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PAPER

Development of ordinal sequence perception in infancy

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Abstract

Perception of the ordinal position of a sequence element is critical to many cognitive and motor functions. Here, the prediction that this ability is based on a domain-general perceptual mechanism and, thus, that it emerges prior to the emergence of language was tested. Infants were habituated with sequences of moving/sounding objects and then tested for the ability to perceive the invariant ordinal position of a single element (Experiment 1) or the invariant relative ordinal position of two adjacent elements (Experiment 2). Experiment 1 tested 4- and 6-month-old infants and showed that 4-month-old infants focused on conflicting low-level sequence statistics and, therefore, failed to detect the ordinal position information, but that 6-month-old infants ignored the statistics and detected the ordinal position information. Experiment 2 tested 6-, 8-, and 10-month-old infants and showed that only 10-month-old infants detected relative ordinal position information and that they could only accomplish this with the aid of concurrent statistical cues. Together, these results indicate that a domain-general ability to detect ordinal position information emerges during infancy and that its initial emergence is preceded and facilitated by the earlier emergence of the ability to detect statistical cues.

Research highlights

- The current study tested the prediction that the ability to perceive the ordinal position of a sequence element – an ability critical to many cognitive and motor functions – is based on a domain-general perceptual mechanism and, thus, that it emerges prior to the emergence of language.
- Results from Experiment 1 showed that 4-month-old infants do not perceive the invariant ordinal position of a single element in a sequence of moving/impacting objects because they attend to inconsistent statistical cues but that 6-month-old infants can ignore the statistical cues and, thus, can perceive ordinal invariance.
- Results from Experiment 2 showed that 6- and 8-month-old infants do not perceive the invariant relative ordinal position of two adjacent elements, despite the availability of correlated statistical cues, but that 10-month-old infants do and that they depend on statistical cues to accomplish this task.
- Together, the results show that the developmental emergence of ordinal sequence perception skills occurs prior to the acquisition of language and that this is preceded and facilitated by the earlier-emerging ability to detect statistical sequential cues.

Introduction

Speech, language, music, and behavioral action all depend in large part on the specific way in which the basic components that constitute them are sequentially organized (Keele, Ivry, Mayr, Hazeltine & Heuer, 2003; Lashley, 1951; Martin, 1972; Zacks & Tversky, 2001). For example, the sentence ‘The boy hit the girl’ has a very different meaning from the sentence ‘The girl hit the boy’. Similarly, a particular set of musical notes yields different melodies depending on the specific sequential arrangement of the notes. Finally, complex action sequences such as a tennis serve, playing an instrument, or typing on a keyboard all depend on our ability to correctly sequence a series of actions. As these examples illustrate, sequences are fundamental to perception and action. If so, it would be highly adaptive if the ability to perceive and learn them emerged as early as possible in human development.

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Perception of sequences depends, by default, on the perception of temporal information. Therefore, the development of temporal perception must precede the development of sequence perception. Indeed, evidence indicates that starting at birth infants exhibit a perceptual sensitivity to temporal information and that the ability to perceive various aspects of temporal structure improves rapidly during infancy (Lewkowicz, 1989, 2000, 2012). For example, studies have found that newborn infants can distinguish between different language classes on the basis of their rhythmic/prosodic attributes (Nazzi, Bertoncini & Mehler, 1998) and that infants as young as 2 months of age can perceive the rhythmical characteristics of auditory patterns (Chang & Trehub, 1977a, 1977b; Demany, McKenzie & Vurpillot, 1977; Demany, 1982; Trehub & Thorpe, 1989). In addition, studies have found that infants as young as 4 months of age can perceive the temporal features of auditory, visual, and audiovisual sequences (Brandon & Saffran, 2011; Lewkowicz, 1988a, 1988b, 1992b, 2003; Lewkowicz & Marcovitch, 2006; Pickens & Bahrick, 1997) and that they can perceive the relationship between auditory and visual information on the basis of temporal information (Allen *et al*., 1977; Lewkowicz, 1986, 1992a, 2010; Mendelson, 1986; Scheier, Lewkowicz & Shimojo, 2003). Finally, it has been found that temporal discrimination increases in precision during infancy (Brannon, Suanda & Libertus, 2007).

Given that infants are sensitive to temporal information from an early age, it is not surprising that they also exhibit an early ability to perceive and learn sequences and their structure. Importantly, however, this does not mean that they are capable of perceiving and learning complex sequential structure. For example, it is not until the second year of life that children become capable of learning complex seriated sets that depend on an understanding of the concepts of reversibility and hierarchical structure (Fragaszy, Galloway, Johnson-Pynn & Brakke, 2002). Overall, the extant evidence indicates that infants are capable of perceiving and learning two basic sequence properties: statistics and simple syntactic rules. The statistics of a sequence specify the transitional probabilities of particular sequence elements (e.g. hearing a particular person's voice leads to the expectation that we will see a particular person walk through the door). In contrast, syntactic rules specify abstract sequential relations between different classes of information (e.g. hearing children's voices makes us expect children, whereas hearing adults' voices makes us expect adults).

With specific regard to statistics, studies have found that infants as young as 2 months of age can learn the underlying statistics of temporally and spatiotemporally organized sequences regardless of whether the sequences consist of nonsense syllables (Gómez, 2002; Gómez & Maye, 2005; Saffran, Aslin & Newport, 1996), musical tones (Saffran, Johnson, Aslin & Newport, 1999), or abstract shapes (Fiser & Aslin, 2002; Kirkham, Slemmer & Johnson, 2002; Kirkham, Slemmer, Richardson & Johnson, 2007; Marcovitch & Lewkowicz, 2009). With specific regard to syntactic rules, studies have found that infants as young as 5 months of age can learn and distinguish between an AAB and an ABA rule (A and B represent different classes of information) when such rules are instantiated by abstract visual shapes and concurrent speech syllables (Frank, Slemmer, Marcus & Johnson, 2009). Other studies have found that infants as young as 7 months of age can learn these same rules when they are specified by syllables (Gerken, 2006; Gómez & Gerken, 1999; Marcus, Vijayan, Rao & Vishton, 1999) and by pictures of dogs or cats (Saffran *et al*., 2007). Considered together, these findings show that infants can perceive and learn sequence statistics and simple syntax and that this ability is domain-general in nature.

