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Communicative signals promote abstract rule learning by 7-month-old infants

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Abstract

Infants' ability to detect patterns in speech input is central to their acquisition of language, and recent evidence suggests that their cognitive faculties may be specifically tailored to this task: Seven-month-olds reliably abstract rule-like structures (e.g., ABB vs. ABA) from speech, but not other stimuli. Here we ask what drives this speech advantage. Specifically, we propose that infants' learning from speech is driven by their representation of speech as a communicative signal. As evidence for this claim, we report an experiment in which 7-month-old infants ($N=28$) learned rules from a novel sound (sine-wave tones) introduced as a communicative signal, but failed to learn the same rules from tones presented in non-communicative contexts. These findings highlight the powerful influence of social-communicative contexts on infants' learning.

Keywords: language development; abstract rule learning; statistical learning; social cognition; grammar; infants

Introduction

The human capacity to learn language is unparalleled in the animal kingdom. Typically developing human infants efficiently learn the complexities of sounds, syllables, words, and sentences, but non-human animals – even those raised in rich linguistic environments – seem incapable of doing so (Pinker, 1994). What might explain this striking divide between humans and even our closest evolutionary cousins? One longstanding hypothesis is that humans have cognitive machinery dedicated to language acquisition (e.g., Chomsky, 1965; Pinker, 1994); however, identifying language-dedicated machinery has proven difficult. Several previous candidate language learning mechanisms – fast mapping of novel words, tracking transitional probabilities between syllables, and categorically perceiving speech – are now known to be engaged equally well by non-linguistic stimuli. In this paper, we assess the extent to which another candidate mechanism – abstract rule learning – is uniquely engaged by human speech. Specifically, we ask whether the well-documented “speech advantage” in rule learning might result from infants' processing of speech *per se*, or whether it might result from infants' attention to communicative signals including, but not limited to, speech.

Abstract rule learning is the ability to extract generalizable regularities from a stream of input (Aslin & Newport, 2012). For example, given several sequences of syllables such as *go-la-la*, *mu-fi-fi*, and *be-da-da*, one might detect that all sequences follow an ABB rule (in which the latter two elements are identical and distinct from the former). This abstract rule contrasts with stimulus-specific rules (e.g., transitional probabilities, such as that *la* follows *go* 100% of the time, or that all sequences end with /a/) because one could recognize the instantiation of the abstract rule in an entirely novel sequence such as *ci-ru-ru*. Such generalizations are crucial to learning in many domains, but particularly in language acquisition. A hallmark of language proficiency is the ability to comprehend and produce novel utterances, and it seems that humans do so by generalizing rules (e.g., grammatical relations) and categories (e.g., semantic and syntactic groupings) from the linguistic input.

Abstract rule learning in infancy appears to be specifically enhanced by speech. From seven months of age, infants reliably abstract simple ABB, AAB, and ABA rules from streams of spoken syllables (Gómez & Gerken, 1999; Marcus, Vijayan, Rao, & Vishton, 1999). In contrast, infants do not reliably abstract rules from non-speech auditory or visual stimuli (e.g., tones, animal sounds, geometric shapes; Johnson et al., 2009; Marcus, Fernandes, & Johnson, 2007). Even infants exposed to language in another modality (i.e., sign language) do not robustly uncover underlying rules (Rabagliati, Senghas, Johnson, & Marcus, 2012). These observations support the proposal that abstract rule learning may be a speech-tuned mechanism, and may help explain why human infants rapidly learn language while other species do not (Marcus & Rabagliati, 2008).

