFBG). Finally, Experiment 3 investigated infants' ability to learn and generalize invariant ordinal position knowledge by probing for generalization of ordinal position information when the target element was presented in the

context of familiar elements while controlling for statistical similarity to the habituation items. In addition, Experiment 3 investigated whether the statistical relations between the target element and the other sequence elements might have contributed to responsiveness. Thus, we once again habituated infants to a series of sequences where the target element was presented in an invariant ordinal position and then administered two sets of test trials. One set assessed whether infants were sensitive to a change in the target's ordinal position by contrasting response to its familiar and novel position in the absence of familiar statistical information. The other set assessed

them to three different sequences consisting of four distinct moving objects and their impact sounds. Across these sequences, the target object and its sound maintained an invariant ordinal position (i.e., was always either second or third in the sequence), whereas the other three objects/sounds varied in their ordinal positions (see Table 1). Following habituation, we assessed infants' ability to encode ordinal information by administering two sets of test trials. In one set, the target element was presented in the context of the other familiar objects/sounds, either in its original ordinal position or in a novel and inconsistent ordinal position (e.g., ABCD vs. ACBD where B is

Table 1. Design of Experiment 1 and the specific sequences presented to one group of infants in each of the habituation groups during the habituation and test trials. The various letters in the table designate the different objects and their corresponding impact sounds (see Method section for more details).

	Habituation Group 1	Habituation Group 2
Habituation		
Trial 1	ABCD	ACBD
Trial 2	CBDA	CDBA
Trial 3	DBAC	DABC
Test Trials		
Familiar Consistent	ABCD	ACBD
Familiar Inconsistent	ACBD	ABCD
Novel Consistent	EBFG	EFBG
Novel Inconsistent	EFBG	EBFG

whether infants were sensitive to statistical relations by contrasting responsiveness to familiar versus novel statistical relations between the target and the other sequence elements.

Experiment 1

Experiment 1 examined the learning of ordinal rules using the same types of sequential events presented by Lewkowicz (2004). To give infants the opportunity to encode the invariant ordinal position of a target sequence element, we first habituated

the target element). In the other set, the target was presented in the context of unfamiliar objects/sounds, either in its original position or in a novel ordinal position (e.g., EBFG vs. EFBG). If infants successfully encoded the target's ordinal invariance, then we expected them to exhibit response recovery in the inconsistent test trials regardless of whether the context was familiar or not. In contrast, if infants only encoded specific sequential information (i.e., associative relations among adjacent sequence elements) then we expected that they would only exhibit response recovery

in the inconsistent test trial in the familiar context.

Method

Participants. We tested 36 healthy fullterm infants of whom 33 contributed data. The mean age of the 33 infants was 19.3 weeks (SD = 1.2 weeks; 17 boys and 16 girls). We tested an additional nine infants but they did not contribute usable data because of equipment failure (1 infant), fussing (6 infants), distraction (1 infant), and inattentiveness (1 infant). One infant was African American, one was Asian, one was White Hispanic, and the rest were White non-Hispanic.

Apparatus and Stimuli. All stimulus events consisted of multimedia movies. One of these was an attention-getter movie showing a continuously expanding and contracting green disk. A second movie, that served as a Pre- and Post-test trial, was a segment of a Winnie-the-Pooh cartoon (presented at 70-74 dB SPL; ambient sound pressure level of 50 dB). The remaining seven movies showed different sequential orderings of four distinct moving objects and their distinct impact sounds.

Five of the movies showed the four objects seen in Figure 1a (Object A – button; Object B – triangle, Object C – square; Object D – star) arranged in various orders. Figure 1b shows the motion path of the objects during a single cycle of the sequence. As can be seen, at the start of the cycle, the objects emerged one after the other from the spout at the top, moved down and passed in front of the grey rectangle and continued down until they reached the bottom of their downward trajectory. As soon as they contacted the black ramp, they made an impact sound, turned to the right, and moved off to the side. The impact sounds were digital recordings of the following sounds: Object A - a metal object hitting against a glass bottle; Object B – a wooden spoon hitting against a small empty plastic container, Object C – a wooden spoon

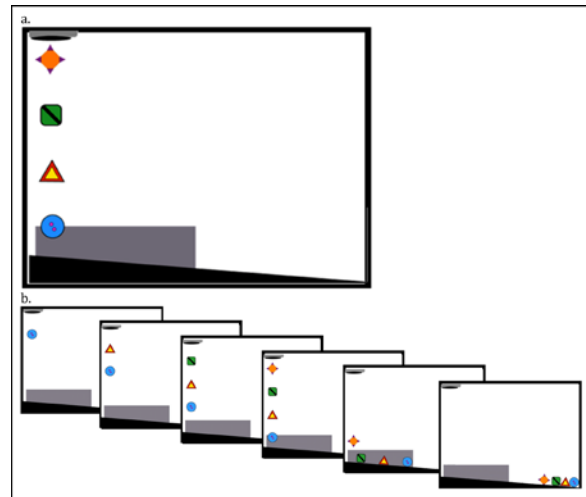


Figure 1. a. The four objects presented during the habituation phase in Experiment 1. b. A schematic representation of the movement of the objects over time during a single sequence cycle.