The fact that infants as young as 5 months of age can learn rudimentary syntactic rules is especially interesting because it implies that young infants possess a domain-general ability to perceive one specific aspect of sequences, namely the ordinal position of sequence elements. That is, it implies that infants can perceive and learn that sequence elements can occupy a specific position (i.e. first, second, third, etc.) in a sequence. Unfortunately, however, the different types of sequences that have been used to date to study rule learning in infancy (e.g. ABA vs. ABB) can be distinguished by whether reduplication is present or absent and, thus, may reflect learning of identity relations rather than ordinal sequence relations. To be sure, some of the rule learning studies did include experiments in which reduplication learning could not have mediated rule learning. For example, Marcus *et al*. (1999) showed that 7-month-olds can learn the difference between an ABA and ABB grammar specifying strings of syllables as well as the difference between an AAB and an ABB grammar. Whereas the former pair of grammars includes a reduplication difference, the latter pair of grammars does not. Johnson, Fernandes, Frank, Kirkham, Marcus, Rabagliati and Slemmer (2009) also demonstrated that 11-month-olds can learn the rules governing strings of abstract visual shapes and that responsiveness did not rely on reduplication but did not provide evidence that 8-month-old infants can learn such rules in the absence of reduplication. Similarly, Frank *et al*. (2009) demonstrated that 5-month-old infants can learn the rules governing sequences of auditory and visual elements but did not rule out reduplication.

Even though it is currently not clear from the rule learning studies whether and at what age infants begin to perceive ordinal sequence information, one study to date has provided unambiguous and direct evidence of this ability. Gerken (2006) familiarized 9-month-old infants with different sequences of three speech syllables each and then tested for detection of an ordinal position change of one of the sequence elements. Results indicated that the infants detected the ordinal position of a particular sequence element and that they generalized that knowledge to novel sequences. These results show that, at least in the language domain, infants as young as 9 months of age can perceive ordinal sequence information.

Given that the only unambiguous and developmentally earliest evidence of ordinal sequence perception comes from 9-month-old infants, and given that this evidence comes from a study of infant response to linguistic materials, it is still not known when domain-general ordinal sequence perception abilities might first emerge. Two studies that attempted to answer this question investigated responsiveness to different orders of sets of moving abstract shapes and their impact sounds in infants as young as 3 months of age (Lewkowicz, 2004, 2008). Results indicated that infants discriminated the different sequence orders. Unfortunately, the main focus of these studies was the contribution of unisensory vs. multisensory attributes to sequence learning and not the separate roles of statistical and ordinal cues to the perception of serial order. Consequently, statistical cues were allowed to co-vary with ordinal cues and, because of this, it cannot be determined from these results whether infants as young as 3 months of age can perceive ordinal sequence cues *per se*.

To specifically address the question of the relative contribution of statistical and ordinal cues to young infants' response to serial order differences, Lewkowicz and Berent (2009) presented to 4-month-old infants audiovisual sequences similar to those used by Lewkowicz (2004, 2008). This time, however, infants were given the opportunity to encode the sequences in terms of their statistical structure or in terms of their ordinal structure, respectively, while holding the other sequence attribute constant. Findings indicated that the infants detected changes in statistical structure even when it was not accompanied by changes in ordinal structure but that they did not detect changes in ordinal structure when those changes were not accompanied by changes in statistical structure. In other words, young infants appear to attend to statistical rather than to ordinal sequence cues when the two compete for their attention.

When the findings to date on infant response to ordinal sequence cues are considered together they suggest two scenarios. Either, only older infants can perceive ordinal sequence cues and/or their detection is specifically tied to the emergence of relatively advanced language processing abilities. If both are true, then, consistent with the Lewkowicz and Berent (2009) findings, younger infants should not respond to ordinal sequence cues. If, however, the temporal pattern perception mechanisms that emerge early (Lewkowicz, 2012) bootstrap the emergence of domain-general sequence learning mechanisms prior to the emergence of language-based rule-learning mechanisms then relatively young infants should be able to perceive ordinal sequence cues. To test this prediction, Experiment 1 investigated the developmental emergence of the ability to perceive the invariant ordinal position of a single sequence element embedded in a set of dynamic, audiovisual sequences composed of arbitrary objects and sounds. Then, Experiment 2 investigated the limits of this ability by examining the developmental emergence of the ability to perceive a more complex form of ordinal sequential information, namely the perception of the relative ordinal position of two adjacent elements.

Experiment 1

To examine whether infants can perceive the ordinal position of a single target element, in Experiment 1 infants were first habituated to the kinds of sequences depicted in the top portion of Figure 1. As can be seen, each sequence consisted of a single target element (the triangle) and three identical non-target elements. In addition, as can be seen, the set of three non-target elements varied across the habituation trials. Represented in terms of letters, where **B** represents the target element and the other letters represent the non-target elements, the sequences shown in the top of Figure 1 were A**B**AA, C**B**CC, and D**B**DD. The infants' task was to learn the invariant ordinal position of the target element vis-à-vis the non-target elements and, at the same time, ignore the specific pair-wise associations (adjacent and non-adjacent) between the target element and the non-target elements. This design differs in a crucial way from the design of the sequences presented during the habituation phase by Lewkowicz and Berent (2009). In that study, the three different non-target elements were the same across the habituation trials but their ordinal position was varied across the sequences. Consequently, the sequences presented in that study were A**B**CD, C**B**DA, and D**B**AC (the **B** is the target element). As is obvious from a close examination of

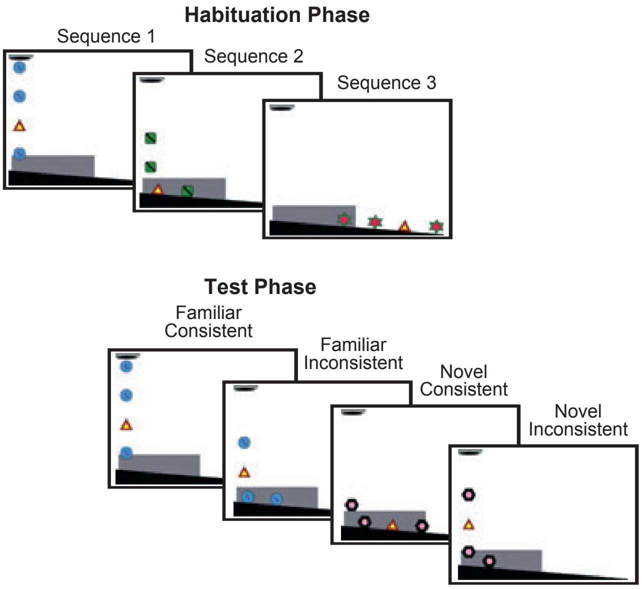

Figure 1 *The sequences and the different objects constituting them presented during the habituation and test phases in Experiment 1 (each unique object had a unique impact sound associated with it). The sets of objects depicted for each respective sequence are deliberately presented in different spatial locations so as to capture the fact that the sequences moved down and across the stimulus display screen.*

these sequences, the total set of unique adjacent and non-adjacent pair-wise associations is larger for these sequences than for the ones presented in the current experiment. The smaller number of statistical associations in the current experiment made it possible to enhance the target's perceptual salience and its ordinal position and made it possible to ask whether this might facilitate 4-month-olds' perception of ordinal information. Of course, it was theoretically possible that the remaining statistical cues might still dominate 4-month-old infants' responsiveness and that the ability to ignore them may not emerge until later. To test this possibility, we tested a group of 6-month-old infants as well.