Others have attempted to explain the “speech advantage” vis-à-vis abstract rule learning without appealing to cognitive adaptations for language. For example, speech may contain phonetic redundancies that guide infants towards an abstract rule (e.g., ABB) in ways that less redundant stimuli do not (Frank, Slemmer, Marcus, & Johnson, 2009a; Thiessen, 2012). Or, being a highly familiar signal, speech may be more efficiently processed relative to other stimuli and thus leave infants' relatively limited cognitive resources free to uncover abstract rules

(Saffran, Pollak, Seibel, & Shkolnik, 2007). Although some empirical evidence supports both of these proposals, they appear limited in explaining the phenomena. Removing phonetic redundancies from speech stimuli does not entirely eliminate rule learning (Thiessen, 2012), and even in cases where stimuli are familiar to infants (e.g., animal sounds), infants fail to abstract rules (Marcus et al., 2007). Thus a satisfying explanation of the speech advantage in abstract rule learning is still outstanding.

Here we propose one such explanation. Unlike previous proposals, our account does not appeal exclusively to infants' perceptual faculties. Instead, we propose that infants may best acquire abstract rules from speech because of its status as a communicative signal.

This hypothesis has its roots in two basic developmental observations. First, several findings lend support to the claim that infants might represent the broad communicative function of speech. Socially-relevant stimuli (e.g., faces, voices) draw infants' attention from very early in life (Valenza, Simion, & Cassia, 1996; Vouloumanos & Werker, 2007). And infants' abilities to reason about agents, intentions, relationships, and psychological states suggest that they may not be limited to recognizing speech by its acoustic properties but by its status as a communicative and socially-relevant signal (see Baillargeon et al., 2013 for review). Second, communicative signals (including, but not limited to speech) have been shown to engage infants' cognitive capacities in ways that non-communicative signals do not. For example, communicative signals appear to modulate infants' encoding of category-relevant information (e.g., of objects; Csibra & Gergely, 2009; Ferguson & Waxman, 2013; Yoon, Johnson, & Csibra, 2008). Likewise, and perhaps most relevant to the present study, infants' acquisition of unfamiliar speech sounds is more successful in communicative than non-communicative contexts (Hoff, 2006; Kuhl, 2007; Kuhl, Tsao, & Liu, 2003). These findings broadly suggest that infants' learning may be enhanced by social-communicative contexts. Collectively, this work offers explanatory power for why speech – being a communicative signal embedded in social contexts – would support infants' abstract rule learning in ways that non-communicative stimuli do not.

This hypothesis also aligns with evidence of tuning effects in infancy. Several studies document that infants tune in to relevant social and communicative signals across the first year of life – for example, to their native language or to human faces (Frank, Vul, & Johnson, 2009b; Pascalis, de Haan, & Nelson, 2002; Vouloumanos, Hauser, Werker, & Martin, 2010; Werker & Tees, 1984). Critically, a similar tuning can be seen in infants' abstract rule learning. Although 7-month-olds reliably fail to acquire abstract rules from tones, one study showed that 4-month-olds can succeed (Dawson & Gerken, 2009). If infants' success in rule learning from speech were due to its communicative status, one might predict tuning of rule learning abilities as infants tease apart the communicative (e.g., speech) from non-communicative sounds (e.g., tones).

In the present study, we predicted that, if communicative signals promote infants' rule learning, then infants should succeed in learning rules from non-speech signals that they believe serve a communicative function. To test this, we asked whether 7-month-olds would abstract rules from sine-wave tones (which have consistently failed to facilitate rule learning in previous studies) if tones were first introduced as a communicative signal. This method was successfully used in a related line of work demonstrating that both speech and non-speech communicative signals facilitate infants' object categorization (Ferguson & Waxman, 2013). Here, we briefly exposed infants to tones in one of two brief vignettes before they were exposed to tones in the rule-learning task of Marcus and colleagues (2007). In one condition, infants were led to believe that tones were communicative: the tones were embedded as a communicative signal in a short video dialogue between two women. In a control condition, the same tones and speech sounds were uncoupled from the communicative dialogue and played in the background of a social – though non-communicative – interchange between the same two women. If a signal's communicative status influences the ability to learn abstract rules, these two vignettes should have different effects on subsequent rule learning: Only infants exposed to *communicative* tones should show evidence of rule learning. In contrast, if infants' abstract rule learning is not influenced by a signal's communicative status, then infants should fail to abstract rules from sine-wave tones, as in previous studies at this age (Dawson & Gerken, 2009; Marcus et al., 2007).

