Local Redundancy Governs Infants’ Spontaneous Orienting to Visual-Temporal Sequences

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Two experiments demonstrate that 5-month-olds are sensitive to local redundancy in visual-temporal sequences. In Experiment 1, 20 infants saw two separate sequences of looming colored shapes that possessed the same elements but contrasting transitional probabilities. One sequence was random whereas the other was based on bigrams. Without any prior exposure, infants looked longer at the random sequence. In Experiment 2, 17 infants looked equally long at bigram- and trigram-based sequences. However, an analysis of local redundancy revealed that in both experiments disengagement from the sequences was governed by local repetitions rather than by global sequence statistics. This finding suggests that a spontaneous sensitivity to stimulus complexity helps orient infants to sequences they can learn from.

It is well known that infants respond to stimulus complexity in static displays. In Cohen’s (1972) seminal study on attention getting and attention holding, 4-month-olds’ attention was held for longer by more complex visual stimuli (checkerboards with greater numbers of squares), supporting an earlier finding by Brennan, Ames, and Moore (1966). According to this view, a sensitivity to complexity might bootstrap infants’ learning by helping them orient to particularly “interesting” stimuli. This is important because natural scenes possess substantial statistical redundancy and numerous correlations in space and time (Field, 1994), not all of which are informative. In spite of this, infants excel at learning from sequential stimuli. Artificial grammar learning (AGL) experiments show that infants can track transitional probabilities (Aslin, Saffran, & Newport, 1998; Saffran, Aslin, & Newport, 1996) and learn other regularities in auditory stimuli (Gómez & Gerken, 1999; Marcus, Vijayan, Bandi Rao, & Vishton, 1999) and in the visual domain (Fiser & Aslin, 2002; Kirkham, Slemmer, & Johnson, 2002; Kirkham, Slemmer, Richardson, & Johnson, 2007). However, none of these studies have examined the complexity of the test materials as a performance factor in itself.

One reason for this gap in research is that complexity is a difficult concept to quantify. For the purposes of this article, we consider global complexity from an information theoretic point of view (Shannon & Weaver, 1949) and local redundancy as measured in terms of repetitiveness. Global complexity requires the infant to encode aspects of the sequence that are true across the sequence as a whole (e.g., the underlying grammar, the transitional probabilities, expected frequencies of co-occurrence), whereas local redundancy only requires the infant to encode information available within a short time window (e.g., the number of times a target item has appeared within the last four or five elements). Chater (1996) initially proposed that the ideas of simplicity and complexity could potentially provide a “unifying principle” for perception, learning, and other phenomena in cognitive science (Chater & Vitanyi, 2003). Hsu, Chater, and Vitanyi (2011) applied these ideas to child language acquisition and a number of authors have applied similar ideas to infant word segmentation (Brent & Cartwright, 1996; Frank, Goldwater, Griffiths, & Tenenbaum, 2010; Venkataraman, 2001). Most recently, Pothos (2010) applied these principles to adult AGL, demonstrating that the relative complexity of the training set and the test items could explain which ones are selected.

Complexity is especially relevant in information-rich domains like language learning, object recogni-
tion, or categorization in which it is difficult to determine what part of a stimulus is signal and what part noise. However, developmental research has largely ignored complexity as a predictive measure of stimulus preference or learning. An exception to this is the work of Son, Smith, and Goldstone (2008) showing that toddlers who learned with simple objects were able to generalize better according to shape than those who learned with complex objects. In a visual category learning task Robinson and Sloutsky (2007) found that increasing stimulus complexity by adding an auditory label increased the time infants spent looking at the stimulus, but reduced their category learning. In both these cases, increased complexity hindered learning. However, much research also shows that the rich and redundant cues in natural speech help rather than hinder infants to learn (e.g., Jusczyk & Aslin, 1995; Jusczyk & Thompson, 1978; Thiessen, Hill, & Saffran, 2005), thus posing somewhat of a conundrum.

It is possible that perceptual and memory constraints could determine when complexity helps or hinders infant learning. Turkewitz and Kenny (1982) speculated that sensory limitations in early infancy might actually be adaptive, simplifying the perceived complexity of the world and facilitating learning. For example, Elman (1993) demonstrated theoretically that reduced working memory could potentially benefit a young language learner by allowing them to “start small,” learning short distance case and clause agreements before long ones. Infants’ performance may be highly dependent on the cognitive resources they have available to them. This suggests that it is important to consider the possible timescales over which statistical learning operates.

