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Extracting Regularities From Noise: Do Infants Encode Patterns Based on Same and Different Relations?

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A fundamental task of the young learner is to extract adjacent and distant dependency relations from the linguistic signal. Previous research suggests that infants successfully learn regularities from mini-grammars that contain a single consistent pattern. However, outside laboratory infants are exposed to a "noisy" linguistic signal that contains multiple regularities and patterns that infants cannot yet interpret. In four experiments we explore how infants extract regularities from a 50% "noisy" input. Using an eye-tracker methodology we investigate how infants integrate patterns of varying complexity (e.g., adjacent and nonadjacent identity relations, or identity- and diversity-based relations) into differential anticipatory eye-movements. In Experiment 1, 7- and 12-month-olds were simultaneously exposed to AA and AB patterns (where As and Bs stand for syllables, such as in *vava*, *valu*) and they showed successful generalization for AA, but not for AB tokens. In Experiment 2, 7-month-olds heard AAB and ABA patterns and generalized only the AAB patterns. However, in Experiment 3 infants could learn the ABA patterns when these were paired with ABC structures. Experiment 4 asked whether identity-based generalizations are restricted to exact physical identity. Infants generalized the $A^hA^lB^h$ patterns (where ^{h} stands for high pitch and ^{l} for low pitch), but not the $A^hB^lA^h$ ones, although in these the A syllables were physically identical. The results suggest that preverbal infants posses powerful abilities to extract

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regularities from a noisy signal, and point to a possible hierarchy in encoding. Adjacent repetitions were computationally preferred over nonadjacent ones, even when adjacent repetitions were based on phonological identity, while non-adjacent ones on physical identity. While infants readily generalized the bi- or tri-syllabic structures based on identity relations they did not do so with the non-identity relations. Conceivably, encoding structures based on "same" relations are easier for infants than encoding diversity, suggesting that generalizations based on "different" relations pose a challenge for the developing cognitive system.

Introduction

In order to make sense of the world, young learners should keep track of a large number of regularities in their physical and social environment, and language acquisition constitutes a particularly good example. Infants will readily learn the words and the rules of their native language from a linguistic input that tends to be highly complex and noisy.

Various possible mechanisms have been proposed to play a role in early language acquisition. For example, it has been argued that infants learn words from the speech they encounter by tracking which syllables tend to co-occur. Specifically, if a syllable like "ba" has a high "transition" probability of being followed by a syllable like "by," infants might conclude that "baby" forms a word. In the last twenty years we gained vast knowledge about how infants learn various co-occurring patterns present in their linguistic (e.g., Aslin, Saffran & Newport, 1998; Saffran, Aslin & Newport, 1996, Lew-Williams, Pelucchi, & Saffran, 2011) or visual environment (Fiser & Aslin, 2002; Kirkham, Slemmer, & Johnson, 2002). However, learners are not only sensitive to transition probabilities between immediately adjacent syllables, but also between syllables across intervening syllables (i.e., second-order transition probabilities, Gómez, 2002; Peña, Bonatti, Nespor, & Mehler, 2002; Endress & Bonatti, 2007).

Tracking distant dependency relations between diverse components of the linguistic signal will allow the young learner to converge to the rules of their native language and to extract its more abstract features. Natural languages are full of nonadjacent morphosyntactic dependency relations, such as the relation between the auxiliary verb "is" and the ending of the main verb "-ing" in English. Studies have explored experimentally how infants learn such dependencies using natural language stimuli (Santelmann & Jusczyk, 1998) or employing artificial mini-grammars with specific organizing principles applied to syllable occurrences or to stress-patterns (Gerken, 2004; Gómez & Gerken, 1999; Marcus, Vijayan, Rao, Bandi & Vishton, 1999). For instance, after a short exposure 9-month-old infants were found to generalize the stress patterns encountered during familiarization to new patterns reflecting the same constraints (Gerken, 2004). Somewhat older infants, 18-month-olds, showed efficient learning of nonadjacent relations of the type AXB or CXD, where there was a dependency between the A and B, and the C and D elements (Gómez, 2002). Infants in this study detected the relation between the first and the last element only if the middle element was highly variable, suggesting that variability may be crucial for generalization. While the question whether word learning and rule learning rely on the same mechanisms is debated (Peña et al., 2002; Perruchet, Tyler, Galland, & Peereman, 2004), recently published studies with 12- and 18-month-olds suggest that sensitivity to structural information (allowing rule-extraction) may even precede a successful analysis of distributional information between co-occurring syllables (Marchetto & Bonatti, 2013).