Methods

Participants

Twenty-eight 7-month-old infants (10 F; $M = 7.54$ months, $SD = .27$), recruited from Evanston, IL, USA and the surrounding area, were included in the final analyses. Each participant was assigned to either the *Communicative* ($N = 16$) or *Non-communicative* ($N = 12$) condition. An additional 12 infants (5 Communicative, 7 Non-communicative) were excluded due to fussing out ($N = 8$), technical failure ($N = 2$), lack of disengagement from visual stimuli on a majority of test trials ($N = 1$), or as a statistical outlier¹ (looking preference > 2.5 SD from the condition mean; $N = 1$).

Procedure

In an adaptation of the Headturn Preference Procedure used in previous studies on infant rule learning (e.g. Marcus et al., 1999, 2007), participants engaged in three experimental

¹ Including this outlier in the final analysis does not influence the results of the main analysis (learning by condition) at $\alpha = .05$. However, inclusion does affect the interpretation of a secondary analysis in which we look at infants' learning by the particular rules contrasted in Familiarization and Test.

phases: an Exposure phase, a Familiarization phase, and a Test phase. For the duration of the experiment, infants sat on their caregiver's lap. Visual stimuli were presented on a centre monitor and two side monitors, and auditory stimuli were presented from speakers beneath each side monitor. Caregivers listened to unrelated music on headphones, and were asked to avoid pointing or speaking with the infant.

The Exposure phase (58 sec) introduced infants to sine-wave tones in a communicative context. Infants watched a brief videotaped vignette that varied by condition. In the *Communicative* condition, two female actors engaged in a brief conversation. One actor, the 'Speaker,' spoke in English. The other actor, the 'Beeper,' communicated by producing sine-wave tones (dubbed over her mouth movements, notes A3-G3). The scene was designed to be engaging for infants: During their conversation, both actors looked, smiled, and waved at the infant and each other. By embedding the tones within this socially rich, contingent exchange, we reasoned that infants might imbue the otherwise inert sine-wave tone sound with communicative status. In the *Non-communicative* condition, infants saw a different vignette in which the same two actors engaged in a social, cooperative interchange (baking). Both actors engaged the baby with eye contact, waving, and smiling, but crucially, they did not verbally communicate with each other. Instead, infants heard the same dialogue from the Communicative condition (at the same volume) as if it were playing on the radio in the "background" of the scene. In this way, the familiarity of the tones – and their alternation with the Speaker's utterances – was identical across both conditions. However, only in the Communicative condition was it made clear that these tones served a communicative purpose.

In the Familiarization phase (2 min 34 sec), infants heard four repetitions of 16 tone sequences that followed a common rule (either AAB, ABB, or ABA).

In the Test phase, infants participated in (up to) 12 trials. Each trial began when a visual stimulus appeared on the centre monitor. After infants fixated on this stimulus, it disappeared and re-appeared on either the left or right monitor (counterbalanced). When infants fixated on this side monitor, infants heard one of two pairs of test sequences. In Familiar trials, infants heard two new tone sequences that followed the same rule as in Familiarization. In Novel test trials, infants heard two new tone sequences that followed a different rule. For example, an infant who heard ABB sequences during Familiarization would hear an ABB pattern during Familiar trials and either AAB or ABA sequences during Novel trials. Each test trial sequence pair repeated until the infant looked away for 2 consecutive seconds or until a maximum of 16 seconds had elapsed. Trials with less than 2 seconds of looking time were excluded and attempted again at the end of the Test phase.

