Cognition 133 (2014) 85–90

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Biased generalization of newly learned phonological alternations by 12-month-old infants

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ARTICLE INFO

Article history:
Received 6 August 2013
Revised 15 May 2014
Accepted 29 May 2014

Keywords:
Phonological alternations
Infant speech perception
Language acquisition
Learning biases
Phonetic similarity

ABSTRACT

Previous work has suggested that learners are sensitive to phonetic similarity when learning phonological patterns (e.g., Steriade, 2001/2008; White, 2014). We tested 12-month-old infants to see if their willingness to generalize newly learned phonological alternations depended on the phonetic similarity of the sounds involved. Infants were exposed to words in an artificial language whose distributions provided evidence for a phonological alternation between two relatively dissimilar sounds ([p ~ v] or [t ~ z]). Sounds at one place of articulation (labials or coronals) alternated whereas sounds at the other place of articulation were contrastive. At test, infants generalized the alternation learned during exposure to pairs of sounds that were more similar ([b ~ v] or [d ~ z]). Infants in a control group instead learned an alternation between similar sounds ([b ~ v] or [d ~ z]). When tested on dissimilar pairs of sounds ([p ~ v] or [t ~ z]), the control group did not generalize their learning to the novel sounds. The results are consistent with a learning bias favoring alternations between similar sounds over alternations between dissimilar sounds.

1. Introduction

Research suggests that infants track the distribution of speech sounds in their language input from an early age and use this information to accomplish a variety of linguistic tasks – discriminating speech sounds (Anderson, Morgan, & White, 2003; Maye, Werker, & Gerken, 2002), learning phonotactics (Chambers, Onishi, & Fisher, 2003), and segmenting words from running speech (Saffran, Aslin, & Newport, 1996). However, many have proposed that phonological learning is biased, such that not all patterns are equally learnable. To determine which biases might be playing a role during phonological acquisition, we must look for cases where infants either (a) fail to learn patterns available in their input (or learn some patterns more slowly than others) or (b) generalize their learning in ways that are not predicted from the input alone. In this paper, we test for the latter.

One bias with ample support in the literature is that complex patterns are more difficult to learn, and less readily generalized, than simpler patterns (adults: Pycha, Nowak, Shin, & Shosted, 2003; Skoruppa & Peperkamp, 2011; infants: Chambers, Onishi, & Fisher, 2011; Cristià & Seidl, 2008; Saffran & Thiessen, 2003; for an overview see Moreton & Pater, 2012a). A more controversial proposal (see Moreton & Pater, 2012b) is that learners prefer patterns with an underlying phonetic motivation, sometimes called a substantive bias (e.g., Wilson, 2006). Under some accounts, learners are biased against "unnatural" or "marked" patterns due to universal grammatical constraints on learning (e.g., Prince & Smolensky, 1993/2004; Tesar & Smolensky, 2000). However, infant studies looking for markedness biases have produced mixed results, with

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http://dx.doi.org/10.1016/j.cognition.2014.05.020
0010-0277/

some providing support (Jusczyk, Smolensky, & Allocco, 2002) and others finding no effect (Seidl & Buckley, 2005).

Another type of substantive bias proposed is that learners prefer phonological processes involving small phonetic changes. Evidence for such a bias has come from language typology (Steriade 2001/2008), artificial language experiments with adults (Skoruppa, Lambrechts, & Peperkamp, 2011; White, 2014; Wilson, 2006), and computational modeling (Peperkamp, Le Calvez, Nadal, & Dupoux, 2006; White, 2013; Wilson, 2006). In this study, we investigated whether 12-month-old English-learning infants' willingness to generalize newly learned phonological alternations is biased in favor of alternations involving phonetically similar sounds.

Phonological alternations occur when surface forms vary systematically depending on their phonological context. For example, in American English the final [t] in *pat* [pæ**t**] is pronounced as a tap sound [ɾ] in *patting* [pæɾɪŋ]. Our testing paradigm and stimuli were based on White et al.'s (2008) study showing that 12-month-olds can learn novel alternations after brief exposure to an artificial language. In their study, infants were exposed to [p] only after consonants and [b] only after vowels (e.g., *rot pevi, na bevi*...), but [s] and [z] appeared after both consonants and vowels. At test, infants preferred listening to novel word pairs beginning with p/b (e.g., *poli/boli*) compared to pairs beginning with s/z (*sadu/zadu*), presumably because *poli* and *boli* were treated as alternating variants of the same word whereas *sadu* and *zadu* were interpreted as distinct words. Infants exposed to the opposite distribution showed the opposite preference at test.

