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BRIEF REPORT

Infants' learning of non-adjacent regularities from visual sequences

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Abstract

Tracking adjacent (AD) and non-adjacent (NAD) dependencies in a sequence of elements is critical for the development of many complex abilities, such as language acquisition and social interaction. While learning of AD in infancy is a domain-general ability that is functioning across different domains, infants' processing of NAD has been reported only for speech sequences. Here, we tested 9- to 12- and 13- to 15-month-olds' ability to extract AxB grammars in visual sequences of unfamiliar elements. Infants were habituated to a series of 3-visual arrays following an AxB grammar in which the first element (A) predicted the third element (B), while intervening X elements changed continuously. Following habituation, infants were tested with 3-item arrays in which initial and final positions were switched (novel) or kept consistent with the habituation phase (familiar). Older infants successfully recognized the familiar AxB grammar at test, whereas the younger group showed some sensitivity to extract to NAD, albeit in a less robust form. This finding provides the first evidence that the ability to track NAD is a domain-general ability that is present also in the visual domain and that the sensitivity to such dependencies is related to developmental changes, as demonstrated in the auditory domain.

1 | INTRODUCTION

Our ability to rapidly extract structured sequential information from the environment underpins many complex behaviors—from language development and social interaction to intuitive decision-making (e.g., Lewkowicz, 2013). Processing of sequential information is critical to adapt to a spatiotemporally bounded environment, and many studies investigated its ontogenetic and phylogenetic roots (Wilson et al., 2018). This ability allows learners to detect the relations between immediately following items (adjacent dependencies, AD; Saffran et al., 1996) or between two temporally or spatially distal elements (non-adjacent dependencies, NAD; Gómez & Maye, 2005).

It is widely demonstrated that AD are easily learned from early in infancy. For example, 8-month-old infants can compute statistics between adjacent syllables and use this information to segment a continuous speech stream into units (Saffran et al., 1996). In contrast, NAD seem to be learned late, during the second year after birth. For example, Gómez and Maye (2005) exposed 12- and 15-month-olds to a speech stream containing AxB mini-grammar structures in which the first element (A) always predicted the third (B); intervening X elements were not predictive. Younger infants failed to track non-adjacent dependencies but starting from 15 months, infants successfully tracked these relations, suggesting that NAD are challenging to master. Other experiments revealed that infants can learn AD and NAD with linguistic stimuli and that this type of learning is relevant for specific aspects of language, such as lexical (see Saffran & Kirkham, 2018) and grammar skills (Jill & Shoaib, 2020).

There is substantial evidence that the ability to track AD is not confined to linguistic stimuli, supporting the idea of a domain-general associative learning mechanism. For example, newborns can discriminate statistics between consecutive items embedded in a sequence of visual shapes (Bulf et al., 2011), and 2- to 8-month-old infants detect AD in a continuous stream of visual stimuli, with no apparent age differences in learning performance (Kirkham et al., 2002). As regards NAD, positive evidence of a domain-general learning comes from studies conducted with animals (Sonnweber et al., 2015) and human adults (Deocampo et al., 2019) in the visual domain. However, it is not known whether the ability to learn NAD based on associative relations (i.e., AxB) is based on domain-general processes present since the early stages of development.

Here, we investigated infants' ability to extract AxB grammars in visual sequences of unfamiliar elements (geometrical shapes and arrays of dots). In line with Gómez and Maye (2005), we explored the developmental trajectory of this learning process by testing two age groups of infants. Infants at 9–12 months and 13–15 months were habituated to a series of 3-item visual arrays following an AxB mini-grammar in which the first element (A) predicted the third element (B), while intervening X elements continuously changed. According to Gómez and Maye (2005), the items in initial/final position and items in intermediate positions were drawn from different categories (i.e., shapes vs. arrays of dots), perhaps facilitating the detection of NAD. Following habituation, infants were tested with novel and familiar 3-item arrays. In the novel arrays, the shapes in initial and final positions were switched, while in the familiar arrays they were kept consistent with habituation (Figure 1). If infants were able to compute AxB grammars in the visual domain, we expected that they would discriminate novel from familiar sequences following the learning phase. Moreover, if the ability to compute visual AxB grammars is sensitive to age differences, as demonstrated by Gómez and Maye (2005) in auditory domain, we expected that the young group may fail to discriminate familiar and novel sequences at test, whereas the old group would successfully learn NAD.