To explore these issues, we focused on Kirkham et al.’s (2002) seminal study of infant sequential learning. They habituated 2-, 5-, and 8-month-olds to a structured sequence of looming colored shapes. Six distinct shapes were assigned into three pairs (see Figure 1b). After habituation, the infants saw six test trials, three with the familiar pair-based structure and three with random, nonrepeating sequences (see Figure 1a). The trials alternated with the order counterbalanced and across the two test conditions the frequencies of the individual shapes were identical. Infants at all ages looked longer at the random sequence. Kirkham et al. took this as evidence of a domain general statistical learning mechanism operating from a very early age. A follow-up study also found a similar preference in newborns (Bulf, Johnson, & Valenza, 2011), although discrimination was only found in a “low demand” condition with four distinct shapes.

Although those studies did demonstrate that even very young infants prefer a more random sequence after habituation to a statistically constrained pattern, neither experiment examined whether infants have a prior preference for a less predictable sequence. There are several reasons to suspect that they would; the structured sequence is more likely to contain highly repetitive runs of alternating items and contains far fewer pairwise transitions than the random sequence. Infants could be responding to local redundancy than the global sequence statistics. Thus, this study aims to investigate infants’ prior preferences and response to local sequence redundancy.

Experiment 1 follows as closely as possible Kirkham et al.’s (2002) methodology, but omits the habituation phase. We chose 5-month-old infants because these were the middle group in the original study. However, unlike Kirkham et al., we allowed each test trial to last up to 90 s to allow a greater opportunity for discrimination.

**Experiment 1—Random vs. Pair-Based Sequences**

**Method**

Participants. Twenty infants (10 females) with a mean age of 154 days (range 144–162) were tested. The participants were full-term infants who had experienced no birth complications and with no history of familial color blindness. A further 11 infants were tested, but are excluded due to fussi-
ness (5), equipment failure (3), experimenter error (2), or parental interference (1). Infants were from a mix of ethnicities and backgrounds, but the sample was predominantly European and middle class. Infants were recruited from a pool of volunteer families who were part of the center’s participant database. Parents were not paid, but travel expenses were reimbursed and infants were given a certificate and a small gift.

Apparatus. A Macintosh G4 computer running MATLAB R2006a was used to control the experiment and stimuli were displayed on a 49-cm Panasonic color monitor. Video of the infant was recorded using a low-light DV camera positioned below the screen, facing the infant. These were situated in a soundproofed testing booth.

Stimuli. The stimuli consisted of six colored shapes (turquoise square, blue cross, yellow circle, pink diamond, green triangle, and red octagon) presented in sequence on a black background. As in Kirkham et al. (2002) shapes loomed on the screen, increasing from 4 to 24 cm in height (2.4°–14.6°) over the course of a second. Shapes were presented one after the other with no interval between them.

In the random condition, the shapes were presented in a different random sequence each time, constrained so that each shape appeared with equal probability, but no shape appeared twice in a row. In the pairs condition, stimuli were assigned to three fixed pairs which repeated randomly (see Figure 1). Each infant saw a total of six trials, three structured and three random. For any given infant, presentation alternated between structured and random sequences and order was counterbalanced so that half the infants saw the structured sequence first, the other half saw the random sequence first.

Procedure. Infants were seated in a car seat, in a darkened room, at a distance of 95 cm from the screen. The caregiver remained in the room, but was seated behind and out of view of the infant and was instructed not to interact with the infant.

An observer viewed the infant on a separate monitor in the main lab, and started and finished each trial on the basis of the individual infants’ looking behavior. The observer depressed the space bar on the computer whenever the infant was attending, releasing it if the infant looked away. Each trial finished if the computer determined that the infant had looked away continuously for 2 s or if the trial had lasted 90 s. Trials always finished when the current shape had finished looming. Between trials the screen showed a small blinking fixation square and, if necessary, infants were reoriented to the screen by an auditory attention getter.

Results

Offline manual coding of the videos produced two datasets for analysis. The first was a looking time measure per trial for each infant, calculated by adding up all the time that the infant was looking at the screen per trial. A second experimenter, blind to the hypothesis, double-coded a randomly selected 25% of the trials. The Pearson correlation between the first and second coders’ judgments of looking time was $r = .981$, $p = .001$. The second dataset comprised of the exact sequence of shapes seen by the infant on a given trial, allowing for any short looks away. Infants were deemed not to have seen a particular stimulus shape if they saw less than either the first 300 ms or last 100 ms of that stimulus. This latter dataset allowed us to explore infants’ response as a function of local redundancy in the sequences.

Looking time analyses. For the purposes of analysis, the six trials were divided into three blocks each consisting of a pair of sequences; one structured, one random (Figure 2). To investigate whether the type of sequence had an influence on the length of looking, a two-within, one-between mixed analysis of variance ($3 \times 2 \times 2$, Block $\times$ Pattern $\times$ Order) was performed. The analysis of variance revealed a highly significant main effect of Block, $F(2, 36) = 14.8$, $p = .001$, generalized $\eta^2 = .23$. Infants looking times decreased across the three pairs of sequence presentations indicating that they became familiar with the overall experimental setup. In line with our hypothesis, there was a significant main effect of Pattern, $F(1, 18) = 4.72$, $p = .043$, generalized $\eta^2 = .017$. Infants looked longer on average at the random pat-
tern in each presentation trial. There was no interaction with Block indicating that the preference is consistent across the three blocks and was present from the first pair of trials. Moreover, order of presentation was not a significant factor.