Using a modified version of White et al.'s (2008) design, we exposed infants to alternations involving either pairs of dissimilar sounds (Bias condition) or pairs of similar sounds (Control condition). Unlike White et al. (2008), we then tested infants on novel pairs of sounds that were more similar (Bias condition) or less similar (Control condition) than the alternating sounds heard during exposure. If infants have a bias to prefer alternations between similar sounds, then we expected generalization from dissimilar to similar sounds (Bias condition), but not from similar to dissimilar sounds (Control condition).

2. Experiment

2.1. Method

2.1.1. Participants

Forty 12-month-olds (26 males, mean age = 370 days, age range = 349–407 days) participated. All had more than 85% input in English based on a parental language questionnaire (Bosch & Sebastián-Gallés, 2001; Sundara & Scutellaro, 2011). Eleven additional infants were tested but excluded due to crying ($n = 9$), experimenter error ($n = 1$), or equipment problems ($n = 1$).

2.1.2. Design and stimuli

Infants were randomly assigned to either the Bias condition or the Control condition. In the Bias condition, we exposed infants to alternations involving dissimilar sounds (i.e., sounds differing in two features: voicing and continuancy): [p ~ v] or [t ~ z]. Infants heard phrases consisting of a monosyllabic "function" word (*na* or *rom*) followed by one of sixteen CVCV "content" words (e.g., *rom poli*). For each infant, sounds at one place of articulation (labials or coronals) were in complementary distribution; voiced fricatives (e.g., [v]) only appeared after *na* and voiceless stops (e.g., [p]) only appeared after *rom*, thus providing evidence for a phonological alternation. Sounds at the other place of articulation ([t] and [z]) appeared after both *na* and *rom*, meaning they were contrastive (i.e., not predictable from context and thus able to differentiate words). Infants were divided into two sub-groups, depending on whether they learned the [p ~ v] alternation (Labial sub-group) or the [t ~ z] alternation (Coronal sub-group). In the Control condition, infants were instead exposed to alternations between similar sounds (i.e., sounds differing only in continuancy): either [b ~ v] or [d ~ z] depending on sub-group. For illustration, sample stimuli are provided in Table 1.

Previous results (White et al., 2008) suggest that infants hearing [p] and [v] in complementary distribution (as in the Labial sub-group of the Bias condition) will assume that *puni* and *vuni* are context-dependent variants of the same word, whereas the overlapping distributions of [t] and [z] will lead the infants to interpret *tilu* and *zilu* as different words.

In the current study, however, the focus was to test for biases on how infants generalize this learning, so we tested infants instead on words beginning with novel pairs of sounds.

Infants in the Bias condition were exposed to an alternation involving dissimilar sounds ([p ~ v] or [t ~ z]), but were tested on the similar pairs of sounds ([b ~ v] or [d ~ z]). Infants in the Control condition had the opposite experience: they were exposed to an alternation involving similar sounds ([b ~ v] or [d ~ z]), but tested on the dissimilar pairs of sounds ([p ~ v] or [t ~ z]). Thus, each infant heard two novel sounds during the test phase ([b, d] in the Bias condition, [p, t] in the Control condition), which were never encountered during exposure.

Within a condition, the same twelve test trials were used for all infants regardless of sub-group. Following White et al. (2008), the test words were presented without *na* or *rom*, removing the conditioning context for the alternation. Because infants could not rely on transitional probabilities at test, finding differences would suggest infants have learned that alternating forms are related at an abstract level.[1]

For each sub-group, one of the two novel test sounds ([b] or [d] in the Bias condition, [p] or [t] in the Control condition) was at the same place of articulation as the sounds taking part in the phonological alternation during exposure (Alternating trials), and the other novel sound was at the place of articulation of the contrastive sounds (Contrastive trials). If infants are biased to prefer alternations between similar sounds, infants in the Bias condition were predicted to have different looking times to the

[1] Still, as a reviewer points out, the assumption that infants treat the stimuli as "words" should be considered speculative given the nature of the task. Our conclusions do not rest on this point.