hitting against a metal pot; and Object D – a light bulb breaking. Two other movies, used to test for generalization learning (see below), showed the objects seen in Figure 2 (Object E - hexagon, Object B - triangle, Object F - star, and Object G - cross). The impact sounds for these objects were: Object E – the sound of a bouncing basketball, Object B – a wooden spoon hitting against an empty plastic

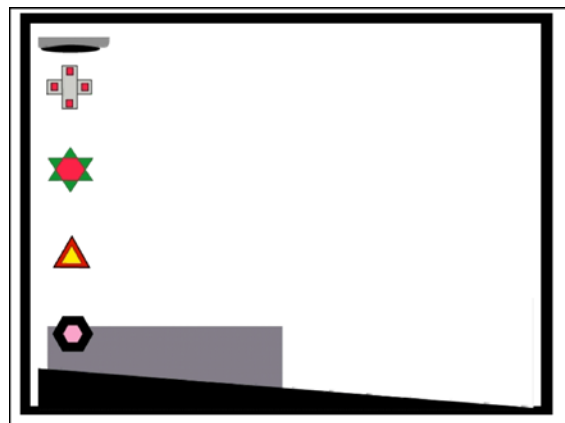


Figure 2. The four objects presented during the generalization test trials in Experiment 1.

container, Object F – a wooden spoon hitting against a wooden surface, and Object G – a deep hollow sound produced by hitting a wooden spoon against a large plastic container. All movies were presented on a 17 inch computer monitor at an approximate distance of 50 cm from the infant. The audio part of the movie was presented through speakers placed on each side of the monitor. The average sound pressure level of the impact sounds was 80 dB (A scale). A camera that transmitted a view of the infant's face to a video monitor was located on top of the stimulus-presentation monitor.

Each movie began with the appearance of the spout, the ramp, and the grey rectangle. As soon as they appeared, the four objects emerged sequentially from the spout at half second intervals and moved down at the same and constant speed. Each object reached the ramp 1.83 s after it emerged from the spout and made an impact sound as it turned to the right. Each object continued to move down the ramp until it came to rest on the right side of the screen. The objects came to rest 4.5, 4.87, 5.2 and 5.5 s, respectively, following their emergence from the spout. Once the last object came to rest, all four objects remained visible for 0.67 s, disappeared for 0.83 s, and then the sequence started again and continued to be presented repeatedly until the infant either looked away or until the maximum trial duration was reached (see below).

Procedure. We used the infant-controlled habituation/test procedure. This allowed the infant's looking behavior to control the onset and offset of each movie presentation and, thus, of each trial. Specifically, whenever the infant looked at the stimulus-presentation monitor the movie began to play and whenever the infant looked away from the monitor for more than one second, or whenever he or she accumulated a total of 55 s of looking time, the movie ended and the attention-getter appeared on the monitor. Duration of looking was recorded during

movie presentation by an experimenter who could neither see nor hear the stimuli being presented.

The experiment began with a single Pre-test trial (the Winnie-the-Pooh cartoon) and then continued with the habituation phase. When the total duration of looking during the last four habituation trials declined to 50% of the total duration of looking during the first four habituation trials, the habituation phase ended and the test phase began. Table 1 shows the sequences presented during the habituation and test phases for each habituation group. As can be seen, the three sequences presented during the habituation phase differed in terms of the ordinal position of all objects and their sounds except for object/sound B (the target). As shown in Table 1, object/sound B remained in an invariant 2nd position for one group of infants and in an invariant 3rd position for the other group. The first test trial for all infants was the Familiar Consistent test trial during which one of the three sequences that was presented during the habituation phase was presented again. To counterbalance the presentation of the three familiar sequences during this test trial we presented each of them an equal number of times across the infants tested in each habituation group, respectively. The remaining three test trials were presented in counterbalanced order across infants in each habituation group. The Familiar Inconsistent test trial involved an ordinal position change of the target in a familiar sequence context and, thus, assessed whether infants learned its specific ordinal position in that context. The familiar-consistent and familiar-inconsistent sequences were matched for the probability of occurrence of adjacent element-pairs in the familiarization trials; however, the consistent familiar sequence had a higher probability of triplet- and quadruplet-element associations. The Novel Consistent test trial involved presentation of the familiar target in its familiar position but in the context of all new objects and their sounds and, thus, was

designed to determine whether infants could generalize their learning about the target to a novel sequence context. Finally, the Novel Inconsistent test trial involved a change in the ordinal position of the familiar target in the context of all new objects and their sounds. The test session ended with a Post-test trial where infants saw and heard the segment of the Winnie-the-Pooh cartoon.