Further evidence for regularity-based generalization in younger infants was documented by Marcus et al. (1999). According to the results of this study, 7-month-olds are sensitive to abstract repetition-based structures implemented in artificial mini-grammars. Infants were familiarized to patterns following a specific structure, for example, ABB (where As and Bs stand for syllables, as in wo-fe-fe). In test they were exposed to new tokens of the same structure and a new structure (e.g., ABA) and they could discriminate them, suggesting that they have learned the familiarization structure. Although the mechanisms underlying infants' behavior in such tasks are debated (Altmann & Dienes, 1999; Eimas, 1999; Endress, Scholl & Mehler, 2005), Marcus et al. have argued that 7-month-old infants are able to extract abstract algebra-like rules that represent relationships between variables. In a further study infants were found to extract repetition-based regularities from non-speech sequences (such as, pure tones, instrument timbres, animal sounds) only if they were first exposed to such regularities in speech sequences (Marcus, Fernandes & Johnson, 2007). The authors argued that extracting regularities from speech facilitates generalization in other domains, because infants may analyze speech input in a special way compared to other acoustic signals. However, repetition-based structures seem to be particularly easy to process, and such abilities do not seem to be specific to language (see evidence from the visual domain or music, Dawson & Gerken, 2009; Saffran et al., 2006) nor to humans, to the extent that rhesus monkeys, rats and even bees are sensitive to them (Giurfa, Zhang, Jenett, Menzel & Srinivasan, 2001; Hauser & Glynn, 2009; Murphy, Mondragon & Murphy, 2008).

Interestingly, while a wealth of studies document infants' powerful abilities to extract regularities from simple mini-grammars, most experimental paradigms have implemented a single consistent pattern. Natural language, in contrast, is much more complex and noisy, and it is largely unexplored how young learners learn from a variable input, containing multiple patterns.

Extracting Structure From Multiple Possible Patterns

Few studies have addressed the question whether infants can extract structures from a complex or noisy input, for instance, when multiple regularities are implemented in the stimuli. Gerken (2006) exposed 9-month-old infants to a set of stimuli where two generalizations were possible, and found that infants made the generalization that was statistically the most consistent with the particular subset of the data they received. In a different study, Kovács & Mehler (2009) explored how monolingual and bilingual 12-month-old infants generalize repetition-based regularities when they are simultaneously exposed to two kinds of structures (AAB and ABA, structures, where As and Bs stand for syllables, see Marcus et al., 1999). They have found that only bilingual infants learned both structures, while monolinguals extracted only one regularity, the one containing adjacent repetitions (AAB). Adjacent repetition-based patterns are easier to process for young infants (Kovács & Endress, 2014), and even newborns are sensitive to AAB, but not to ABA patterns (Gervain, Macagno, Cogoi, Peña & Mehler, 2008).

While the above studies have provided evidence that in case two regularities are present infants seem to choose one, how such learning takes place, and what exact mechanisms are involved remains elusive. Do infants detect that there are two regularities, encode the easier or the more salient one, and ignore the other regularity? Or do they focus on the first found regularity and encode everything else as noise? Infants should possess powerful abilities to extract structure from a complex or "noisy" input, as natural language is considered to be like that from the viewpoint of the young learner. In fact, the speech signal is inherently variable, containing various allophonic variations (Peperkamp, Le Calvez, Nadal & Dupoux, 2006), and samples from different speakers, speech rates, and accents. However, successful language acquisition requires that infants recognize the equivalence of speech sounds. Studies suggest that from around 10 months of age (but not at 7 months) infants can equate words despite changes in talker gender, fundamental frequency, or vocal affect (Houston & Jusczyk, 2000; Singh, Morgan & White, 2004).