Table 1
Example stimuli to illustrate the experimental design. See Appendix for a full list of stimuli. Shaded cells mark alternating forms; non-shaded cells mark contrastive forms.

	BIAS condition				CONTROL condition			
	Labial sub-group		Coronal sub-group		Labial sub-group		Coronal sub-group	
Exposure phrases	*rom poli* *rom poli*	*na voli* *na voli*	*rom poli* *na poli*	*rom voli* *na voli*	*rom boli* *rom boli*	*na voli* *na voli*	*rom boli* *na boli*	*rom voli* *na voli*
	rom timu *na timu*	*rom zimu* *na zimu*	*rom timu* *rom timu*	*na zimu* *na zimu*	*rom dimu* *na dimu*	*rom zimu* *na zimu*	*rom dimu* *rom dimu*	*na zimu* *na zimu*
Test pairs	*buni/vuni, bagu/vagu, dilu/zilu, dari/zari*				*puni/vuni, pagu/vagu, tilu/zilu, tari/zari*			

Alternating and Contrastive test trials. For instance, the Labial sub-group (i.e., those learning that [p] alternates with [v]) should assume that [b] alternates with [v], but because [t] and [z] are contrastive, they should not assume that [d] alternates with [z]. Therefore, *buni/vuni* should be treated as variants of the same word, whereas *dilu/zilu* should be treated as two separate words. Infants in the Coronal sub-group should also make a distinction, but in the opposite direction. The two sub-groups thus act to counterbalance each other, ensuring that any effects are due to training and not to a baseline preference for some test trials over others. No difference in looking time is predicted in the Control condition because learning an alternation between similar sounds should not warrant generalization to a pair of sounds that are less similar to each other.

A full list of the stimuli is provided in the Appendix. The stimuli were produced by a female native English speaker (phonetically trained), who was unfamiliar with the purpose of the study. The recording was done using PcQuirerX (sampling rate = 44,100 Hz) in a soundproof booth using a Shure SM10A head-mounted microphone, whose signal ran through an XAudioBox pre-amplifier and A–D device box. The stimuli were recorded naturally, as two-word phrases for the exposure stimuli and as single words for the test stimuli, using an infant-directed speaking style. Stress was placed on the first syllable of the disyllabic word.

2.1.3. Apparatus

Infants were seated on their caregiver's lap approximately 3.5 feet from a display monitor in a curtained soundproof booth. The auditory stimuli were played at 78 dB over JBL speakers located just next to the monitor. Presentation of stimuli and data recording were handled automatically by Habit X (Cohen, Atkinson, & Chaput, 2004).

The experimenter sat in an adjacent room watching the infant via a monitor connected to a Sony digital video camera hidden just under the display screen in front of the infant. Both the experimenter and the caregiver wore headphones playing music so they could not influence the infant's behavior.

2.1.4. Procedure

Infants were tested using the visual fixation procedure (Werker et al., 1998). At the beginning of each trial, a looming light was paired with a baby giggle to attract the infant's attention. When the infant looked at the screen, a picture of a flower appeared on the screen while an auditory stimulus was played simultaneously over the speakers. One flower appeared for all exposure trials and a different flower appeared for all test trials.

In the exposure phase, infants heard three trials lasting 45 s each for a total of 135 s. Each exposure trial contained all 32 of the exposure phrases for that condition (e.g., *na voli, rom tago, rom poli…*), with a 300 ms pause between each phrase. Each "content" word was presented twice per trial, either once with each of the two "function" words for contrastive words, or twice with the same "function" word for alternating words. Three random orders were generated for the phrases, one for each trial, which remained constant for all infants. The order of the three trials was randomized anew for each infant. The exposure trials were not contingent on infant looking to ensure that each infant had the same amount of exposure.

In the test phase, infants in both the Labial and Coronal sub-groups heard the same test trials (3 blocks X 4 trials = 12). Each trial contained one pair of test words repeated several times (e.g., *bagu, vagu, vagu, bagu…*) with a 300 ms pause between each word. Within a trial, the order of the words was pseudo-randomized with two restrictions: the same word could occur only twice in a row and each word appeared as one of the first two words of each trial. Each pair of test words was presented once per block. Order of the test trials was counterbalanced across infants.