Results and Discussion

We performed a preliminary analysis to determine whether any infants exhibited spontaneous regression to the mean in the Familiar Consistent test trial. We excluded from further analyses the data of three infants whose duration of looking in this test trial exceeded the mean duration of looking in this trial by more than 2 standard deviations.

As can be seen in the left panel of Figure 3, infants exhibited a significant decline in looking during the habituation trials, $F(5, 155) = 74.9, p < .001$. It took the infants an average of 10.4 trials to reach the habituation criterion (range: 8 – 21 trials). As can be seen

in the right panel of Figure 3, infants exhibited differential responsiveness across the consistency conditions in the familiar context condition but not in the novel context condition. We tested this Context (familiar vs. novel) X Consistency (consistent vs. inconsistent) interaction by way of a mixed $2 \times 2 \times 2$ (Habituation Group X Context X Consistency) analysis of variance (ANOVA), with Habituation Group as the between-subjects factor and Context and Consistency as the within-subjects factors. Results indicated that the Context X Consistency interaction was statistically significant, $F(1, 31) = 7.68, p < .01$ as was an overall Context effect, $F(1, 31) = 24.3, p < .001$, but that the 3-way interaction was not significant.

The findings from this experiment show that infants detected a change in the ordinal position of the target in the context of familiar elements but that they did not respond to the change when the target was surrounded by novel elements. To further probe the source of response differences, we compared the data from the different conditions by means of

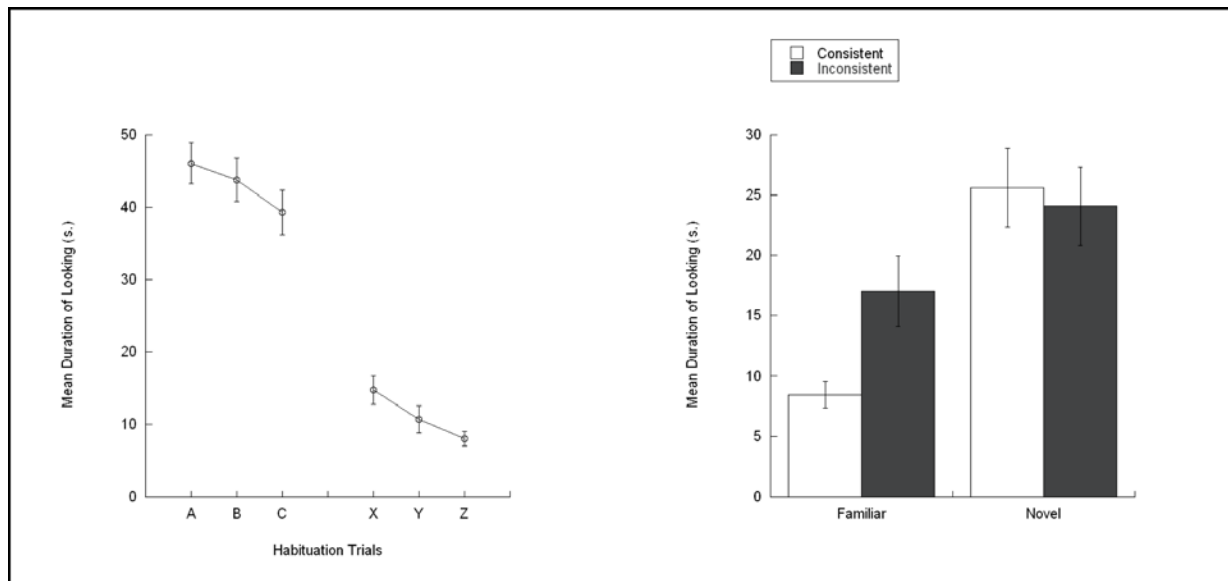


Figure 3. Results from Experiment 1. The left panel shows the duration of looking during the habituation phase. Because the number of trials to reach the habituation criterion varied across infants, the left panel only depicts the average duration of looking in the first (A, B, and C) and the last three (X, Y, and Z) habituation trials. The right panel shows the duration of looking in the test trials. Error bars indicate the standard error of the mean.

three planned comparisons (using the MSE of the omnibus interaction, see (Kirk, 1968)). These tests showed that infants detected the ordinal position change in the familiar context (Familiar Consistent vs. Familiar Inconsistent contrast, $F(1, 31) = 11.07, p < .01$) but that they did not respond to the ordinal position change in the novel context (Novel Consistent vs. Novel Inconsistent, $F(1, 31) = 0.24, ns$). In addition, these analyses indicated that infants detected the change in context (Familiar Consistent vs. Novel Consistent, $F(1, 31) = 44.5, p < .001$, and Familiar Consistent vs. Novel Inconsistent, $F(1, 31) = 36.9, p < .001$). Finally, the findings showed that the failure to exhibit differential responsiveness in the novel context was not due to fatigue effects. This was evident in the fact that response in the Post-test trial was significantly higher than in the Novel Inconsistent test trial, $F(1, 31) = 43.31, p < .001$. In fact, infants looked twice as long (Mean = 49.8 s) in the Post-test trial than they did in the Novel Inconsistent test trial.

