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Visual abstract rule learning by 3- and 4-month-old infants

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Abstract

Infants' ability to detect and generalize abstract rules (e.g., ABB, ABA) in auditory stimuli has been well documented, however their ability to do so from visual stimuli has received considerably less attention. Moreover, the few studies reported suggest that this kind of learning is especially sensitive to details of the experimental design. Here, we focus on 3- to 4-month-old infants ($N=40$) to identify both the origins of visual abstract rule learning in infancy and the conditions that best support it. Our results provide the earliest evidence to date, documenting that by 3 months of age, infants successfully learn and generalize rules in the visual modality. They also reveal that providing infants with an opportunity to examine the stimuli simultaneously may be instrumental to their success.

Keywords: abstract rule learning; abstract relations; comparison; habituation; infants

Introduction

A signature of human cognition is our ability to learn and represent abstract relations (Penn, Holyoak, & Povinelli, 2008). For example, in language, we learn not only about abstract grammatical categories (i.e., nouns, verbs), but also about the hierarchical relations that govern their usage (Chomsky, 1965; Jackendoff, 1990; Pinker, 1984). And, in science, we learn not only about the protons, electrons, and neutrons that make up atoms, but also about the relations among them and, further still, the similarity between these relations and those of other systems (e.g., the solar system; Gentner, 1983). Even our fundamental notions of identity – SAME and DIFFERENT – rely on this capacity for relational thinking.

The importance of abstract relations to human cognition has led researchers to investigate their developmental origins. In a seminal study, Marcus and colleagues asked whether infants as young as 7 months could learn a particular kind of relation, commonly known as an “abstract rule” (Marcus, Vijayan, Rao, & Vishton, 1999). To do so, they devised a now-standard rule learning paradigm in which infants are exposed to triads of speech syllables following a single rule. For example, an infant learning an ABB rule would be familiarized to sequences such as *le-di-di*, *wi-je-je*, and *de-li-li*. Next, to test whether they learned this rule, infants hear a series of test trials composed of novel speech syllables. On half of the test trials, these novel syllables are presented in triads following the rule to which they had been exposed during the learning phase (familiar trials; e.g., *ba-po-po*); on the remaining test trials, these

novel syllables are presented in triads following a different rule (novel trials; e.g., ABA, *ba-po-ba*). If infants learned the rule in training, they should discriminate familiar from novel test trials, as evidenced by a reliable preference for one type of trial over the other. Critically, the stimuli are designed so that any such preference requires that infants represent the abstract relations within the triads and not simply lower-level perceptual features that might otherwise be common to both the familiarization and test stimuli.

Using this design, Marcus and colleagues found that 7-month-olds reliably learned abstract rules from speech syllables (Marcus et al., 1999). This remarkable finding sparked a wave of interest in infants' abstract rule learning from auditory stimuli more generally. These pursuits have revealed a host of insights documenting, for example, that within the first year, infants' rule learning is gradually tuned to speech syllables (Dawson & Gerken, 2009; Marcus, Fernandes, & Johnson, 2007) and to other communicative signals (Ferguson & Lew-Williams, 2014), that rule-learning benefits from vowel and consonant redundancies in spoken syllables (Thiessen, 2012), that infants can learn both adjacent (i.e., repetition) and non-adjacent relations (Gervain & Werker, 2012), that the amount of variability present in the stimuli influences the kind of rule infants will abstract (Gerken, 2006; Kovács, 2014), that infants can learn a rule from a single exemplar (Gerken, Dawson, Chatila, & Tenenbaum, 2014), that infants can even simultaneously learn word- and sentence-level rules from speech (Kovács & Endress, 2014), and that even newborns detect certain repetition-based rules (Gervain, Berent, & Werker, 2012; Gervain, Macagno, Cogoï, Peña, & Mehler, 2008).

Considerably fewer studies have investigated infants' ability to learn abstract rules when stimuli are presented in the visual modality. Moreover, the evidence reported to date does not yet offer a clear picture of the conditions that best support this learning. For example, Johnson and colleagues (2009) examined visual rule learning in 8- and 11-month-olds. The design was identical to Marcus et al. (1999)'s studies, except that instead of listening to sequences of speech syllables, infants viewed a series of sequentially-presented two-dimensional shapes looming on a screen. For example, an infant familiarized to an ABB rule might see *triangle-circle-circle* as one sequence. The results were mixed: Eleven-month-olds successfully learned AAB and ABB rules, but failed to learn ABA rules. Eight-month-olds fared even worse, learning ABB rules but neither AAB or ABA. This was interpreted as evidence that infants' ability

to learn rules in the visual domain is considerably less robust than in the auditory domain and, in particular, from speech.