The test trials were fully contingent on infant looking. The next test trial began either after the infant had looked away from the screen for more than one second or after the maximum test trial duration (20 s). A trial was repeated if the infant looked away during the first two seconds of the trial.

2.2. Results

The results were analyzed using a $2 \times 2 \times 2$ mixed ANOVA with between-subjects variables for Condition (Bias or Control) and Sub-group (Labial or Coronal), a within-subjects variable for Trial Type (Alternating vs. Contrastive), and looking time (in seconds) as the dependent variable. Recall that which test trials counted as Alternating or Contrastive depended on which alternation the infants learned during training, and thus on their sub-group.

The ANOVA revealed no main effect of Condition, $F(1, 36) = .01$, $p = .93$, $\eta_p^2 = 0$, and no main effect of Trial Type, $F(1, 36) = 1.50$, $p = .23$, $\eta_p^2 = .04$, but there was a significant Condition by Trial Type interaction, $F(1, 36) = 5.74$, $p = .02$, $\eta_p^2 = .14$. The main effect of Sub-group and each of its associated interactions were non-significant (all $p > .10$), so the two sub-groups were collapsed in subsequent analyses.

To further investigate the significant Condition by Trial Type interaction, we conducted post hoc paired-samples *t*-tests (with Bonferroni-adjusted alpha levels of .025). In the Bias condition, infants looked significantly longer to Contrastive trials than to Alternating trials, $t(19) = 3.36$, $p < .01$, Cohen's $d = .31$ (Table 2). In the Control condition, however, there was no statistical difference in looking time between Contrastive and Alternating trials, $t(19) = .658$, $p = .52$, Cohen's $d = .09$. Non-parametric tests support this finding: 15 out of 20 infants in the Bias condition looked longer to Contrastive trials (Wilcoxon $Z = 2.84$, $p < .01$), compared to 9 out of 20 infants in the Control condition (Wilcoxon $Z = .52$, $p = .60$), see Fig. 1.

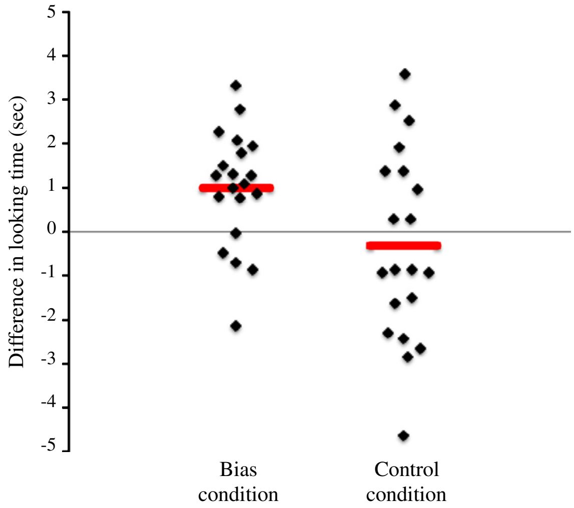

Fig. 1. Mean difference in looking time between Contrastive trials and Alternating trials, plotted individually for each infant in the Bias and Control conditions. Individual points have been jittered along the *x*-axis to improve readability. Bars indicate the group means.

3. Discussion

As predicted, there was a difference in looking time to Alternating and Contrastive trials in the Bias condition, but not in the Control condition. Recall that infants had no direct evidence from the input that could have led them to treat the two types of trials differently – all test trials had novel sounds not presented during the exposure phase. These results have implications for understanding how phonological alternations are learned and generalized.

Previous work suggests that 12-month-olds can learn novel phonological alternations based on distributional evidence after brief exposure to an artificial language (White et al., 2008). The current results provide corroborating evidence for this conclusion because infants differentiated the Alternating and Contrastive trials in the Bias condition. Only if infants had learned the alternations presented during exposure would we expect differences between the test items in either condition. It is worth noting that the direction of the effect was different in the current study and in White et al.'s study: we found that infants listened longer to Contrastive trials whereas White et al. found the opposite pattern. This difference is plausibly due to the fact that we tested generalization to novel sounds whereas White et al. tested the same alternations that were presented during exposure.