**Local redundancy analysis.** An alternative analytic approach is to identify when infants choose to look away in a sequence; that is, do they look away when there is high local redundancy? For example, infants may look away when they see a run of items that goes ...-blue-red-blue-red-blue-red (Figure 3). Repetitive intervals are more likely in constrained grammars and therefore on average infants may look less at these due to the transient presence of more local redundancy in such sequences. Consequently, we analyzed the results of Experiment 1 in terms of local redundancy, adapting a measure introduced by Jamieson and Mewhort (2005). (See Appendix.)

Mean item and pairwise local redundancy scores were calculated looking back over the previous six items from the last item the infant looked at, the last but one item and so on, averaged across all trials (Figure 4). We used a six-item window as there were six different shapes and much smaller or larger windows would not capture a local effect. Moreover, trials averaged 33 items in length so six-item window provides a good contrast with global effects. Analyses based on eight- and four-item windows showed a similar pattern of results. The graphs slope upward suggesting that infants looked away when local redundancy increased. This was confirmed with repeated measures analysis of variance with distance from end of trial as the repeated measure (six levels). There was a significant effect for item-wise local redundancy $F(1, 118) = 4.15, p = .044$, generalized = .035, and for pairwise local redundancy, $F(1, 118) = 4.25, p = .042$, generalized = .036. These results show: (a) that infants are sensitive to both item and pairwise redundancy, and (b) that they are more likely to look away when the sequences become more locally redundant.

**Discussion**

Five-month-olds spontaneously looked longer at a random temporal sequence compared with a sequence of bigrams. Frequencies of individual items were equal, so infants could only discriminate these sequences on the basis of pairwise transitions or some measure of sequence complexity. They discriminated spontaneously from the first block without any prior exposure to either sequence type. This suggests that a process simpler than global statistical learning is in operation. Results from the redundancy analysis indicate that infants’ performance is determined by short-term repetitions in the stochastic sequences presented to the individual infants.

However, infants could still have very rapidly learned some aspects of the grammar, perhaps a single pairing of shapes, the repetition of which leads them to disengage from that particular sequence. These two possibilities are confounded in the current experiment because the pairwise grammar has more repetition than the random grammar. If the infants respond more to local redundancy than to grammar then we would predict that, in a new task where both sequences have a grammatical structure, there would be no difference in looking...
time between conditions but local redundancy scores would still predict when infants looked away. Experiment 2 aims to resolve this issue.

Experiment 2 — Pairs vs. Triplets
In Experiment 2 we compare the pairs sequence from Experiment 1 to a more predictable sequences consisting of the same shapes arranged in two triplets. If infants look longer at globally complex sequences then, in this case, they should look longer at the pair-based sequence. If, however, they are responding to local repetition, then disengagement should be predicted by an increase in the redundancy scores at the end of the trials.

Method
Participants. A total of 17 infants (eight females) completed the experiment, their mean age was 154 days (range 137–163). A further two were excluded due to experimental error and equipment failure, whereas eight were excluded due to fussiness. Infants were screened and recruited as in Experiment 1.

Procedure and stimuli. The procedure was identical to Experiment 1. The six trials alternated between three sequences consisting of three pairs, and three sequences consisting of two triplets of shapes. Figures 1(b) and (c) illustrate the types of sequence used in this experiment.

Results
The videos were coded as before and a second experimenter blind to the hypothesis double-coded a randomly selected 25% of the data. The Pearson correlation between the coders scores was $r = .989$, $p = .001$. Looking times are plotted in Figure 5.

Looking time analysis. We conducted the same analysis as in Experiment 1. There was a highly significant main effect of Block, $F(2, 30) = 21.5$, $p = .001$, generalized = .29. This was due to the general decrease in looking throughout the experiment. There was also a significant Pattern by Order interaction $F(1, 15) = 11.1$, $p = .005$, generalized = .066. This interaction is a consequence of the general decline in looking over the trials irrespective of pattern; half the infants saw triplets followed by pairs, T1-P1-T2-P2-T3-P3, whereas the others saw the opposite order, P1-T1-P2-T2-P3-T3. Therefore, due to the global decline in looking across trials, Tx>Px for the former infants whereas Px>Tx for the latter. Importantly, there was no main effect of pattern, $F(1, 15) << 1$. There were no other significant main effects or interactions. Infants do not look longer at either the sequences generated by a pair-based or a triplet-based grammar.