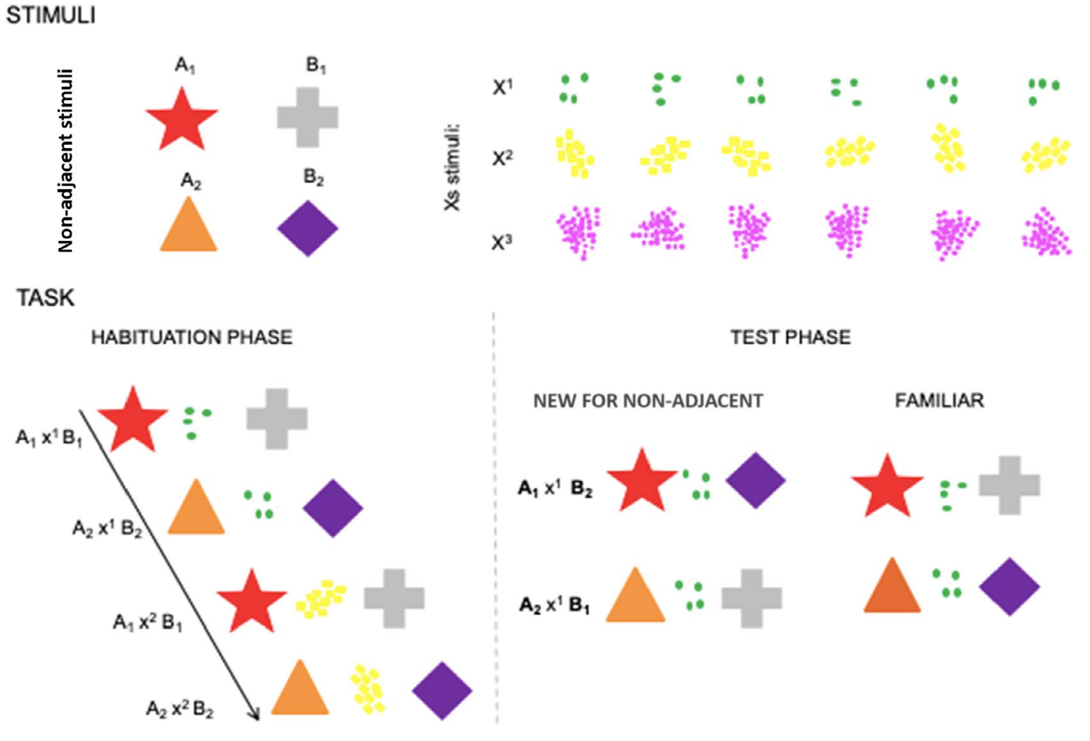

FIGURE 1 Schematic representation of the stimuli and the procedure.

2 | METHODS

2.1 | Participants

The final sample was composed of 28 infants (mean age =12.95; *SD* =1.98). The sample has been split into two different age group using a cutoff of 380 days which correspond to the median age: The younger group was composed by fourteen 9- to 12-month-old infants (mean age =11.40 months, *SD* =1.06; 6 females), while the older group was composed by fourteen 13- to 15-month-old infants (mean age =14.50 months, *SD* =1.36; 8 females). Four additional infants were tested but excluded because fixation time was less than 1 s on one or more test trials (n = 1), or because their looking times exceeded 3 SD beyond the mean on at least one test trial (n = 3). The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before any assessment or data collection. All procedures involving human subjects in this study were approved by the North General Institutional Review Board at the University of California, Los Angeles.

2.2 | Stimuli

The visual stimuli were organized into AxB grammars and presented using Macromedia Director on a Macintosh computer with a 61.5 cm diagonal screen. Items in first/third position and items in the intermediate position were drawn from different categories, that is, geometrical shapes vs. arrays of dots. Four colored shapes (star, square, triangle, and cross) were used for the A_B items, while X elements were selected from a pool of 18 arrays of dots. There were 3 quantities of dots (4, 10, 25; ratio: 2.5) with 6 distinct configurations for each quantity (Figure 1). Two unique shapes were assigned to group A (e.g., star and triangle) and two to group B (e.g., cross and diamond). The stimuli were presented on a black background, and each shape was embedded in a virtual square of 10° × 10° visual angle.

For the habituation phase, the A and B images were combined to create 2 distinct AxB grammars in which the first shape (A) was paired to the third non-adjacent shape (B) with intervening X elements randomly selected (Figure 1). In the test sequences, the familiar items were the same used during the habituation phase. The novel stimuli were created by switching the third element between the two AxB grammars, thus disrupting the non-adjacent relations learned during the habituation phase.