Second, the results suggest that infants take phonetic similarity into consideration when generalizing alternations to new sounds. The Alternating and Contrastive test trials were differentiated in the Bias condition, where word-initial sounds at test were more similar than the word-initial sounds presented during exposure, but not in the Control condition, where the word-initial sounds at test were less similar than those presented during exposure. We know, both from previous work (White et al., 2008) and from the Bias condition of the current study, that 12-month-olds are capable of learning alternations like those presented in the Control condition, which suggests that the lack of a difference in the Control condition is due to a failure to generalize rather than a failure to learn the alternations in the first place. This asymmetry in generalization (i.e., from less similar sounds to more similar sounds, but not *vice versa*) is consistent with the proposal that learners are biased to prefer alternations between phonetically similar sounds (Peperkamp et al., 2006; Steriade, 2001/2008; White, 2013, 2014; Wilson, 2006).

What is the nature of this bias? Insights from computational modeling allow us to generate some hypotheses about the role that such a bias might play during learning. For instance, in a distributional learning model implemented by Peperkamp et al. (2006), linguistic filters rule out alternations if any sound is phonetically "intermediate" between the potentially alternating sounds (where intermediate is defined in terms of relevant phonetic properties).[2] Although such a hard bias helps the model avoid erroneous phonological mappings, it would also rule out certain phonological patterns documented in existing natural languages (White, 2013, 2014). In contrast, other approaches have implemented the bias in maximum entropy learning models by assigning greater prior likelihoods to alternations involving small perceptual changes compared to those involving large perceptual changes (White, 2013; Wilson,

Table 2
Mean looking time (in sec) according to Condition and Trial Type. Standard deviations are given in parentheses.

	Bias condition	Control condition
Contrastive trials	8.34 (3.36)	7.60 (3.34)
Alternating trials	7.35 (3.02)	7.92 (3.44)

[2] Note that Peperkamp et al. (2006) actually focused on purely allophonic rules rather than alternations in testing their model. However, as the authors point out in their conclusions, it is worthwhile to consider how such a learning model would fare for other types of phonological patterns (such as those resulting in alternations) as well.

2006). Under this implementation, learners have a soft bias, such that alternations between dissimilar sounds are initially dispreferred, but still learnable given enough input. Such models predict asymmetrical generalization of alternations, that is, a greater tendency to generalize from less similar sounds to more similar sounds than *vice versa* (White, 2013), as was found with infant learners in the current study, as well as adult learners in previous work (White, 2014).

Finally, these results make explicit predictions about the time course of phonological acquisition. If the results found here are indeed due to a bias favoring alternations between similar sounds, infants should learn alternations between similar sounds earlier than alternations between less similar sounds, all else being equal. Further studies are necessary to evaluate this prediction.

Acknowledgements

We would like to thank Bruce Hayes, Sharon Peperkamp, Kie Zuraw, and three anonymous reviewers for helpful comments that led to the improvement of this work. We would also like to thank Chad Vicenik, Robyn Orfitelli, Nancy Ward, and research assistants in the UCLA Language Acquisition Lab for their assistance with scheduling and testing infants. An earlier version of this project was presented at the 37th Boston University Conference on Language Development. Any remaining errors are our own. This research was funded by NSF Grant BCS-0951639 to MS.

Appendix A.

Full list of stimuli.

Bias condition

	Labial sub-group				Coronal sub-group			
rom	*poli*	*panu*	*pezi*	*pika*	*tovi*	*tago*	*turo*	*timu*
na	*voli*	*vanu*	*vezi*	*vika*	*zovi*	*zago*	*zuro*	*zimu*
rom/na	*tovi*	*tago*	*turo*	*timu*	*poli*	*panu*	*pezi*	*pika*
	zovi	*zago*	*zuro*	*zimu*	*voli*	*vanu*	*vezi*	*vika*
Test pairs	*buni/vuni, bagu/vagu, dilu/zilu, dari/zari*							

Control condition

	Labial sub-group				Coronal sub-group			
rom	*boli*	*banu*	*bezi*	*bika*	*dovi*	*dago*	*duro*	*dimu*
na	*voli*	*vanu*	*vezi*	*vika*	*zovi*	*zago*	*zuro*	*zimu*
rom/na	*dovi*	*dago*	*duro*	*dimu*	*boli*	*banu*	*bezi*	*bika*
	zovi	*zago*	*zuro*	*zimu*	*voli*	*vanu*	*vezi*	*vika*
Test pairs	*puni/vuni, pagu/vagu, tilu/zilu, tari/zari*							

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