Other studies using different experimental designs have reported more successful rule learning. For example, two studies found that 5- and 7-month-olds reliably learned rules when a single rule was presented simultaneously in the auditory and visual modalities (i.e., presenting a visual sequence, *triangle-circle-circle* in conjunction with an auditory sequence, *bo-pa-pa*; Frank, Slemmer, Marcus, & Johnson, 2009; Thiessen, 2012). Another study found that 7-month-olds reliably learned rules from images of familiar stimuli (dogs and cats) were presented sequentially and then remained together briefly on the screen (allowing infants to observe the sequence in its entirety; Saffran, Pollak, Seibel, & Shkolnik, 2007).

We suspect that two features of Saffran et al.'s (2007) design supported infants' rule learning, permitting their 7-month-olds to succeed where Johnson et al.'s (2009) 8-month-olds had failed. First, in Saffran et al. (2007), the rules were instantiated in images of dogs and cats; these may have been easier process, and perhaps more interesting, than Johnson et al.'s (2009) geometric shapes. Second, in Saffran et al. (2007), once an image appeared, it remained on the screen until all images in the triad had appeared; and after the final image appeared, the entire triad remained visible for almost a second. Why might this latter presentation style best support rule learning? First, permitting each image to remain on the screen meant that infants did not need to remember each image in sequence in order to detect the rule. In contrast, the greater memory requirement in Johnson et al. (2009) may have taxed infants' limited visual working memory which, even by 6 months, can maintain a representation of only a single object (Kwon, Luck, & Oakes, 2014; Ross-Sheehy, Oakes, & Luck, 2003; see also Frank & Tenenbaum, 2011 for computational-level discussion of memory demands in rule learning). Second, having the images remain on the screen may also facilitate their comparison of the images which in turn should facilitate their abstraction of the rule (Ferry, Hespos, & Gentner, in press; Gentner & Markman, 1997; Gentner & Medina, 1998; Oakes & Ribar, 2005).

In the present study, our primary goal was to ask whether infants at just 3 to 4 months of age could successfully learn visual abstract rules under these more supportive conditions¹. To do so, we adapted the experimental design introduced by Saffran et al. (2007), presenting triads composed of dog images sequentially, but permitting each image to remain

¹ While one study by Addyman and Mareschal (2010) concludes that 4-month-olds have the ability to represent at least one of the prerequisite abstract relations (DIFFERENT) required for this task, learning a rule requires not only detecting this relation but also encoding its location in a sequence. Thus it is still an open question whether infants this age can learn rules from visual modality.

visible for the duration of each sequence and briefly thereafter.

Our second goal was to extend this design to identify the influence of infant-directed speech on visual rule learning at 3-4 months. Several recent studies have converged to suggest that infant-directed speech and other communicative signals promote young infants' learning (Csibra & Gergely, 2009; Ferguson & Lew-Williams, 2014; Ferguson & Waxman, 2013; Ferry, Hespos, & Waxman, 2010; Kuhl, 2007; Marcus et al., 2007; Vouloumanos & Waxman, 2014; Wu, Gopnik, Richardson, & Kirkham, 2011; Wu, Tummeltshammer, Gliga, & Kirkham, 2014; Yoon, Johnson, & Csibra, 2008). For example, in one study at 3- and 4-months, infants failed to form object categories while listening to tones, yet they succeeded in the very same task while listening to speech (Ferry et al., 2010). To ascertain whether speech might also facilitate visual rule learning at this age, for half of the participants, each triad of dogs was presented in conjunction with a phrase of infant-directed speech; for the remaining infants, the triads were presented in silence. All infants were tested in silence. If speech facilitates infants' visual abstract rule learning, then those infants listening to speech during the learning phase should be more successful in detecting abstract rules.

Methods

Participants

We tested 40 3- to 4-month-old infants (17 F; $M = 4.18$ months, *range* 3.00 – 4.97) recruited from Evanston, IL, USA and the surrounding area. Each participant was assigned to either the *Speech* ($N = 20$) or *Silent* ($N = 20$) condition. An additional 26 infants (13 in each condition) were excluded due to either irritability that forced the experiment to end before the test phase ($N = 14$), irritability during test ($N = 1$), looking on fewer than 2 trials of each rule type ($N = 7$), technical error ($N = 3$), or parental interference ($N = 1$).