Infants were assigned to one of two rule contrasts (ABB-AAB, ABB-ABA) in one of four orders across Familiarization-Test: ABB-AAB, AAB-ABB, ABB-ABA, and ABA-ABB. By counterbalancing infants across

contrasts and orders, we ensured that any overall preferences at Test could not be explained by an intrinsic preference for any particular rule. This permitted us to ask whether infants' learning was robust across all rules, or whether certain rules were easier to learn than others (e.g., Gervain et al., 2008).

Stimuli

Auditory All tone sequences contained three 300-ms tones separated by a 250-ms silent pause. A 1000-ms pause occurred between sequences. During Familiarization, the sequences were constructed from the same categories of *A* tones (C, C#, F#, and G) and *B* tones (F, D#, E, and D). During Test, to assess whether infants would generalize an abstract rule, the sequences were constructed from novel *A* tones (G#, B) and *B* tones (A#, A).

Visual We used an image of the Beeper's face looming pseudorandomly (extracted from the vignette) as the visual stimulus in both conditions. This image varied slightly between Familiarization and Test, to help keep infants interested in the task. A pilot study revealed that visual stimuli used in previous Headturn Preference studies (e.g., a flashing light or a coloured spinning wheel) were unable to keep infants interested in the task, likely due to the extended length of our experiment relative to previous studies (Frank, Slemmer, Marcus, & Johnson, 2009a; Marcus et al., 1999; 2007).

Coding

Using custom MATLAB software, each infant's looking time to the side monitors on each test trial was coded online by a trained observer.

Analyses

The dependent measure was each infant's mean looking time to the side monitor during Novel and Familiar trials. On average, infants contributed an equal number of trials of each type ($M_{\text{Familiar}} = 5.43$, $M_{\text{Novel}} = 5.25$), paired $t(27) = 1.10$, $p = .28$. Based on previous studies on abstract rule learning, we expected that infants who reliably generalized the abstract rule from Familiarization to Test would look longer during Novel trials than Familiar trials.

A preliminary ANOVA did not find any effect of sex and familiarized rule (between-subjects) or monitor side (within-subjects) on looking time (all p 's > .3), therefore subsequent analyses collapsed across these factors.

To assess whether infants generalized the abstract rules to the test trials, and whether this ability varied by condition, we entered the data into a mixed 2x2 ANOVA with Trial type (Familiar vs. Novel, within-subjects), Condition (Communicative vs. Non-Communicative, between-subjects), and their interaction as model parameters predicting looking times during test trials.

If infants are capable of abstracting rules from novel, non-speech communicative signals, we predicted that

infants would show a novelty preference in the Communicative condition but not the Non-communicative condition.

Results

In accord with our predictions, the results revealed that infants in the Communicative condition learned the abstract rules, but infants in the Non-communicative condition did not. Overall, infants showed evidence of rule learning, preferring Novel ($M = 5.90$ s [5.15, 6.65], $SD = 1.94$) over Familiar ($M = 5.37$ s [4.70, 6.05], $SD = 1.74$) trials, $F(1,26) = 4.35$, $p = .047$. However, this preference was qualified by a reliable Rule by Condition interaction, $F(1,26) = 7.81$, $p = .01$. Planned simple-effects tests revealed that only infants in the Communicative condition looked more during Novel ($M = 6.75$ s [5.69, 7.82], $SD = 2.01$) than Familiar trials ($M = 5.72$ s [4.74, 6.71], $SD = 1.84$), paired $t(15) = 4.30$, $p < .001$ (14/16 preferred the novel rule). Infants in the Non-communicative condition had no preference for Novel ($M = 4.75$ s [4.05, 5.46], $SD = 1.11$) over Familiar trials ($M = 4.90$ s [3.92, 5.89], $SD = 1.55$), paired $t(11) = -.41$, $p = .69$ (4/12 preferred the novel rule).