Method

Participants

Sixty-nine healthy full-term infants, who comprised two separate age groups, were tested. One was a group of 4-month-old infants (N = 34, 17 boys; M age = 16.9 weeks, SD = .65 weeks) and the other was a group of 6-month-old infants (N = 35, 17 boys; M age = 25.9 weeks, SD = .61 weeks). Twelve additional infants were tested but did not contribute usable data because of fussing (seven infants), inattentiveness (four infants), and experimenter error (one infant).

Apparatus and stimuli

All stimulus events were presented as multimedia movies. One of these movies, whose purpose was to attract the infants' attention to the stimulus-presentation monitor, showed an attention-getter that consisted of a continuously and silently expanding and contracting green disk. A second movie, that was used for the Pre- and Post-test trials, was a segment of a Winnie-the-Pooh cartoon (presented at 70–74 dB SPL; ambient sound pressure level of 50 dB). The remaining eight movies were designed to investigate sequence perception and learning. Here, infants could see and hear a series of objects moving and making impact sounds.

Figure 1 shows the types of objects presented during the habituation and test phases of the sequence movies for one of the two groups of infants and the motion path that the objects followed as they moved during a single event cycle. In three of the habituation-phase movies, the target object (Object B – triangle) and one of three other objects (either Object A – button, Object C – square, or Object D – star), respectively, were arranged in a sequence such that the target object and its impact sound were always presented in the second ordinal position. This can be seen in the top portion of Figure 1 where the sequences presented during the habituation phase for one group of infants are depicted. The other three habituation-phase movies that were presented to the other group of infants were identical except that the target object and its impact sound were presented in the third ordinal position across the three movies.

The two remaining movies – depicted in the bottom portion of Figure 1 and labeled 'Novel Consistent' and 'Novel Inconsistent' – were presented during the test phase and were designed to examine generalization of learning. These movies presented a series of novel non-target objects (Object E – a hexagon) and their impact sounds (a bouncing basketball) together with the same target stimulus and its impact sound as in the other six movies.

For all sequence movies, each cycle consisted of the following set of events. The objects emerged one after the other from the spout at the top of the screen, moved down, passed in front of the grey rectangle as they reached the bottom of their downward trajectory, made an impact sound as they contacted the black ramp, turned to the right without stopping and continued to move to the right until they came together at the far end of the screen. They rested there briefly before disappearing. The impact sounds were digital recordings of the following auditory events: 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 hitting against a metal pot; and Object D – a light bulb breaking. All movies were presented on a 17-inch computer monitor at a distance of 50 cm from the infant in a dimly lit, sound-attenuated, single-wall testing chamber (iModules Software, Overland Park, KS). Most infants were seated alone in an infant seat except for those few who refused. These infants were seated in the parent's lap and the parent was blind with respect to the hypothesis under test, wore headphones while listening to white noise during the test, and was instructed to sit as still as possible and not interact with the baby. The impact sounds were 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 located outside the testing chamber was located on top of the stimulus-presentation monitor.

Each movie began with the simultaneous appearance of the spout, the ramp, and the grey rectangle. The four objects then began to emerge one after the other 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 then 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 an 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. The experimenter was seated outside the testing chamber and, thus, could neither see nor hear the stimuli being presented. While observing the infant on the video monitor, the experimenter activated the presentation of a movie via a mouse click whenever the infant looked at the stimulus-presentation monitor; whenever the infant looked away from the monitor for more than 1 second, or whenever he or she accumulated a total of 55 s of looking time, the experimenter stopped pressing the mouse button and the movie presentation ended. At this point, the attention-getter appeared. The amount of time that the mouse button was depressed during movie presentation was recorded and constituted the duration of looking during a particular trial.

The experiment consisted of a single Pre-test trial (when the Winnie-the-Pooh cartoon was presented), a habituation phase, a test phase, and a single Post-test trial (when the cartoon was presented again). Habituation trials continued until 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. Once this criterion was met, the habituation phase ended and the test phase began. Table 1 shows the sequences presented during the habituation and test phases for each of the two habituation groups. As can be seen, the three sequences presented during the habituation phase were identical in terms of the ordinal position of the target object and its impact sound but differed in terms of the specific non-target objects and their impact sounds.

Table 1 also shows that the target object and its impact sound were presented in an invariant second ordinal position for one group of infants and in an invariant third ordinal 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. This trial was presented first to permit evaluation of the possible effect of spontaneous regression to the mean during the test phase. 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 element in the familiar sequence context and, thus, assessed whether infants learned its specific ordinal position in

Table 1 *Design of Experiment 1. The various letters in the table designate the different objects and their corresponding impact sounds (see Methods section for more details). Shown are the specific sequences presented to each of two groups of infants during the habituation phase. Also shown are the test sequences presented to one of the three subgroups of infants in each habituation group*

	Habituation Group 1	Habituation Group 2
Habituation		
Trial 1	A**B**AA	AA**B**A
Trial 2	C**B**CC	CC**B**C
Trial 3	D**B**DD	DD**B**D
Test trials		
Familiar Consistent	A**B**AA	AA**B**A
Familiar Inconsistent	AA**B**A	A**B**AA
Novel Consistent	E**B**EE	EE**B**E
Novel Inconsistent	EE**B**E	E**B**EE

the familiar context. The Novel Consistent test trial involved presentation of the familiar target element in its familiar position but in the context of all new non-target elements. Finally, the Novel Inconsistent test trial involved a change in the ordinal position of the familiar target element but again in the context of new non-target elements. Together, the Novel Consistent and Novel Inconsistent test trials assessed whether infants could generalize their knowledge of the ordinal position of the target element to a novel sequence context.

Results and discussion

First, a preliminary analysis was carried out to determine whether any infants exhibited spontaneous regression to the mean in the Familiar Consistent test trial. This was defined as looking duration greater than 2 standard deviations above the mean for that test trial. Five 4-month-old infants and two 6-month-old infants exhibited spontaneous regression and, as a result, their data were excluded from further analyses. The remaining data from the four test trials were submitted to a 2 × 2 × 2 (Age × Context × Consistency) repeated-measures analysis of variance (ANOVA), with Age (4 and 6 months) as the between-subjects factor and Context (Familiar, Novel) and Consistency (Consistent, Inconsistent) as the within-subjects factors. The results of this analysis yielded a significant Context × Consistency interaction, $F(1, 67) = 4.6$, $p < .05$, and no other effects. This interaction indicates that infants responded differently to ordinal position changes in the familiar and novel sequence contexts.