2.3 | Apparatus and procedure

Infants sat on their caregiver's laps in a quiet, dark room at approximately 60 cm from the screen. Above the monitor, a video camera recorded the infant's face and looking behavior was coded online by an experimenter who was blind to the experimental condition. An infant controlled habituation procedure was used. Before each habituation trial, an attention-getter appeared in the center of the screen to attract the infant's attention. The experimenter recorded infants' looking times by pressing a key on the computer keyboard whenever the infant looked at the stimulus. As soon as infants looked at the screen, the experimenter pressed the key to begin the trial. In each habituation trial, the 3-item arrays were presented in random order and were displayed sequentially on the monitor from left to right. The first item appeared for 500 ms on the left side of the screen, the second item appeared for 500 ms in the center of the screen, and the third element appeared for 500 ms on the right side of the screen. Thus, each trial sequence lasted 1500 ms. A blank screen separated each triplet for 500 ms. Each trial ended when infants looked away for 2 consecutive s or fixated the stimuli for a maximum of 60 s. The habituation phase terminated when infants viewed a maximum of 12 trials or reached the habituation criterion, which was defined as a 50% decline in mean-looking time over four consecutive trials relative to the mean-looking time of the first four trials. Following habituation, infants were presented 6 alternating familiar and novel 3-item arrays. The order of presentation (i.e., familiar vs. novel first) was counterbalanced among participants. The dependent variable was looking time (s) toward novel and familiar sequences.

2.4 | Statistical analyses

Log transformation was applied on looking time collected during habituation and test trials of the task to reduce skewed distributions which is often the case in the visual habituation procedure with young infants (e.g., Csibra et al., 2016; Kirkham et al., 2007; Tummeltshammer et al., 2017). To compare the infant's performance during the habituation phase in the two age groups, two independent *t*-tests were run on total looking times and the number of trials. To determine whether infants are able to extract NAD, an ANOVA was run on looking time at the test with Group (young, old infants) and Test Order (familiar first, novel first) as between-participants factors, and Test Trial Type (novel, familiar) as a within-participants factor.

3 | RESULTS

The young infants required an average of 119.17 seconds (*SE* = 12.71) and 8.43 (*SE* = .56) number of trials to habituate to the sequence, while old infants required 171.43 (*SE* = 27.62) seconds and 8.79 number of trials (*SE* = .60). An independent *t*-test revealed that the two age groups did not differ in total looking times, $t(26) = -1.764$, $p = .089$, Cohen's $d = .667$, and in number of trials, $t(26) = -.433$, $p = .669$, $d = .165$.

The ANOVA on looking times (logarithmically transformed) at test revealed an effect of Test Trial Type × Group interaction, $F(1,24) = 4.34$, $p = .048$, $\eta^2 = .153$, and a Test Trial Type × Group × Test Order interaction, $F(1,24) = 5.23$, $p = .031$, $\eta^2 = .179$. To explore these interactions, a 2 × 2 ANOVA was performed for each age group, with Test Trial Order (familiar first, novel first) as a between-subjects factor and Test Trial Type (novel, familiar) as within-subjects factor. For the young infants group, the ANOVA revealed a Test Trials Type × Test Order interaction, $F(1,12) = 4.95$, $p = .046$, $\eta^2 = .292$, revealing that infants who began with familiar at test looked longer at familiar ($M = 3.77$, $SE = .079$) than novel test trials ($M = 3.64$, $SE = .079$; $p = .014$). No other effects or interactions attained significance. In particular, the Test Trial Type main effect did not attain significance, $F(1, 12) = .102$, $p = .755$, $\eta^2 = .008$, suggesting that the young group did not discriminate between familiar ($M = 3.83$, $SE = .052$) and novel items ($M = 3.81$, $SE = .079$) at test. For the old infants group, the ANOVA revealed a main effect of Test Trial Type, $F(1,12) = 5.32$, $p = .040$, $\eta^2 = .307$, as infant looked longer at novel ($M = 3.98$, $SE = 0.68$) than familiar ($M = 3.84$, $SE = .063$) test trials. No other significant effects were found (*p*s > .246).

4 | DISCUSSION

The present study was aimed at investigating whether infants' ability to extract NAD from linguistic sequences (Gómez & Maye, 2005) can be found in the visual domain as well, and whether this ability develops with age. After habituation to AxB visual arrays, 13- to 15-month-old infants showed a reliable preference for novel vs. familiar stimuli, providing evidence that they were able to extract the non-adjacent regularities presented during the habituation phase. Conversely, 9- to 12-month-olds looked longer at the familiar test stimuli, but only when a familiar test trial was presented first, suggesting that they might possess some sensitivity to extract to NAD, albeit in a less robust form. Infants' tendency to pay attention to the more familiar stimuli in the test phase of a familiarization/habituation task is a well-known behavior when the complexity of the stimulus material is too high (see Flom et al., 2018), pointing to the idea that age differences in learning NAD can be explained by an increasing proficiency to detect and utilize information relevant to cognitive tasks, such as the amount of information infants can process over time (i.e., their processing window; Diego-Balaguer et al., 2016; Elman, 1993; Santelmann & Jusczyk, 1998). However, as we have a restricted age range—we tested just two age groups (i.e., 9–12 vs. 13–15)—the effect of age on infants' visual NAD learning should be explore more carefully. For example, future research should test wider age ranges, as well as directly compare infants' ability to learn visual NAD with their linguistic and attentional abilities.