Our analysis also identified a main effect of Condition on overall looking during test. Infants in the Communicative condition looked significantly longer overall ($M = 6.24$ s [5.24, 7.23], $SD = 1.87$) than in the Non-communicative condition ($M = 5.90$ s [5.15, 6.65], $SD = 1.94$), $F(1,26) = 5.24$, $p = .030$. This suggests that infants in the Communicative condition may have stayed more engaged in the task than those in the Non-communicative condition. However, there was no reliable difference between total looking during the familiarization phase, $t(26) = -1.26$, $p = .22$, suggesting that the overall looking time difference may be the result of infants in the Communicative condition being particularly interested by the Novel sequences at test.

Finally, in the Communicative condition, infants discriminated both rule contrasts (ABB-AAB or ABB-ABA) equally well, $t(14) = -.21$, $p = .84$.

Discussion

These findings reveal the powerful influence of a signal's communicative status on infants' capacities to learn abstract rules. Infants who were introduced to sine-wave tones as a communicative signal successfully abstracted rules from tones, and their learning was robust across a variety of rules. In contrast, infants who were introduced to tones in the context of a social – though non-communicative – exchange did not subsequently abstract rules from tones.

This experiment complements previous work looking at perceptual influences on infants' rule learning (e.g., Frank, Slemmer, Marcus, & Johnson, 2009a; Saffran et al., 2007; Thiessen, 2012) by documenting that a signal's communicative status bears on infants' abilities to detect its rule-based structures. It also provides the first evidence that

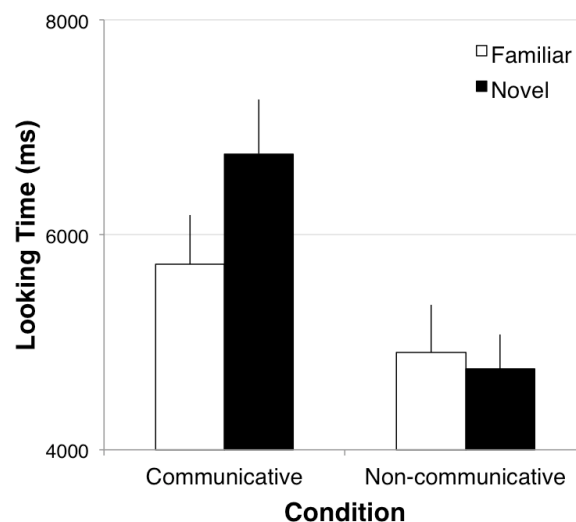


Figure 1: Infants' looking at test by condition. Only infants in the Communicative condition showed a reliable preference for Novel trials.

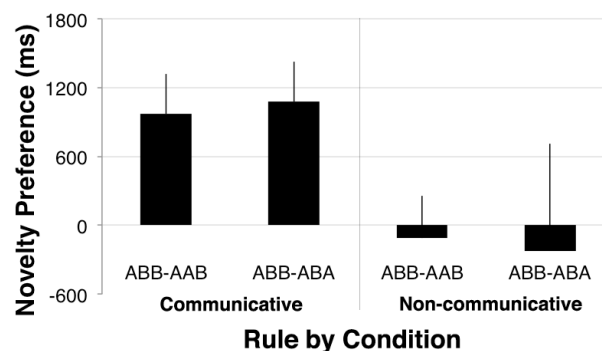


Figure 2: Infants' mean preference for the novel trials by rule and condition. Infants in the Communicative condition discriminated both rule contrasts. Infants in the Non-communicative condition did not.

7-month-old infants can learn abstract rules from a non-speech auditory signal (cf. Dawson & Gerken, 2009; Marcus et al., 2007). In light of these new data, we propose that infants' representations of speech as a communicative signal underlie the speech advantage observed in previous rule learning studies (e.g., Marcus et al., 2007; Marcus & Rabagliati, 2008).

We turn now to two open questions regarding infants' identification of relevant communicative signals and their links to abstract rule learning.