Despite the fact that an interaction between Age and either of the other two factors was not found, an inspection of the results from the test trials (see Figure 2) indicated that the response profile of the two age groups was different in the Familiar Context test trials. As can be seen in Figure 2, the 4-month-old infants did not appear to exhibit response recovery in the Familiar Context trials, whereas the 6-month-old infants did. Planned comparison tests at each age confirmed this difference. That is, a comparison of responsiveness in the Familiar Consistent test trial versus responsiveness in the Familiar Inconsistent test trial showed that the 4-month-old infants did not exhibit significant response recovery in the latter trial, $F(1, 67) = 0.78$, *ns*, but that the 6-month-old infants did, $F(1, 67) = 4.30$, $p < .05$. To determine whether infants generalized learning to a novel sequence context, the data from the two Novel Context test trials were compared via planned comparison tests. These comparisons showed that neither age group exhibited response recovery (Novel Consistent vs. Novel Inconsistent contrast, $F(1, 67) = 0.12$, *ns*, for the 4-month-olds; $F(1, 67) = 2.96$, *ns*, for the 6-month-olds). The absence of significant response recovery in the Novel Context test trials is not surprising in the 4-month-olds given that these infants did not detect a change in the ordinal position of the target sequence element in the Familiar Context test trials. In contrast, the absence of significant response recovery in the Novel Context test trials in the 6-month-olds indicates that these infants did not generalize their learning of ordinal position information to a novel sequence context.

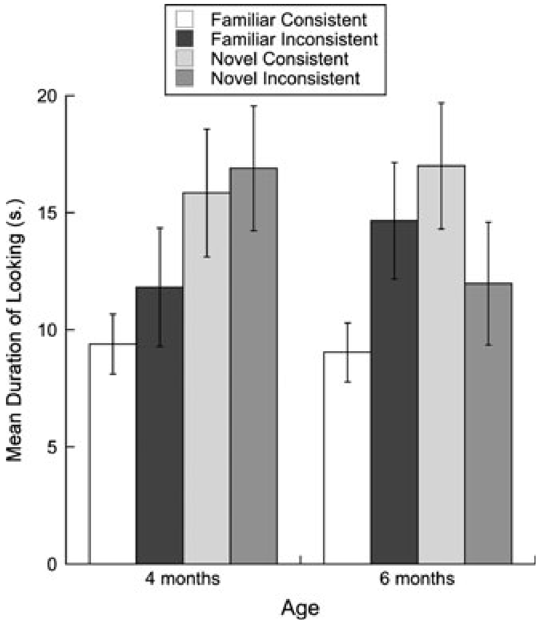

Figure 2 *Mean duration of looking in the four types of test trial in Experiment 1. Error bars indicate the standard error of the mean.*

Additional analyses were conducted to rule out the possibility that (a) response differences during the habituation phase might have contributed to different outcomes at the two ages and/or (b) that fatigue effects might have played a role in test-trial responsiveness. The first of these analyses compared the data from the first four and last four habituation trials at each age by way of a 2 × 8 (Age x Trials) repeated-measures ANOVA, with Age as the between-subjects factor and Trials as the within-subjects factor. Results indicated that the Trials factor was significant, $F(7, 469) = 85.8$, $p < .001$, but that the Age × Trials interaction was not significant. This shows that, regardless of their age, infants habituated to the sequences in a similar fashion and, thus, rules out the possibility that differential performance during the encoding phase of the experiment accounted for test-trial performance differences.

The second analysis was aimed at determining whether fatigue effects might have played a role in the 4-month-olds' failure to detect ordinal position changes or that ceiling effects might have prevented the 6-month-olds from generalizing ordinal position learning. To rule out fatigue effects at 4 months, the duration of looking in the Novel Consistent trial was compared to the duration of looking in the Familiar Consistent trial. This comparison indicated that the 4-month-olds detected the context change, $F(1, 67) = 5.15$, $p < .05$. Furthermore, the durations of looking in the Post-test trial and the Novel Inconsistent test trial were compared because the cartoon presented in the Post-test trial can be considered to be even more novel than the novel sequence presented in the Novel Inconsistent test trial. To perform this comparison, the overall ANOVA of the test trials was conducted again except that this time the data from the Post-test trial were included and then this was followed by the planned comparison of interest. This comparison indicated that the 4-month-olds detected the novelty in the Post-test trial, $F(1, 67) = 87.5$, $p < .001$. In fact, the 4-month-old infants' duration of looking score in the Post-test trial was three times as long (Mean = 48.9 s) as in the Novel Inconsistent test trial. These comparisons make it clear that fatigue effects cannot account for the 4-month-olds' failure to detect ordinal position differences nor for their failure to generalize. Finally, the failure of the 6-month-olds to exhibit evidence of generalization of learning was neither due to fatigue nor to a ceiling effect because their response in the Post-test trial was significantly higher than in the Novel Inconsistent trial, $F(1, 67) = 70.6$, $p < .001$. In fact, the 6-month-olds looked nearly four times longer in the Post-test trial (Mean = 40.3 s) than in the Novel Inconsistent test trial.

Overall, the results from Experiment 1 indicate that the ability to detect a change in the ordinal position of a target element in the context of familiar non-target elements is absent at 4 months of age and that it emerges by 6 months of age. Importantly, the 6-month-old infants' newly emerged ability could not have been based on responsiveness to statistical cues for two reasons. First, the statistical cues available in this experiment were in direct conflict with ordinal cues. Second, successful detection of the ordinal cues required infants to actively ignore the statistical cues that were available. Interestingly, the current data also indicate that when the ability to detect simple ordinal relations first emerges, it is limited to the detection of such relations within a familiar sequence context. This is evident in the fact that the 6-month-olds did not generalize their learning of ordinal position information to a novel sequence context.

Experiment 2

Experiment 1 indicated that detection of the ordinal position of a single sequence element embedded in moving audiovisual sequences emerges by 6 months of age. Although the detection of this type of information is relatively simple, its emergence as late as 6 months of age suggests that it is relatively difficult for infants. Nonetheless, the fact that infants become capable of perceiving and learning this sequence property by 6 months means that they can now begin to discover more complex ordinal position relations such as, for example, the relative ordinal relation between adjacent sequence elements. Adjacent ordinal relations play an important role in our everyday life. For example, in English, one must learn that articles precede nouns and that helping verbs precede verbs. The opposite relative order is not permissible.

Although there is little doubt that detection and learning of rules that govern invariant adjacent ordinal relations is cognitively more demanding, developmentally this can be accomplished by relying initially on statistics. That is, the initial discovery of adjacent sequential relations within specific sequences can be facilitated by the detection of adjacent forward and backward statistics. Given that the forward and the backward transitional probability between two ordinally related sequence elements in a particular sequence is always 1.0, when the relative order of the two elements changes (i.e. the first element becomes the second and the second element becomes the first), the change is also cued by a change in the forward and backward statistics of each element. As Lewkowicz and Berent (2009) have shown, young infants take advantage of statistical cues in sequence learning tasks. Moreover, the combined results from the Lewkowicz and Berent (2009) study and Experiment 1 suggest that the early emerging ability to perceive statistical cues helps bootstrap the subsequent emergence of the perception of ordinal sequence cues. Therefore, given the reasonable assumption that detection and learning of adjacent ordinal relations is more difficult, it is likely that this ability emerges later in infancy. In addition, when this ability first emerges it is likely that it depends on sequence statistics.