Local redundancy analysis. An identical set of complexity analyses were carried out as in Experiment 1. The results showed the same pattern as before (Figure 6); infants appear to look away at points when the sequence is more repetitive and locally redundant than average. As before we confirmed this with a repeated measure analysis of variance with distance from end of trial as the repeated measure (six levels). There were significant effects for both item-wise local redundancy $F(1, 100) = 9.25$, $p = .003$, generalized = .092, and for pairwise local redundancy $F(1, 100) = 13.5$, $p = .001$, generalized = .048. Thus, infants were sensitive to both item- and pairwise local redundancy. They were more likely to look...
away when the sequences became more locally repetitive.

Discussion

In Experiment 2 infants looked equally long at pair- and triplet-based grammars. This does not support the hypothesis that infants would look longer at the globally more complex (pair-based) sequence. However, as in Experiment 1, it was found that single-item and pairwise redundancy measures were significantly above average at the point when infants looked away. Thus, infants were more likely to look away when the most recent few items they had seen were more repetitive.

General Discussion

We conducted two experiments exploring 5-month-olds’ responses to visual-temporal sequences with no prior learning or familiarization. Taken together they provide strong evidence that young infants are sensitive to complexity and will spontaneously prefer more complex, less orderly grammatical sequences. A detailed local redundancy analysis of the items and pairs the infants saw at the point they disengaged from these sequences supported the idea that the infants were not learning global properties of the grammars presented, but were responding to local redundancy over a six-item window.

First, these findings suggest a possible alternative interpretation to the results of Kirkham et al. (2002) and Bulf et al. (2011). This study shows that there need not have been any statistical learning in those studies. Infants may, instead, have spontaneously detected differences in local redundancy between the grammatical and random sequences. Performance in all cases could be explained as response to relatively localized simple features rather than sophisticated global statistical or grammar learning.

It is worth emphasizing that these findings do not in themselves undermine other results showing statistical learning in infants. A great deal of research shows that infants can use frequency information and transition probabilities to segment sequential stimuli (Fiser & Aslin, 2002; Kirkham et al., 2007; for a review and new model of sequence learning see French, Addyman, & Mareschal, 2011). However, this study underscores the need for direct measures of learning in these types of studies as discrimination can potentially be attributed to differences in local redundancy (see also Pothos, 2007). For example, some studies have used counterbalancing and single-item test cases to control for alternative explanations (e.g., Aslin et al., 1998; Pelucchi, Hay & Saffran, 2009a,b). In fact, Experiment 4 of Kirkham et al. (2007) demonstrated reduced eye movement latencies to statistically more likely spatial transitions. There is even direct evidence of statistical learning in newborns using ERP measures (Teinonen, Fellman, Näätäinen, Alku, & Huotilainen, 2009). Thus, the novel contribution of this study is less about striking a cautionary note when exploring statistical learning, but more to reiterate the importance of the question raised by Cohen (1972) and more recently Chater and Vitanyi (2003). Namely, how does a spontaneous sensitivity to stimulus complexity interact with the basic attentional mechanisms that direct perception or learning?

Cohen (1972) found that increasing complexity of a static visual stimulus predicted attention holding. Our results clearly demonstrate that considerations of local redundancy are strongly predictive of infants’ disengagement from a display. This merits further investigation in a wider range of contexts. In particular, it suggests that more links should be made between the study of infant learning as a statistical associative process and the cognitive constraints governing that process. Stimulus complexity has been largely overlooked in previous infant AGL research.

Our results are most straightforwardly explained in terms of infant sensitivity to local redundancy (Jamieson & Mewhort, 2005) in the stimulus stream. This supports the findings of Haith and colleagues (Adler & Haith, 2003; Haith, 1993; Haith, Adler, & Was, 1996) that infants as young as 3 months will learn to anticipate regularities in spatiotemporal sequences over a window of a few seconds. Similarly, just as Pothos (2010) demonstrates a role for complexity in adult AGL research, the present results suggest an analogous importance in the interpretation of infant AGL results and potentially more widely. This is one of the first studies, along with Kidd, Piantadosi, and Aslin (2012), to demonstrate that complexity or simplicity principles that operate in adult cognition also hold in early infancy.

In conclusion, this study shows that infants have a spontaneous sensitivity to complexity of visual-temporal sequences. Infants’ disengagement from the stimulus was best explained in terms of an awareness of local redundancy and not global (grammatical) structure. This finding offers a more parsimonious explanation of some infant statistical
learning results, reopens an old debate in the infancy literature on stimulus complexity, and underscores the centrality of complexity in early cognition.

References


Supporting Information

Additional supporting information may be found in the online version of this article at the publisher’s website:

Appendix S1. Measuring Local Redundancy.