How do infants identify communicative signals?

Our interpretation assumes that infants in the Communicative condition listened to the tones in the exposure phase as a potentially relevant communicative

signal. However, it remains unclear what elements of the exposure video would be crucial to this inference. Combining the present data with previous studies on infants' communicative development, we argue that the overt 'turn-taking'-like contingency between tones and other familiar communicative signals is a likely candidate (Csibra, 2010). Infants have been shown to discriminate high-contingency social interactions (e.g., between mother and child) from low-contingency interactions by just two months of age (Nadel, Carchon, Kervella, Marcelli, & Reserbat-Plantey, 1999). Infants also use social contingency to infer that objects are communicative agents (Beier & Carey, 2013; Johnson, 2000). From this perspective, the Communicative dialogue in the present experiment was highly supportive of the inference that tones were communicative: Tones were highly contingent with the English speaker's speech, and they were used simultaneously with other communicative signals, such as smiling, laughing, and waving.

How might communicative signals promote rule learning?

After infants identify a stimulus as communicative, how might it then facilitate learning? Here we consider three possible explanations.

First, learning could result from the well-documented finding that communicative and social input engages infants' attention in ways that other stimuli do not (Frank, Vul, & Johnson, 2009b; Valenza et al., 1996; Vouloumanos & Werker, 2007). In concert with this idea, Marcus et al. (2007) hypothesized that it may be infants' profound and early interest in speech that drives the speech advantage in rule learning (see Kuhl et al., 2003 and Kuhl, 2007 for similar arguments regarding infants' phonological development). This attentional account provides a clear explanation for the present data: Although all infants were exposed to identical tone sequences during familiarization, infants' encoding and processing of these sequences may have been most effective in the Communicative condition because they attended more to the tones. Importantly, our data indicate that the attentional boost afforded by communicative signals is covert (i.e., beyond the measure of looking time), because infants' gaze to the visual stimulus during familiarization did not differ across conditions.

A second possibility is that communicative signals do more than broadly attract infants' attention – they may engage and target a particular kind of cognitive processing. It has recently been claimed that communicative signals serve a "naturally pedagogical" function for human infants and engage the cognitive processes that underlie generalization (Csibra & Gergely, 2009; Ferguson & Waxman, 2013; Yoon et al., 2008). This cognitive bias in the context of conspecifics' communicative signals is said to be one of several adaptations that support humans' capacity to learn socially from others (Csibra & Gergely, 2011; see also Tomasello, 2008). On this account, abstract rule learning, being one kind of cognitive capacity supporting

generalization, may be directly enhanced by communicative contexts.

A third possibility is that infants have domain-specific expectations about structure, which privilege learning of repetition-based rules from speech-like stimuli. Dawson and Gerken (2009) proposed this hypothesis after observing that 4- but not 7-month-olds learn rules from tones. In the intervening months, they posit that infants learn that repetitions in tonal stimuli (i.e., music) are too common to be structurally informative. However, because repetitions are relatively rare in speech, they remain an informative structural cue in this domain. Applying this logic to the current data, the communicative exposure may have made tones more speech-like, leading infants to detect repetitions. This explanation is promising, but requires further examination for two reasons. First, if infants can initially learn repetition-based rules from any stimuli, why then do 5-month-olds fail to detect these rules in speech (Frank et al., 2009a)? Second, in order to infer that infants are developing structural expectations for tones (and are not just tuning them out), one would need to demonstrate that infants can learn rules from tones when cues to structure are informative and domain-relevant.

At present, we favour the simple explanation offered by the attentional account. However, future research will better assess the latter two possibilities.

Conclusion

Does infants' prodigious learning from speech result from a speech-specific adaptation for language acquisition or, more generally, from an interest in communicative signals? Given the present data on the detection of abstract rules, we favour the latter hypothesis and suggest that infants' interest in communication is an underlying catalyst for language learning.

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