To test these predictions, groups of 6-, 8-, and 10-month-old infants were tested with dynamic, audiovisual sequences similar to those presented in Experiment 1 except that here the task was to learn the relative ordinal relation of two adjacent sequence elements. Moreover, because infants are sensitive to backward as well as forward statistics (Pelucchi, Hay & Saffran, 2009), the sequences presented here were designed in such a way that forward and backward statistics were available to facilitate detection of adjacent ordinal relations.

Method

Participants

In total, 77 healthy full-term infants, who comprised three separate age groups, were tested. One was a group of 6-month-old infants (*N* = 27; 15 boys; *M* age = 26 weeks, *SD* = .79 weeks), the second was a group of 8-month-old infants (*N* = 24; 12 boys; *M* age = 34.3 weeks, *SD* = 1 week), and the third was a group of 10-month-old infants (*N* = 26; 13 boys; *M* age = 43.1 weeks, *SD* = .66 weeks). Eight additional infants were tested but did not contribute usable data because of fussing (one infant), distraction (two infants), inattentiveness (three infants), and experimenter error (two infants).

Apparatus and stimuli

The apparatus and stimuli were identical to those used in Experiment 1 with the following exceptions. In this experiment, sequences were composed of five audiovisual elements. Figure 3 shows the objects presented during the habituation and test phases for one of the two groups of infants and the motion path that the objects followed as they moved during a single event cycle. As can be seen, there were two target elements (Object B – the triangle and the sound of a wooden spoon hitting against a small empty plastic container during impact, and Object C – the square and the sound of a wooden spoon hitting a metal pot). The three non-target elements consisted of identical objects and their impact sounds (Object A – the button and the sound of a metal object hitting a glass bottle). As can be seen in Figure 3, the five objects and their impact sounds were arranged such that the target objects and their impact sounds were always presented adjacent to one another. This can be seen in the top portion of Figure 3 where a schematic of the three types of movies presented during the habituation phase for one group of infants is depicted. As can also be seen, the absolute ordinal position of both target elements varied across the three different habituation sequences. To control for primacy effects, neither target element was presented in the first ordinal position. The three habituation movies that were presented to the other group of infants were identical except that the relative ordinal positions of the two target elements were reversed.

Procedure

The procedure was identical to that used in Experiment 1. Table 2 shows the sequences presented during the habituation and test phases. As can be seen, the test phase only included a Consistent and an Inconsistent test trial. The reason that no generalization test trials were given in this experiment was because generalization was not expected. Generalization would only be expected if infants were able to ignore statistics. As indicated earlier, however, the data from the Lewkowicz

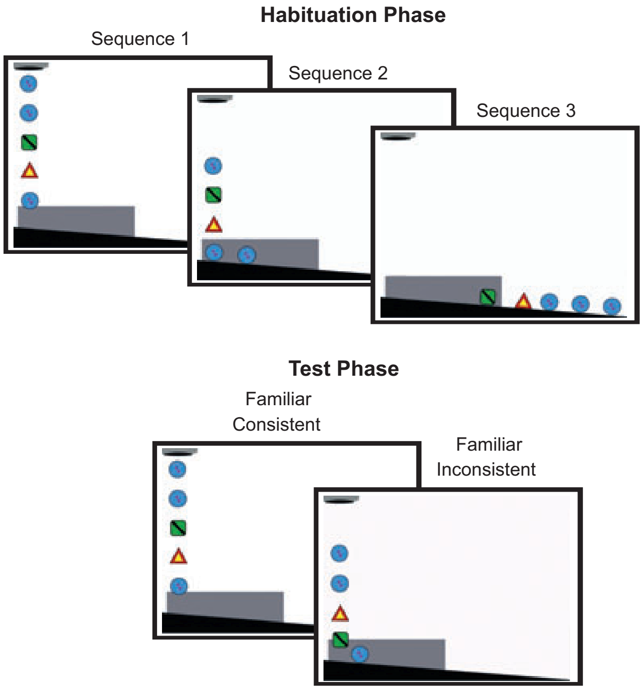

Figure 3 *The sequences and the different objects constituting them presented during the habituation and test phases in Experiment 2 (each unique object had a unique impact sound associated with it). The sets of objects depicted for each respective sequence are deliberately presented in different spatial locations so as to capture the fact that the sequences moved down and across the stimulus display screen.*

Table 2 *Design of Experiment 2. The various letters in the table designate the different objects and their corresponding impact sounds (see Methods section for more details). Shown are the specific sequences presented to each of two groups of infants during the habituation phase. Also shown are the test sequences presented to one of the three subgroups of infants in each habituation group*

	Habituation Group 1	Habituation Group 2
Habituation		
Trial 1	A**BC**AA	A**CB**AA
Trial 2	AA**BC**A	AA**CB**A
Trial 3	AAA**BC**	AAA**CB**
Test trials		
Consistent	A**BC**AA	A**CB**AA
Inconsistent	A**CB**AA	A**BC**AA

and Berent (2009) study and Experiment 1 suggest that when infants are initially discovering ordinal sequence relations, they rely on statistics. Thus, there would be little reason to expect that infants would generalize learning of adjacent ordinal relations when they first discover them.

The first test trial for all infants was the Consistent test trial during which one of the three sequences that was presented during the habituation phase was presented again to one of three subgroups of infants. The bottom of Table 2 shows the specific sequences presented during the two test trials for one of the three subgroups. As can be seen, for this subgroup, the target elements were presented in the second and third ordinal positions within the sequence. For the other two subgroups (not shown in Table 2), the target elements were presented in the third and fourth position, and in the fourth and fifth position, respectively. Following presentation of the Consistent test trial, infants received the Inconsistent test trial where the target elements were again presented in the same absolute sequential position as during the Consistent test trial but with the relative ordinal position of the two target elements reversed.

Results and discussion

The preliminary analysis to determine whether any infants exhibited spontaneous regression to the mean in the Consistent test trial indicated that two 6-month-old, one 8-month-old, and two 10-month-old infants exhibited regression. The data from these infants were excluded from further analyses. The test trial data from the remaining infants were then submitted to a 3 × 2 (Age × Consistency) ANOVA, with Age (6, 8, and 10 months) as the between-subjects factor and Consistency (Consistent, Inconsistent) as the within-subjects factor. Results yielded a significant Age × Consistency interaction, $F(2, 69) = 3.39$, $p < .05$, and no other effects. This interaction indicates that infants responded differently to relative ordinal position changes across age (see Figure 4). To identify the source of these differences, planned comparison analyses were conducted at each age, respectively. These analyses indicated that the 6-month-old infants did not exhibit greater looking in the Inconsistent test trial, $F(1, 69) = 0.18$, *ns*, and that the 8-month-olds did not either, $F(1, 69) = 0.0$, *ns*. In contrast, the analyses showed that the 10-month-old infants did exhibit significantly greater looking in the Inconsistent test trial, $F(1, 69) = 8.93$, $p < .01$. Together, these results demonstrate that neither the 6- nor the 8-month-old infants perceived and learned the invariant relative ordinal position information but that the 10-month-old infants did.