In sum, the most reasonable interpretation of the findings from this experiment is that infants encoded the sequential relation of the target in the context of familiar elements but that they did not generalize that knowledge to a novel sequential context.

Experiment 2

Infants' failure to generalize invariant ordinal information to novel sequences suggests that they may not encode invariant ordinal information. It is possible, however, that infants may be able to encode invariant ordinal information but fail to generalize it to novel sequences because of information-processing limitations. That is, the demands associated with the processing of four different test trials in Experiment 1 might have taxed infants' information-processing system beyond their normal capacity and, thus, have

prevented them from learning the ordinal information.

The purpose of Experiment 2 was to test this possibility. To do so, we repeated Experiment 1 except that this time we reduced the information-processing load by administering only the two test trials during which the novel test sequences were presented. If excessive information processing demands accounted for the infants' failure to generalize ordinal position learning in Experiment 1 then they would be expected to generalize in Experiment 2. Specifically, infants should exhibit greater response recovery in the novel inconsistent test trial than in the novel consistent test trial. If, however, infants of this age do not generalize ordinal information knowledge then the insensitivity to ordinal invariance should persist despite the reduction in processing load.

Method

Participants. The sample consisted of 24 healthy, full-term infants (mean age = 19 weeks, $SD = 1.3$ weeks; half were girls). We tested an additional six infants in this experiment but did not use their data because five of them were fussy and one was sleepy. Two infants were White Hispanic and the rest were White non-Hispanic.

Apparatus and Stimuli. The apparatus and stimuli were identical to those used in Experiment 1.

Procedure. The procedure was identical to that used in Experiment 1 except that here we administered only the Novel Consistent and the Novel Inconsistent test trials. As in Experiment 1, we began the test session with the Pre-test trial and ended it with the Post-test trial.

Results and Discussion

The left panel of Figure 4 shows the results from the habituation trials. As can be seen, infants exhibited a significant decline in looking during the habituation trials, $F(5,$

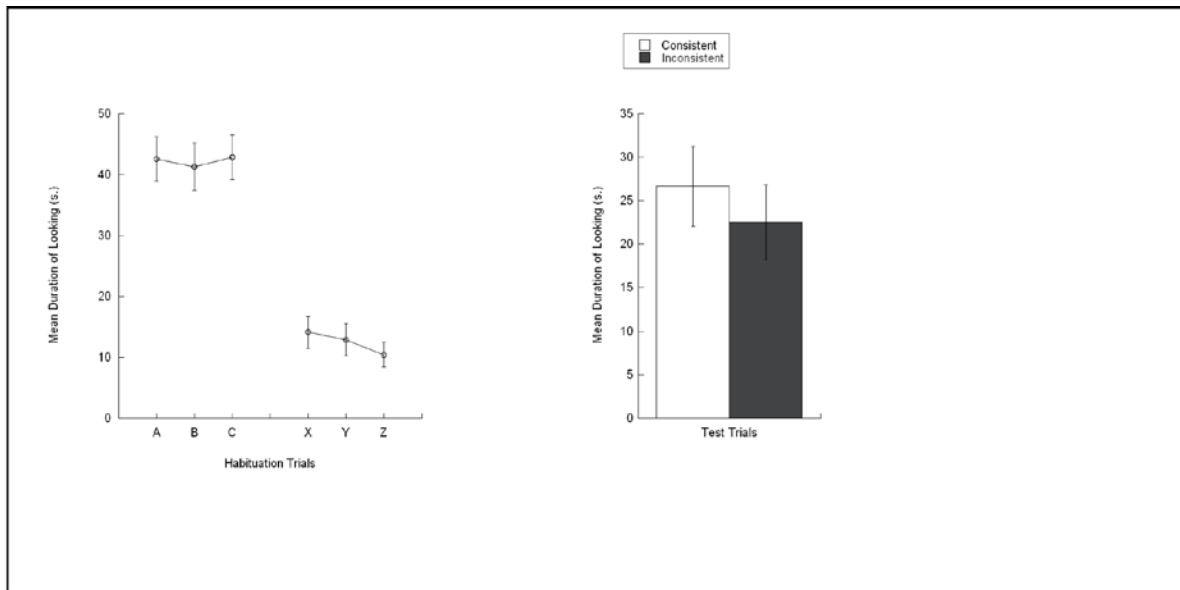


Figure 4. Results from Experiment 2. The left panel shows the duration of looking during the first three (A, B, and C) and last three (X, Y, and Z) habituation trials and the right panel shows the duration of looking in the test trials. Error bars indicate the standard error of the mean.