Procedure

We designed the task to match that of Saffran et al. (2007), and therefore included a Habituation and a Test phase.

During Habituation trials, all infants saw triads of dog images on a screen that each followed the same rule (either ABB or ABA, randomized between-subjects). Each dog appeared in sequence, in 330ms intervals and remained visible thereafter. All three then remained on the screen together for 1840ms following the third dog's appearance², during which time infants in the Speech condition heard a phrase of infant-directed speech and infants in the Silent

² We extended the simultaneous viewing period for 1s longer than in Saffran et al. (2007) because it catered to the slower visual processing speed of younger infants and gave us the time required to present the Speech stimuli while infants viewed the triads in their entirety.

condition observed the triads in silence. A blank screen separated each triad by 500ms. Triads continued to be displayed in this manner until infants looked away from the screen for 2s; at this point, the trial ended and infants saw an attention-getter presented at the center of the screen. When infants looked to the attention-getter for 250ms, a new habituation trial began. This continued until infants habituated, which occurred either when their trial looking time (averaged across the three consecutive trials) fell below 50% of their mean looking time during the first three trials, or when infants had viewed the maximum number (25) of habituation trials (only two infants hit the maximum).

After Habituation, the Test phase began. The Test phase included 8 trials. In each, infants viewed triads comprised of entirely novel dog images. In 4 of the trials, the dogs formed an ABB pattern while, in the other 4 trials, the dogs formed an ABA pattern, thus resulting in trials that matched either the familiar (habituated) rule or a novel rule. Trials were presented in two blocks of four; within each block, the order of familiar rule and novel rule trials was randomized. Within each trial, each triad had the same timing as during Habituation and, for all infants, were presented in silence. Test trials lasted until infants looked away for 2s.

Stimuli

Visual The dog images were identical to those of Saffran et al. (2007) and organized into the same *A* and *B* categories. During habituation, the *A* elements were the *Alaskan Malamute*, *Norwegian Elkhound*, *Shiba Inu*, and *Nova Scotia Duck Tolling Retriever*, and the *B* elements were the *Australian Cattle Dog*, *Belgian Malinois*, *Canaan Dog*, and *German Shepherd*. During test, the *A* elements were the *Finnish Spatz* and *Akita*, and the *B* elements were the *Anatolian Shepherd* and *Belgian Tervuren*.

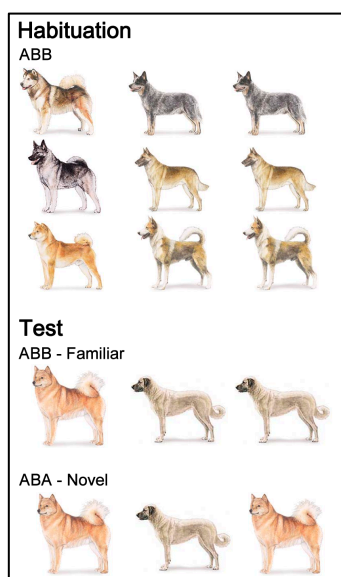


Figure 1: Representative stimuli. Infants were habituated to triads of dogs all following the same rule (e.g., ABB) and, at

test, were shown trials in which new dogs were organized to follow the familiar rule or a novel rule (e.g., ABA).

Auditory Immediately after the appearance of the third image in each triad, infants in the Speech condition heard one of two phrases, “*Look at the toma!*” and “*Do you see the toma?*” (adapted from Balaban & Waxman, 1997; Ferry et al., 2010; Waxman & Markow, 1995). Although for older infants, naming phrases like these direct infants’ attention to commonalities among objects (Fennell & Waxman, 2010; Namy & Waxman, 2000), infants at 3-4 months do not yet reliably segment individual words from the speech stream (Bortfeld, Morgan, Golinkoff, & Rathbun, 2005; Seidl, Tincoff, Baker, & Cristia, 2014). These phrases were pre-recorded and played from speakers beneath the screen.

Coding

Using custom MATLAB software, each infant’s looking time to the screen was coded online by a trained observer blind to the study’s hypotheses.