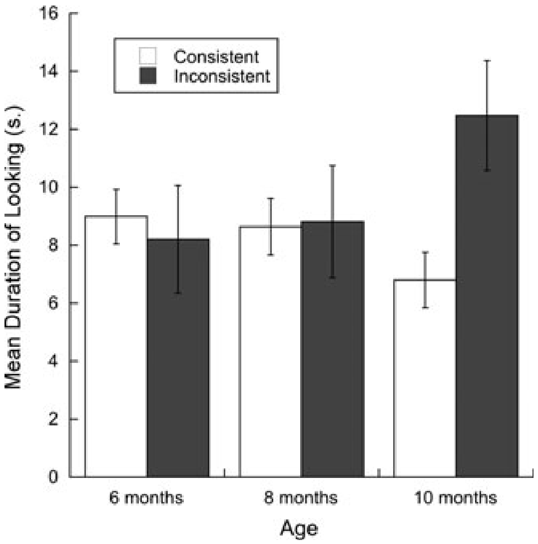

Figure 4 *Mean duration of looking in the test trials in Experiment 2. Error bars indicate the standard error of the mean.*

To rule out the possibility that differences in encoding during the habituation trials and/or fatigue during the test trials might have been responsible for the 6- and 8-month-old infants' failure to exhibit evidence of learning and discrimination, two separate analyses were performed. First, responsiveness during the habituation trials was compared across the three age groups by way of a 3 × 8 (Age, Trials) repeated-measures ANOVA, with Age as the between-subjects factor and Trials as the within-subjects factor. Results indicated that there was a main effect of Trials, $F(7, 483) = 85.8$, $p < .001$, indicating that all infants exhibited habituation. Importantly, the Age × Trials interaction was not significant, $F(14, 483) = 1.46$, *ns*, indicating that the failure of the two youngest age groups to exhibit learning and discrimination could not have been due to differences in responsiveness during the learning phase. The second analysis consisted of planned comparisons of responsiveness in the Consistent and Post-test trials at each of the two youngest ages, respectively. These comparisons were based on a 3 × 3 (Age, Test Trials) ANOVA of the test trial data that this time included the Post-test trial data. The planned comparisons indicated that the 4-month-old infants looked longer in the Post-test trial, $F(1, 69) = 117.6$, $p < .001$, and that the 6-month-old infants did so as well, $F(1, 69) = 66.5$, $p < .001$. These findings show that the 6- and the 8-month-old infants were not fatigued which, in turn, indicates that the absence of response recovery in the Inconsistent test trial in both of these age groups reflects a failure to detect and learn relative ordinal position information.

When the results from the three age groups are considered together, they indicate that the ability to perceive the invariant relative ordinal position of two adjacent sequence elements emerges by 10 months of age. Follow-up analyses showed that, regardless of age, infants responded in a similar fashion during the habituation trials. This rules out the possibility that differential performance during the encoding phase of the experiment might have accounted for differences in response during the test trials. Follow-up analyses also indicated that fatigue effects could not have accounted for the 6- and 8-month-old infants' failure to perceive the relative ordinal information. Finally, it should be noted that the 10-month-old infants' successful performance cannot be attributed to primacy effects because the target elements were never presented in first sequence position.

The successful detection of relative ordinal relations by the 10-month-old infants raises interesting questions about how they accomplished this task. A close examination of Figure 3 and Table 2 reveals that several transitional probabilities were correlated with the targets' ordinal positions, both with respect to each other and with respect to the non-target elements during the habituation phase. Keeping in mind that the objects appeared at the top of the screen and then moved down until each produced its impact sound, the first informative transitional probability is the forward one between the first target element (the triangle and its sound) and the non-target element (the button and its sound) that precedes it and is equal to 1.0. The next two are the backward transitional probability between the first target element and the second one (1.0) and the forward transitional probability (1.0) between the second target and the first one. The backward transitional probability between the second target element and a non-target element is only predictive in two out of the three habituation sequences (0.67). Thus, when the ordinal position of the two target elements changed in the Inconsistent test trial for this group of infants, forward and backward transitional probabilities signaled the change. What makes the current findings especially interesting is that statistics alone were not sufficient for the 6- nor the 8-month-old infants to perceive the relative ordinal information. This suggests that the usefulness of statistical cues in sequence processing tasks depends, in part, on the complexity of the task.

General discussion

The current study investigated the prediction that the ability to detect the ordinal position of a sequence element is based on a domain-general perceptual mechanism and that, as a result, this ability emerges prior to language. The findings confirmed this prediction and also indicated that the initial emergence of the ability to detect ordinal position information is preceded and facilitated by the earlier emergence of the ability to detect statistical cues. To test the domain-general nature of this ability, the sequences presented here consisted of a series of abstract moving/impacting objects. Two specific questions were addressed in this study. In Experiment 1, the question was: when does the ability to perceive the invariant ordinal position of a single sequence element emerge? In Experiment 2, the question was: when does the ability to perceive the relative ordinal position of two adjacent sequence elements emerge? Experiment 1 indicated that 4-month-old infants do not detect the invariant ordinal position of a single sequence element but that 6-month-old infants do and, thus, showed that this particular ability emerges by 6 months of age. Experiment 2 indicated that neither 6- nor 8-month-old infants detected the invariant relative ordinal position of two adjacent sequence elements but that 10-month-old infants did.

The failure of the 4-month-old infants in Experiment 1 to detect the ordinal position of a single sequence element is consistent with prior results from studies in which infants' response to sequence order was tested with similar, spatially dynamic, audiovisual sequences (Lewkowicz, 2004, 2008; Lewkowicz & Berent, 2009). The findings from Lewkowicz and Berent (2009) are especially relevant in the present context. These investigators found that 4-month-old infants detected the ordinal position change of a target element when the change was accompanied by differential statistical cues that were consistent with that change (in Experiment 1 of that study) but not when statistical cues were not informative with regard to an ordinal position change (in Experiment 3 of that study). Similarly, in Experiment 1 in the current study 4-month-old infants failed to perceive the ordinal position of the target element but here it was because the statistical cues were in direct conflict with the ordinal position cues. In other words, in this experiment infants were unable to ignore the specific sequence statistics and, as a result, failed to detect ordinal position information. The fact that they could not ignore sequence statistics adds to the previous results (Lewkowicz, 2004, 2008; Lewkowicz & Berent, 2009) and shows that 4-month-olds fail to detect ordinal sequence cues both when statistical cues are absent or when they conflict directly with ordinal cues. Unlike the 4-month-olds, the 6-month-olds did successfully detect the ordinal cues in Experiment 1. This indicates that by this age infants are able to ignore sequence statistics and that they can do so even when they conflict directly with ordinal cues. Together, the findings from the two age groups indicate that reliance on statistical sequence cues declines between 4 and 6 months of age. In addition, however, the findings indicate that the newly emerged ability to detect ordinal position information is limited to familiar sequences because infants did not generalize their learning to novel sequences.