110) = 44.2, $p < .001$, and examination of the number of trials needed to reach habituation indicated that it took the infants an average of 10.8 trials to reach the habituation criterion (range: 8 – 23 trials). Furthermore, as indicated by a non-significant Trials \times Experiment interaction, $F(5, 275) = 0.83$, ns , the habituation-trials response profile obtained in the current experiment did not differ from that in Experiment 1. The right panel of Figure 4 shows the results from the test trials and as can be seen, similar to the outcome in these two test trials in Experiment 1, infants did not respond differentially. A mixed 2 \times 2 (Habituation Group \times Test Trial Type) ANOVA, with Habituation Group as the between-subjects factor and Test Trial Type as a within-subjects factor, confirmed this fact by indicating that neither the trials effect ($F(1, 22) = 1.7$) nor any other effects were statistically significant. As in Experiment 1, the failure to generalize was not due to fatigue effects because response in the Post-test trial

($M = 51.4$) was greater than in the Novel Inconsistent trial, $F(1, 22) = 40.39$, $p < .001$.

Because a Familiar test trial was not administered in this experiment, it is important to ensure that response in the two generalization test trials reflected response recovery. To determine whether this was the case, we compared the duration of looking obtained in the test trials in this experiment (see Fig. 4) with the duration of looking obtained in those same two test trials in Experiment 1 (see Fig. 3). This comparison indicated that response in these two trials across the two experiments was comparable. This, in turn, means that, as was the case in Experiment 1, the magnitude of response in these two test trials was more than double that obtained in the Familiar test trial in Experiment 1. To further ensure that the response obtained in this experiment reflected response recovery, we compared the response in each of the two test trials in this experiment with the response in the last habituation trial in

this experiment. This comparison indicated that the response in the Novel Consistent test trial was significantly higher than in the last habituation trial, $F(1, 22) = 13.6, p < .01$, as was the response in the Novel Inconsistent trial, $F(1, 22) = 11.2, p < .01$. In sum, these results suggest that the infants' failure to detect ordinal invariance was not due to excessive processing load.

Experiment 3

Experiment 1 indicated that infants were sensitive to invariant sequential information in a familiar context but that they failed to generalize such information to novel sequences. Experiment 2 replicated this result and showed that it was unlikely that infants' failure to generalize was related to information-processing demands. This repeated failure to generalize might suggest that 4-month-old infants may not encode invariant ordinal information when the task involves the learning of dynamic, audiovisual sequences. It is possible, however, that our infants' failure to generalize ordinal position information was due to the fact that we tested for generalization of such knowledge in the context of novel test elements (i.e., ones that were not presented during the habituation phase). That is, it may be that the sheer novelty of the test elements may have drawn the infants' attention away from the sequential nature of the event and, in the process, may have prevented them from detecting the target's invariant ordinal position. This interpretation is consistent with the findings from Experiments 1 and 2 showing that sequences comprised of novel elements elicited significantly longer looking than did sequences comprised of familiar elements.

To address the possibility that the failure to generalize was due to the novelty of the non-target sequence elements, Experiment 3 probed for generalization of ordinal position knowledge in the context of familiar test

elements. Thus, as in the previous experiments, we first habituated infants to three different sequences where the target element was presented in an invariant ordinal position. This time, however, the sequences presented during the test phase consisted of the same four sequence elements that were presented during the habituation phase except that, in contrast to Experiment 1, here the target's novel position could not be determined on the basis of its statistical relations to the other sequence elements.

The test trials administered in this experiment consisted of two sets. One set tested for detection of ordinal position differences by contrasting responsiveness to the target element in a familiar versus novel ordinal position. If infants' failure to detect the target's new ordinal position in Experiments 1-2 was due to the novelty of the non-target test elements then the infants in this experiment should detect the target's new ordinal position. If, however, 4-month-old infants truly find it difficult to encode invariant ordinal position information then, despite the familiarity of all test elements, they may once again fail to detect the target's new ordinal position. If infants fail to detect the target's new ordinal position even when all the test-sequence elements are familiar then this would suggest that this persistent failure to generalize ordinal position knowledge may be due to the fact that infants of this age encode sequential information primarily by tracking the statistical relations of specific sequence elements. To examine this possibility, the second set of test trials in the current experiment tested for statistical learning *per se*.

Overall, the two sets of test trials in this experiment manipulated the sequential consistency of habituation- and test-sequences along two dimensions (see Table 2). One was their ordinal consistency, defined by the ordinal relation of the target element to the other elements during the habituation phase

Table 2. Design of Experiment 3 showing the specific sequences presented to one group of infants in each of the habituation groups during the habituation and test trials. The various letters in the table designate the different objects and their corresponding impact sounds (see Method section for more details).