Analyses

Our dependent measure was each infant’s mean looking time to the screen during novel and familiar trials at Test. Our prediction is that, if infants learn the rule during Habituation, they will discriminate novel from familiar test trials. In most studies, infants who learn the rule look longer during novel trials. However, in some studies that have tested learning under particularly difficult conditions, infants look longer during familiar trials (Gerken et al., 2014; Thiessen, 2012). Given the very young age of our participants and nature of the task, we considered both *a priori* possibilities and thus used two-tailed statistical tests throughout. In contrast, if infants failed to learn the rule, we predicted that there would be no differences between looking during familiar and novel trials.

We excluded all test trials in which infants looked less than 2.5 seconds (the length of one sequence) to be sure that infants discriminated novel from familiar sequences (57 trials, 17% of total). (Including these trials does not change the pattern of results or significance of *p*-values reported below.)

Preliminary analyses revealed that neither the infants’ sex nor the rule that they were habituated to (ABB or ABA) predicted looking preferences at test (all *p*’s > .32); we therefore collapsed across these factors in further analyses.

Results

In a preliminary set of analyses, our goal was to ascertain whether infants (1) habituated during the Habituation phase and (2) dishabituated at Test. First, to assess habituation, we compared infants’ attention during the first three habituation trials to their attention during the final three habituation trials (see Figure 2). Infants’ attention did indeed decline, $t(39) = 6.52, p < .001$. There were no differences between conditions in either the time to habituate (silent: $M = 137.06s$, speech: $M = 115.62s, p = .33$) or the trial number

on which they habituated (silent: $M = 10.55$, speech: $M = 8.80$, $p = .27$). Second, to assess whether infants dishabituated at test (when the new images of dogs were introduced), we compared infants' mean looking during the final three habituation trials to their mean looking during test trials. Indeed, infants did dishabituate overall (M difference = 2.93s, $p = .033$).

This outcome, which provides assurances that infants at least noticed the new images presented at test, permitted us to address our primary questions: At test, did infants distinguish between the familiar and novel rules? And did their ability to do so differ between the Speech and Silent conditions? To address these questions, we entered infants' looking times at test into a 2 (Condition: Speech, Silent) x 2 (Trial Type: Novel, Familiar) ANOVA. We found a reliable main effect of Trial Type ($F(1,38) = 6.49$, $p = .015$) but no main effect of Condition ($F(1,38) = .008$, $p = .93$) and no interaction ($F(1,38) = .27$, $p = .61$). A follow-up t-test confirmed that, overall, infants looked significantly longer at familiar test trials ($M = 10.56s$, $SD = 9.29$) than novel test trials ($M = 7.80s$, $SD = 4.20$), $t(39) = -2.57$, $p = .014$, $d = -.41$. A non-parametric Wilcoxon signed rank test corroborated the direction and significance of this preference, $p = .029$, as did infants' dishabituation patterns at Test: Infants reliably dishabituated to familiar rule trials ($M = 4.30s$, $p = .016$) but not to novel rule ($M = 1.55s$, $p = .16$) trials.

These results indicate that infants in both conditions learned the abstract rule during Habituation and, critically, generalized this rule to the novel stimuli at Test. Because there was no interaction between Trial Type and Condition, infants' learning did not differ between Speech and Silent conditions.

Two features of infants' performance warrant further comment. First, notice that in both conditions, infants preferred the test trials depicting the familiar rule to those depicting the novel rule. This suggests that detecting the rule in these visual stimuli was cognitively demanding and thus required further attention and processing (Colombo & Bundy, 1983; Roder, Bushnell, & Sasseville, 2000). Given that several rule learning studies with 7-month-olds have reported familiarity preferences (e.g., Gerken et al., 2014; Thiessen, 2012), it is perhaps unsurprising that these 3- and 4-month-olds revealed their learning in the same manner.

Second, it is clear from Figure 3 that the magnitude of infants' familiarity preference decreases with age. This effect of age was confirmed in a linear model predicting infants' difference scores at test by age, condition, and their interaction. This model revealed a reliable intercept (i.e., a reliable overall familiarity preference; $\beta = -2.88$, $t(36) = -2.85$, $p = .0072$), a significant effect of age ($\beta = 5.08$, $t(36) = 2.85$, $p = .0071$), and no effect of condition or interaction between age and condition, both p 's > .38. This effect of age – in which younger infants (i.e., slower processors) had larger familiarity preferences than older infants (i.e., faster processors) – is exactly what is predicted by existing