Experiment 2 extended the findings from Experiment 1 by showing that the ability to detect and learn more complex sequential relations, namely the relative ordinal relation between two adjacent target elements, does not emerge until 10 months of age. In this experiment, infants were habituated to a set of three different sequences and their task was to encode the invariant ordinal relation between two adjacent target elements. It is important to note that the task in Experiment 2 did not require infants to encode a rule. That is, the target elements were the same across the habituation trials and, thus, even though infants were required to encode the invariant relation between two different sequence elements, they did not have to do this at the category level. Moreover, because the two target elements were the same across different sequences, infants could take advantage of forward and backward statistics which clearly differentiated between the two different ordinal relations. That is, unlike in Experiment 1, here statistical cues facilitated detection of ordinal cues rather than prevented their detection. This design feature was incorporated deliberately into Experiment 2 based on the theoretically reasonable expectation that detection and encoding of relative adjacent relations of two abstract audiovisual sequence elements would be relatively difficult for infants. Indeed, the findings from Experiment 2 supported this theoretical expectation in that neither 6- nor 8-month-old infants detected and encoded adjacent ordinal relations. Only the 10-month-old infants did. Thus, detection of a fairly complicated set of forward and backward statistics marking the relative ordinal position of two sequence elements is too difficult for infants younger than 10 months of age.

Overall, the data from both experiments suggest an interesting developmental scenario. Initially, when infants begin to learn sequential relations, they rely on sequence statistics because learning them only requires the detection of associations among individual elements. As noted by Saffran *et al*. (2007), this is a relatively easy task because it is mediated by a domain-general mechanism. The advantage of such a mechanism is that it permits the learning of associations over a broad class of stimuli, including abstract ones, and therefore can facilitate the discovery of higher-level sequence attributes (e.g. ordinal, rule-bound, hierarchical). Once infants discover these higher-level attributes, they become capable of generalizing their learning at the category level and, as a result, the need for learning identity relations based on statistical cues declines. Crucially, the data from this study suggest that infants' reliance on statistical cues does not decline at one particular age; rather, the age at which its use declines depends on task complexity. The data from this study show that the greater the complexity of the task, the later into development infants rely on statistics to bootstrap their discovery of higher-level sequence attributes.

The present study is the first to provide evidence of ordinal cue processing in infants as young as 6 months of age – when the cues specify the ordinal position of a single sequence element – and in infants as young as 10 months of age – when the cues specify the relative ordinal position of two sequence elements. With the exception of one study (Gerken, 2006), no studies to date have provided unambiguous evidence that infants can extract the ordinal position information of either a single sequence element or of multiple elements. Previous studies have demonstrated that infants can learn adjacent as well as non-adjacent statistical relations (Fiser & Aslin, 2002; Gómez, 2002; Gómez & Maye, 2005; Kirkham *et al*., 2002; Marcovitch & Lewkowicz, 2009; Saffran *et al*., 1996; Saffran *et al*., 1999), that they can learn rudimentary grammatical rules (Frank *et al*., 2009; Gerken, 2006; Marcus *et al*., 1999; Marcus, Fernandes & Johnson, 2007; Saffran *et al*., 2007), and that they can detect serial order differences (Lewkowicz, 2004, 2008; Lewkowicz & Berent, 2009). None of these studies, however, have shown that infants younger than 9 months of age can extract ordinal information *per se*.

It is interesting to note that even though the design of Experiment 1 was similar to that of Experiment 2 in the Gerken (2006) study, no evidence of generalization was found despite the fact that 6-month-olds successfully learned and discriminated the ordinal position of a target element in a familiar sequence context. One possible reason for this difference might be that the infants in Experiment 1 were 3 months younger than those in the Gerken (2006) study. This difference may either reflect younger infants' inability to generalize non-speech ordinal information or it may reflect a general inability to generalize learning of any type of ordinal information earlier in infancy. As noted earlier, studies to date have not specifically tested younger infants' ability to detect the ordinal position of speech syllables in the absence of reduplication cues. Therefore, if it is ultimately found that 6-month-old infants can also generalize sequences composed of audible-only speech syllables then the failure to obtain generalization in Experiment 1 would reflect a limitation in the generalization of non-speech ordinal information. This would argue for the special status of speech.

Regardless of the ultimate answer to the generalization question, the results from Experiment 1 make it clear that by 6 months of age infants possess a domain-general ability to extract the invariant ordinal position of a single audiovisual sequence element. The results from Experiment 2 indicate that this domain-general ability extends to the perception of the invariant ordinal relation of two sequence elements. Importantly, however, the findings from Experiment 2 show that this ability does not emerge until 10 months of age and that when it first emerges it depends on the detection of correlated statistical cues. The latter fact demonstrates that the newly emerged ability to process more complex ordinal relations at 10 months of age is relatively immature and suggests that it undergoes further development thereafter. This developmental scenario raises interesting questions for future research. For example, at what point in development does reliance on statistical cues for the detection of relative ordinal relations cease and when does the ability to generalize knowledge of such relations emerge? Regardless of the answers to these questions, there is little doubt that the domain-general sequence perception skills found here provide the early foundation for a fundamental aspect of human behavior.

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References

Allen, T.W., Walker, K., Symonds, L., & Marcell, M. (1977). Intrasensory and intersensory perception of temporal sequences during infancy. *Developmental Psychology*, **13**, 225–229.

Brandon, M., & Saffran, J.R. (2011). Apparent motion enhances visual rhythm discrimination in infancy. *Attention, Perception, & Psychophysics*, **73** (4), 1016–1020.

Brannon, E.M., Suanda, S., & Libertus, K. (2007). Temporal discrimination increases in precision over development and parallels the development of numerosity discrimination. *Developmental Science*, **10** (6), 770–777.

Chang, H.W., & Trehub, S.E. (1977a). Auditory processing of relational information by young infants. *Journal of Experimental Child Psychology*, **24** (2), 324–331.

Chang, H.W., & Trehub, S.E. (1977b). Infants' perception of temporal grouping in auditory patterns. *Child Development*, **48** (4), 1666–1670.

Demany, L. (1982). Auditory stream segregation in infancy. *Infant Behavior and Development*, **5** (3), 261–276.

Demany, L., McKenzie, B., & Vurpillot, E. (1977). Rhythm perception in early infancy. *Nature*, **266** (5604), 718–719.

Fiser, J., & Aslin, R.N. (2002). Statistical learning of new visual feature combinations by infants. *Proceedings of the National Academy of Sciences, USA*, **99** (24), 15822–15826.

Fragaszy, D.M., Galloway, A.T., Johnson-Pynn, J., & Brakke, K. (2002). The sources of skill in seriating cups in children, monkeys and apes. *Developmental Science*, **5** (1), 118–131.