		Habituation Group 1	Habituation Group 2
Habituation			
Trial 1		ABCD	ACBD
Trial 2		EBFG	EFBG
Trial 3		HBIJ	HIBJ
Test Trials			
Ordinally Consistent	Statistically Consistent	ABCD	ACBD
	Statistically Inconsistent	GBCJ	HCBE
Statistically Inconsistent	Ordinally Consistent	DBGJ	AEBH
	Ordinally Inconsistent	DGBJ	ABEH

while the other was their statistical consistency, defined by the associations of specific elements during the habituation phase. Specifically, the first set of test trials investigated infants’ response to ordinal consistency by examining ordinal position knowledge in the absence of relevant statistical information. It did so by contrasting responsiveness to the target in its familiar versus novel ordinal position across sequences whose elements no longer bore the same statistical relations vis-à-vis one another as they did during the habituation phase. If infants encoded the target’s invariant ordinal position then they should respond differentially in these test trials despite the (equal) disruption of statistical information in both. The second set of test trials explicitly investigated infants’ response to the statistical information inherent in the habituation sequences. It did so by contrasting responsiveness to the target in its familiar position while maintaining its statistical relations versus responsiveness to it in its familiar position when some of the statistical relations between it and the other sequence elements were disrupted. Here, we expected that if infants encoded sequential information

primarily by learning the statistical relations among sequence elements then they should only respond differentially in this second set of test trials.

Method

Participants. The sample consisted of 36 healthy, full-term infants (mean age = 17.5 weeks, SD = 2.9 weeks; 19 girls and 17 boys). We tested an additional 16 infants but did not use their data because of equipment problems (one infant), fussing (13 infants), falling asleep (one infant), and distraction (one infant). All infants were White non-Hispanic except two who were White Hispanic.

Apparatus and Stimuli. The apparatus was identical to that employed in Experiment 1. The sequences presented in this experiment are depicted in Table 2. As can be seen, the A, B, C, D, E, F, and G stimuli were the same as in Experiment 1 but stimuli H, I, and J were new. Object H resembled a mushroom with a black top and a green stem; Object I was a purple pentagon with an orange outline and three smaller pentagons placed inside the three corners of the large pentagon; and Object J was an oval shape consisting of three increasingly smaller, differently colored

(yellow, blue, and light orange) oval rings. The impact sounds that corresponded to these objects were as follows: Object H – the JungleSingDrumMono.wav file included with the Microsoft Windows 98 operating system, Object I – the UtopiaDink.wav file included with Windows 98, and Object J – a digital recording of a wooden spoon hitting against a large metal pan.

Procedure. The procedure was identical to that used in Experiment 1 except that here we administered the test trials seen in Table 2. In addition, as in Experiment 1, the test session began with the Pre-test trial and ended with the Post-test trial. Table 2 shows the sequences presented during the habituation and test phases for each habituation group. As can be seen, the three sequences presented during the habituation phase differed in terms of the ordinal position of all objects and their sounds except for object/sound B (the target). As Table 2 shows, object/sound B remained in an invariant 2nd position for one group of infants and in an invariant 3rd position for the other group.

Of the four test trials, the first test trial for all infants was the Statistically Consistent (Ordinally Consistent) test trial. During this trial one of the three familiar sequences that was presented during the habituation phase was presented again. To counterbalance the specific type of sequence presented during this test trial, we presented each of the three habituation sequences an equal number of times across infants in each habituation group. The remaining three test trials were presented in counterbalanced order across the infants in each habituation group. The Statistically Inconsistent (Ordinally Consistent) test trial involved a disruption of the statistical relations between the target and one of the sequence elements that it was associated with during habituation (e.g., ABCD vs. GBCJ). This was done by presenting a sequence element adjacent to the target element that was never associated with it during the habituation phase.

In this way, we were able to assess whether infants were attending to the statistical relations inherent in the sequences. The Ordinally Consistent (Statistically Inconsistent) test trial involved presentation of the target element in its familiar ordinal position in the context of the other familiar objects and their sounds. As can be seen in Table 2, however, the sequential position of the other familiar objects was rearranged such that the two sequence elements that were adjacent to the target element were never associated with it during habituation. In this way, infants had to judge the ordinal position of the target element in the absence of statistical information. Finally, the Ordinally Inconsistent (Statistically Inconsistent) test trial involved presentation of the target element in a novel ordinal position in the context of the other familiar sequence elements again arranged such that no statistical information could be used to ascertain ordinal position.

Results and Discussion

A preliminary analysis, designed to determine whether any infants exhibited spontaneous regression to the mean in the Familiar test trial, indicated that three infants did. The data from these infants were excluded from any further analyses. Fig. 5 shows the results from the habituation and test trials for the remaining 33 infants.