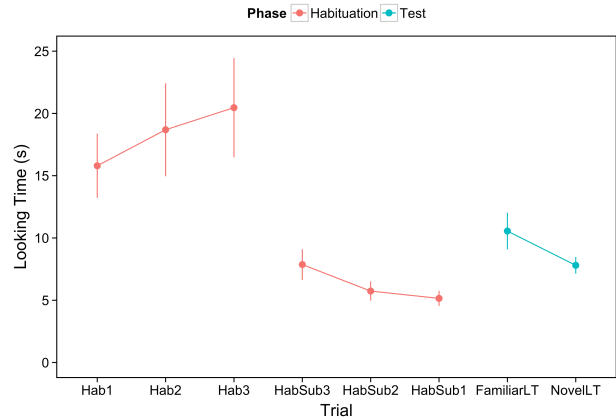


Figure 2: Infants' looking times during the first three habituation trials (Hab1-3), the last three habituation trials (HabSub1-3), and at test (FamiliarLT and NovelLT). Error bars represent one standard error.

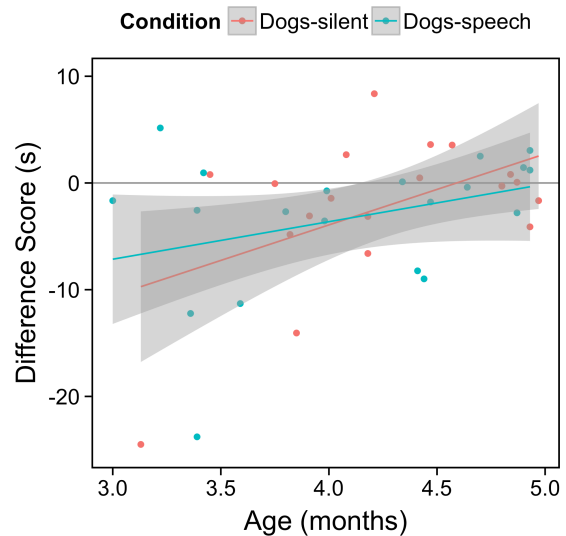


Figure 3: Infants' preference for novel trials (difference score) by Age and Condition.

accounts of familiarity and novelty preferences (e.g., Colombo & Bundy, 1983). With time, infants become faster processors and thus more likely to show novelty preferences in the same tasks in which they once showed familiarity preferences. Moreover, this proposed trajectory is plausible because by at least 7 months, infants show novelty preferences with these same stimuli (Saffran et al., 2007).

Discussion

We have revealed for the first time that infants as young as 3 months of age can learn abstract rules from visual stimuli. Together with findings from auditory rule learning (e.g., Gervain et al., 2008), these findings suggest that the

foundations of one signature of human cognition – our capacity for detecting relations - are in place early within the first months of life and, moreover, able to operate over both auditory and visual modalities.

Moreover, we found that visual rule learning at this age was robust both while listening to speech and in silence. Nevertheless, the cognitive advantages of human speech and other communicative signals may be apparent under more taxing learning conditions. By manipulating features of the present design (e.g., habituation time, visual stimuli), further research can better clarify what advantages, if any, speech and other communicative signals have on early abstract rule learning.

Communicative contexts aside, these findings lay the groundwork for an even broader investigation into the conditions that best support very young infants' relational abstraction in rule learning tasks. Comparing the present study (in which 3- and 4-month-olds learned abstract rules in the visual domain) with that of Johnson et al. (2009; in which 8-month-olds failed to learn in all but one case), we suggest that two critical paths for future investigation will be to assess the contribution of: (1) the kind and complexity of visual stimuli presented (e.g., dogs versus shapes) and, (2) the way in which these stimuli are presented (e.g., with each image available for only a brief inspection versus allowing for simultaneous comparison).

We suspect that the conditions that best support rule learning are likely to differ across modalities and stimuli. For example, although we have suggested that allowing infants an opportunity to view the images in each triad simultaneously (albeit briefly) may have been instrumental to their success here and in Saffran et al. (2007), this does not guarantee that simultaneous comparison will always be essential in rule learning, even within the visual modality. On the contrary, we suspect that it will not be required for infants to learn rules from sequences of actions that, by their nature, are temporally ordered and cannot occur simultaneously. Furthermore, existing evidence from rule learning from speech and tones (Dawson & Gerken, 2009; Marcus et al., 1999) documents that, in the auditory modality, infants can learn rules when individual elements are presented only in sequence. Indeed, harmonics aside, this temporal property is a requirement of this modality. We therefore propose that what allows infants to detect an abstract relation and learn a rule may vary, both as a function of the endowments of the perceptual modality and the properties of the particular stimuli themselves.

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