Frank, M.C., Slemmer, J.A., Marcus, G.F., & Johnson, S.P. (2009). Information from multiple modalities helps 5-month-olds learn abstract rules. *Developmental Science*, **12**, 504–509.

Gerken, L. (2006). Decisions, decisions: infant language learning when multiple generalizations are possible. *Cognition*, **98** (3), B67–B74.

Gómez, R.L. (2002). Variability and detection of invariant structure. *Psychological Science*, **13** (5), 431–436.

Gómez, R.L., & Gerken, L. (1999). Artificial grammar learning by 1-year-olds leads to specific and abstract knowledge. *Cognition*, **70** (2), 109–135.

Gómez, R.L., & Maye, J. (2005). The developmental trajectory of nonadjacent dependency learning. *Infancy*, **7** (2), 183–206.

Johnson, S.P., Fernandes, K.J., Frank, M.C., Kirkham, N., Marcus, G.F., Rabagliati, H., & Slemmer, J.A. (2009). Abstract rule learning for visual sequences in 8- and 11-month-olds. *Infancy*, **14**, 2–18.

Keele, S.W., Ivry, R., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The cognitive and neural architecture of sequence representation. *Psychological Review*, **110** (2), 316–339.

Kirkham, N.Z., Slemmer, J.A., & Johnson, S.P. (2002). Visual statistical learning in infancy: evidence for a domain general learning mechanism. *Cognition*, **83** (2), B35–B42.

Kirkham, N.Z., Slemmer, J.A., Richardson, D.C., & Johnson, S.P. (2007). Location, location, location: development of spatiotemporal sequence learning in infancy. *Child Development*, **78** (5), 1559–1571.

Lashley, K.S. (1951). The problem of serial order in behavior. In L.A. Jeffress (Ed.), *Cerebral mechanisms in behavior: The Hixon symposium* (pp. 123–147). New York: Wiley.

Lewkowicz, D.J. (1986). Developmental changes in infants' bisensory response to synchronous durations. *Infant Behavior and Development*, **9** (3), 335–353.

Lewkowicz, D.J. (1988a). Sensory dominance in infants: I. Six-month-old infants' response to auditory-visual compounds. *Developmental Psychology*, **24** (2), 155–171.

Lewkowicz, D.J. (1988b). Sensory dominance in infants: II. Ten-month-old infants' response to auditory-visual compounds. *Developmental Psychology*, **24** (2), 172–182.

Lewkowicz, D.J. (1989). The role of temporal factors in infant behavior and development. In I. Levin & D. Zakay (Eds.), *Time and human cognition: A life-span perspective* (pp. 9–62). Amsterdam: North-Holland.

Lewkowicz, D.J. (1992a). Infants' response to temporally based intersensory equivalence: the effect of synchronous sounds on visual preferences for moving stimuli. *Infant Behavior and Development*, **15** (3), 297–324.

Lewkowicz, D.J. (1992b). Infants' responsiveness to the auditory and visual attributes of a sounding/moving stimulus. *Perception & Psychophysics*, **52** (5), 519–528.

Lewkowicz, D.J. (2000). The development of intersensory temporal perception: an epigenetic systems/limitations view. *Psychological Bulletin*, **126** (2), 281–308.

Lewkowicz, D.J. (2003). Learning and discrimination of audiovisual events in human infants: the hierarchical relation between intersensory temporal synchrony and rhythmic pattern cues. *Developmental Psychology*, **39** (5), 795–804.

Lewkowicz, D.J. (2004). Perception of serial order in infants. *Developmental Science*, **7** (2), 175–184.

Lewkowicz, D.J. (2008). Perception of dynamic and static audiovisual sequences in 3- and 4-month-old infants. *Child Development*, **79** (5), 1538–1554.

Lewkowicz, D.J. (2010). Infant perception of audio-visual speech synchrony. *Developmental Psychology*, **46** (1), 66–77.

Lewkowicz, D.J. (2012). The development of multisensory temporal perception. In M.M. Murray & M.T. Wallace (Eds.), *The neural bases of multisensory processes* (ch. 17). Boca Raton, FL: CRC Press.

Lewkowicz, D.J., & Berent, I. (2009). Sequence learning in 4-month-old infants: do infants represent ordinal information? *Child Development*, **80** (6), 1811–1823.

Lewkowicz, D.J., & Marcovitch, S. (2006). Perception of audiovisual rhythm and its invariance in 4- to 10-month-old infants. *Developmental Psychobiology*, **48**, 288–300.

Marcovitch, S., & Lewkowicz, D.J. (2009). Sequence learning in infancy: the independent contributions of conditional probability and pair frequency information. *Developmental Science*, **12** (6), 1020–1025.

Marcus, G.F., Fernandes, K.J., & Johnson, S.P. (2007). Infant rule learning facilitated by speech. *Psychological Science*, **18** (5), 387–391.

Marcus, G.F., Vijayan, S., Rao, S., & Vishton, P. (1999). Rule learning by seven-month-old infants. *Science*, **283** (5398), 77–80.

Martin, J.G. (1972). Rhythmic (hierarchical) versus serial structure in speech and other behavior. *Psychological Review*, **79**, 487–509.

Mendelson, M.J. (1986). Perception of the temporal pattern of motion in infancy. *Infant Behavior and Development*, **9** (2), 231–243.

Nazzi, T., Bertoncini, J., & Mehler, J. (1998). Language discrimination by newborns: toward an understanding of the role of rhythm. *Journal of Experimental Psychology: Human Perception & Performance*, **24** (3), 756–766.

Pelucchi, B., Hay, J.F., & Saffran, J.R. (2009). Learning in reverse: eight-month-old infants track backward transitional probabilities. *Cognition*, **113** (2), 244–247.

Pickens, J., & Bahrick, L.E. (1997). Do infants perceive invariant tempo and rhythm in auditory-visual events? *Infant Behavior and Development*, **20**, 349–357.

Saffran, J.R., Aslin, R.N., & Newport, E.L. (1996). Statistical learning by 8-month-old infants. *Science*, **274** (5294), 1926–1928.

Saffran, J.R., Johnson, E.K., Aslin, R.N., & Newport, E.L. (1999). Statistical learning of tone sequences by human infants and adults. *Cognition*, **70** (1), 27–52.

Saffran, J.R., Pollak, S.D., Seibel, R.L., & Shkolnik, A. (2007). Dog is a dog is a dog: infant rule learning is not specific to language. *Cognition*, **105** (3), 669–680.

Scheier, C., Lewkowicz, D.J., & Shimojo, S. (2003). Sound induces perceptual reorganization of an ambiguous motion display in human infants. *Developmental Science*, **6**, 233–244.

Trehub, S.E., & Thorpe, L.A. (1989). Infants' perception of rhythm: categorization of auditory sequences by temporal structure. *Canadian Journal of Psychology*, **43** (2), 217–229.

Zacks, J.M., & Tversky, B. (2001). Event structure in perception and conception. *Psychological Bulletin*, **127** (1), 3–21.

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