As can be seen in the left panel of Figure 5, infants exhibited a significant decline in responsiveness during the habituation trials, $F(5, 155) = 8.65, p < .001$. Overall, it took the infants an average of 12.5 trials to reach habituation (range: 8-27). As can be seen in the right panel of Figure 5, infants exhibited differential responsiveness across the consistency conditions in the statistical information test trials but not in the ordinal information test trials. To evaluate the differences between the means, we first conducted an overall mixed 2 X 2 X 2

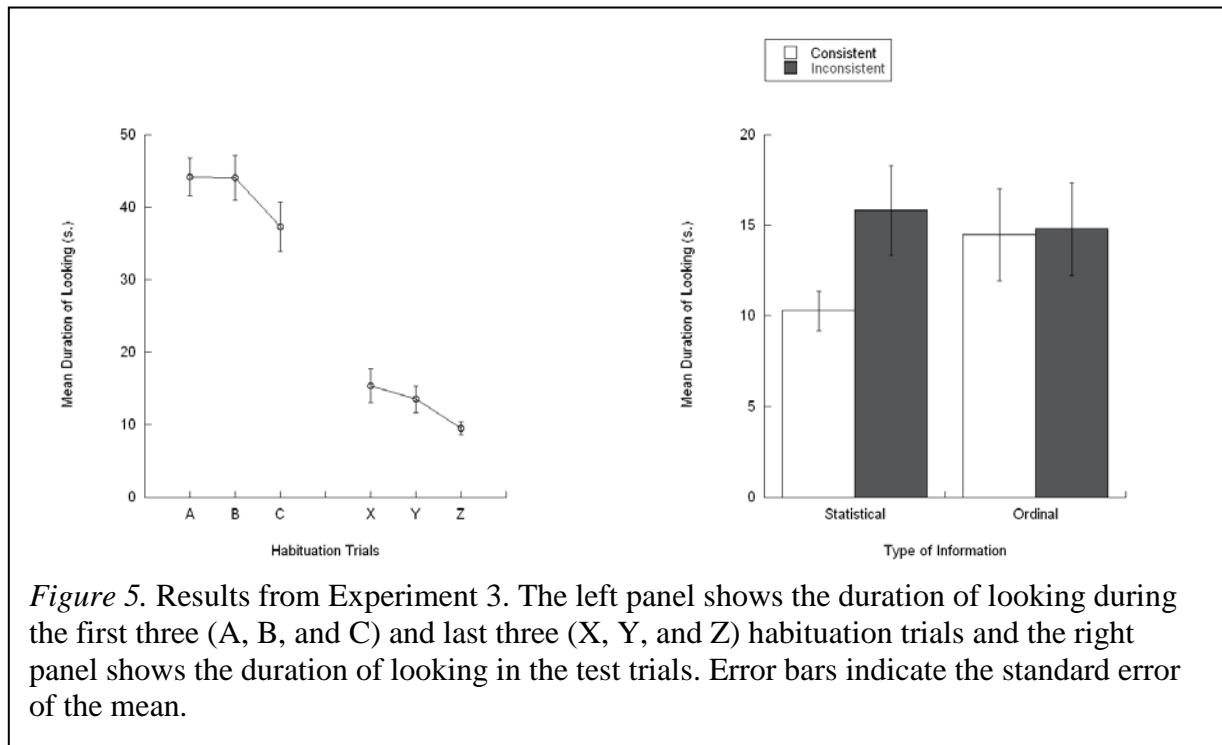


Figure 5. Results from Experiment 3. The left panel shows the duration of looking during the first three (A, B, and C) and last three (X, Y, and Z) habituation trials and the right panel shows the duration of looking in the test trials. Error bars indicate the standard error of the mean.

(Habituation Group X Type of Information (Statistical vs. Ordinal) X Consistency (Consistent vs. Inconsistent)) ANOVA, with Habituation Group as the between-subjects factor and Type of Information and Consistency as the within-subjects factors, and then followed up with planned comparisons. This ANOVA did not yield any significant effects.

We then examined infants' sensitivity to ordinal and statistical information by means of two planned comparisons. To evaluate sensitivity to ordinal information, we compared responsiveness in the Ordinally Consistent (Statistically Inconsistent) and Ordinally Inconsistent (Statistically Inconsistent) test trials. This comparison indicated that looking time did not differ in these two test trials, $F(1, 31) = .02$, ns, suggesting that infants did not encode ordinal position information. Infants' failure to exhibit differential responsiveness to the disruption of ordinal information was not simply due to an overall failure to detect a change (i.e., to exhibit response recovery). This is evident in

the fact that responsiveness to the Ordinally Inconsistent (Statistically Inconsistent) test trial differed significantly from responsiveness to what was in essence a familiar test trial, namely, the Statistically Consistent (Ordinally Consistent) test trial, $F(1, 31) = 4.47$, $p < .05$. Likewise, a comparison of responsiveness in the Ordinally Consistent (Statistically Inconsistent) test trial yielded a marginally significant difference, $F(1, 31) = 3.88$, $p < .06$.