Our results can be interpreted in light of previous studies investigating AxB grammar learning with auditory stimuli. Tracking NAD is a cognitively complex task that is modulated by the characteristics of the learner, such as age (Gómez & Maye, 2005; Mueller et al., 2019) and attentional resources (de Diego-Balaguer et al., 2016), and by the stimulus characteristics (Gómez, 2002; Marchetto & Bonatti, 2013). For example, 9- and 12-month-olds exploited NAD embedded in linguistic input

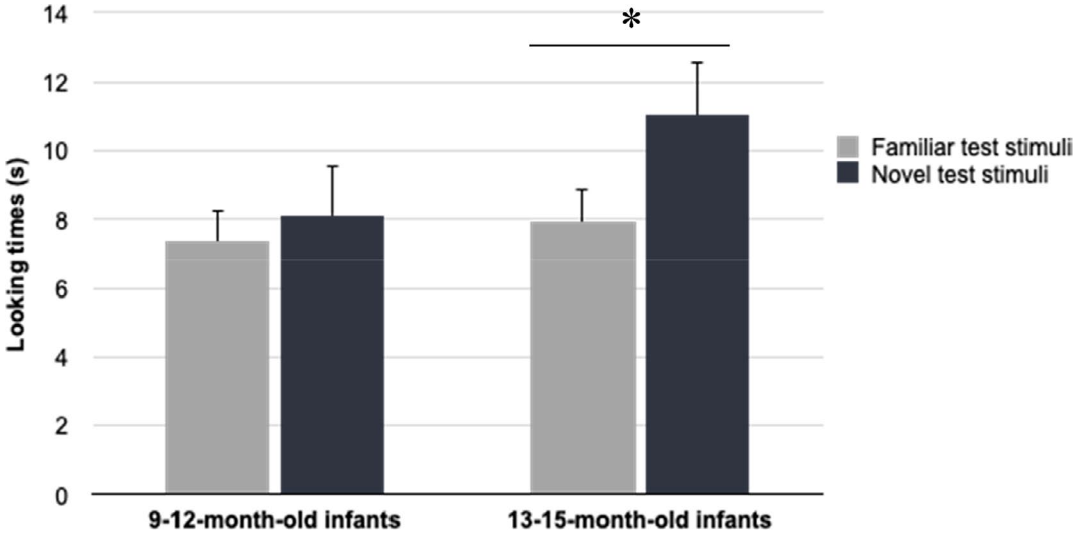

FIGURE 2 Mean of looking time (s) for novel and familiar test stimuli for each age group.

when the stream was segmented by pauses (Kabdebon et al., 2015; Marchetto & Bonatti, 2013) and when the variability of the intervening X elements was high (i.e., set size of 24 elements; Gómez, 2002; Gómez & Maye, 2005). Even though in our study the variability of the X elements was lower than in Gómez et al.'s studies, the NAD were highlighted by multiple cues: Intervening X elements belonged to a different category relative to the A_B stimuli, and the visual stream was segmented by pauses (cf. Marchetto & Bonatti, 2013). Moreover, the 3-item arrays were presented onto space from left to right, and previous studies have demonstrated that spatial information has a facilitatory role in infants' ability to extract rules from the visual input (Bulf et al., 2017; de Hevia et al., 2014; Ferguson et al., 2018; Johnson et al., 2009). Further research should systematically explore the conditions under which learning occurs in the visual modality (like examining the variability of intervening elements and the nature of the visual input—e.g., using familiar visual material such as faces), as well as investigate to what extend auditory and visual NAD share the same learning mechanisms and the constraints under which NAD operates. For example, some learning constraints might overlap between the two modalities, while other factors might differ due to the specific nature of the auditory and visual inputs (e.g., temporal vs. spatial cues; Conway & Christiansen, 2009), as already shown for AD learning (Krogh et al., 2013).

The present findings provide the first evidence that infants can learn non-adjacent statistical dependencies in the visual domain and that this learning ability might change during the first postnatal year, suggesting that learning of NAD is a domain-general mechanism, not confined to the linguistic domain (Gómez & Maye, 2005). Moreover, our data suggest that the ability to learn NAD may appear later during development relative to infants' learning of AD (Bulf et al., 2011; Kirkham et al., 2002), most probability because it requires more complex computations.

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