To evaluate sensitivity to statistical information, next we compared responsiveness in the Statistically Consistent (Ordinally Consistent) and Statistically Inconsistent (Ordinally Consistent) test trials. The significance of this contrast indicated that infants exhibited response recovery to the disruption of statistical information, $F(1, 31) = 6.72$, $p < .025$. When this finding is considered together with the fact that infants did not detect ordinal position changes in the other set of test trials, it suggests that infants failed to learn ordinal invariance and that they

only encoded the statistical relations among specific sequence elements.

General Discussion

This study investigated how 4-month-old infants represent sequential information inherent in dynamic, multimodal sequences and asked whether they can encode abstract ordinal position information (e.g., that element B occurred “second” in ABCD) or whether they can only track the statistical relations of specific tokens (e.g., paired association, AB, BC, etc.) . Using a habituation/test procedure, in Experiment 1 we habituated infants to several different sequences consisting of the same four moving/sounding objects. Across these sequences, a target object and its sound remained in an invariant ordinal position while the other three objects/sounds varied in their ordinal positions. Following habituation, we administered two sets of test trials in which the target’s ordinal position was either familiar or novel. In one set of test trials, the target element was presented in the context of familiar elements (e.g., ABCD vs. ACBD) whereas in the other set of test trials, the target element was presented in the context of novel elements (e.g., EBF~~G~~ vs. EFB~~G~~). If infants encoded invariant order then we expected that they would discriminate consistent from inconsistent sequences *irrespective* of whether neighboring elements were familiar or not. In contrast, if infants encoded the statistical relations of specific elements, we expected that they would discriminate consistent from inconsistent sequences only if the statistical relations between the target element and its original neighbors were disrupted during the test trials.

The results from Experiment 1 showed that infants detected changes in the position of a target element in the context of familiar sequences but not in the context of novel sequences. Thus, infants failed to generalize the ordinal invariance information provided in

the habituation phase in their response to novel sequences. To determine whether this failure may have been due to excessive information-processing demands imposed by requiring the infants to respond to four separate test trials, we tested their ability to generalize learning in Experiment 2 by administering only the test trials involving the novel sequence elements (i.e., the generalization test trials). Despite the reduced information-processing load, infants still failed to exhibit evidence of generalization and, thus, of the acquisition of invariant ordinal position knowledge.

This consistent failure to generalize might indicate that infants did not detect the change in the target’s ordinal position during the test trials because they were distracted by the sheer novelty of the non-target sequence elements. Alternatively, this failure to generalize might indicate that infants encoded the statistical relations of specific sequence elements rather than their ordinal position. Experiment 3 evaluated both of these possibilities. To gauge learning of ordinal information, we retested infants’ sensitivity to the disruption of ordinal invariance in the context of familiar elements while controlling for their statistical properties. To gauge learning of statistical relations *per se*, we also assessed infants’ sensitivity to the disruption of statistical relations while ordinal invariance was kept constant. Results showed that, despite the fact that the test sequences consisted of familiar elements, infants still did not exhibit evidence of ordinal position learning although they exhibited clear evidence of statistical learning.

Although prior studies have provided impressive evidence of sequence learning in early human development (Fiser & Aslin, 2002; Gerken, 2006; Gómez, 2002; Gómez & Maye, 2005; Jusczyk et al., 1994; Kirkham et al., 2002; Marcus et al., 1999; Richardson & Kirkham, 2004; Saffran et al., 1996; Saffran et al., 1999), none of these studies have explicitly tested whether the ability to detect sequential

invariance in multimodal events might involve the representation of ordinal rules. The current study is the first to do so by investigating the separate contribution of ordinal and statistical information to sequence learning in young infants. Consistent with the results of prior studies, the findings from three experiments in the current study indicate clearly that young infants encode sequential relations based on token associations. It is up to future research to determine the precise nature of such associations - whether they are formed at the level of bigrams, trigrams, long-distance dependencies among nonadjacent segments or entire sequences. Regardless of the eventual answer to this question, the current findings show for the first time that 4-month-old infants encode sequential order by tracking the statistical relations of specific events, rather than by representing ordinal information. The fact that infants failed to exhibit evidence of ordinal position learning across three separate experiments, that they did so regardless of whether the test sequences were composed of familiar or novel elements, and that they exhibited evidence of statistical learning speaks against the possibility that this failure is due to methodological limitations.

In conclusion, the current findings shed light on the development of rule-learning in infancy. Prior research has demonstrated that infants can detect and learn the statistical relations inherent in temporally distributed patterns of auditory and visual information and that they can do so as early as two months of age. In addition, prior research has shown that older infants - seven months and older - can learn simple sequential rules. The most impressive aspect of this ability is that it enables infants to learn simple sequential rules within a matter of minutes and to then generalize them to sequences consisting of novel elements. The findings from the present study are particularly interesting in this context because they show that younger, 4-month-old, infants not only do not learn rules nor

generalize them to novel sequences but that they don't even do so when the sequences are familiar. It is up to future research to determine when this critical cognitive skill first emerges in development and to characterize the mechanisms underlying its developmental emergence.

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