Furthermore, sometimes language acquisition seems a real challenge, as many infants around the world are exposed to multiple languages; some acquire their language from non native speakers, and all learners must experience segments that contain mispronunciations or mistakes. Nevertheless, they seem to be able successfully deal with such input in real life (Newport, 1999; Petitto et al., 2001; Pearson, Fernez, & Oller, 1993). In laboratory circumstances, however, studies with both adults and infants seem to suggest that noise or variability can have a detrimental effect on learning (but see Hudson Kam & Newport, 2009). For instance, tracking distributional regularities in word segmentation tasks seem to be disrupted if multiple sets of statistics are implemented (Lew-Williams & Saffran, 2012; Weiss, Gerfen & Mitchel, 2009). Studies have found that 9- and 10-month-old infants fail to segment a continuous stream of syllables if they are first exposed to a stream containing disyllabic words followed by another stream with trisyllabic words, but succeed with streams that contain only one word type (Lew-Williams & Saffran, 2012).

Given the above findings, it is unclear why infants succeed to extract a pattern from a noisy input in some cases (Gerken, 2006; Kovács & Mehler, 2009), while learning is disrupted in others (Lew-Williams & Saffran, 2012). Keeping in mind that these studies used different stimuli and methods, addressing different questions (pattern extraction vs. speech segmentation), one could intuitively argue that a segmentation task should be easier than a generalization task (but see Marchetto & Bonatti, 2013). A possible explanation for such discrepant findings could be that in the case of the study by Kovács & Mehler (2009), one regularity was more salient and easier to encode, and infants might have considered everything else as noise. In contrast, there was no salience difference between the two streams in the stimuli of Lew-Williams & Saffran (2012). However, evidence that young infants can indeed learn from a noisy input is still very scarce, given that, as mentioned earlier, the stimuli of Kovács & Mehler actually contained two regularities. Thus it is difficult to decide whether infants considered the second regularity as noise, or they have realized that there is yet another regularity and ignored it.

Learning Identity and Diversity-Based Relations

To address these questions here we investigate whether infants as young as 7 months can successfully learn when they are exposed in 50% of the trials to a well defined regularity (e.g., AA, that is words like *vava, lulu*) and in the remaining 50% of trials to a random pattern (e.g., AB, such as *valu, luva*), which in this case would stand for "noise" in the input. While we predicted that infants would learn the identity-based structure (AA, corresponding to a same relation) and ignore the diversity-based structure (AB, corresponding to a different relation), it is not clear how diversity-based structures might be encoded. One might argue that infants could learn the two patterns with the same facility, as representing identity and representing diversity might be computationally equivalent. Indeed, training studies with various kinds of animals suggest that they seem to be able to learn both repetition-based (matching-to-sample) and diversity-based (mismatch-to-sample) patterns (Giurfa et al., 2001; Hauser & Glynn, 2009; Murphy et al., 2008). However, while there is extensive research suggesting that infants readily encode repetition-based structures (Gerken, 2006; Kovács & Endress, 2014; Kovács & Mehler, 2009; Marcus et al., 1999), evidence showing that infants can learn diversity-based patterns is scarce.

It was argued that repetition-based structures might not rely on specifically linguistic processes (Gómez & Gerken, 2000), but rather on a "repetition detector" (Endress, Dehaene-Lambertz & Mehler, 2007). Thus, while repetitions such as AA might be easily encoded, diversity-based patterns, such as AB, might be difficult to encode. On the one hand, when a child is exposed to patterns containing two different syllables (AB, CD, EF), s/he could perceive them as random patterns or noise, rather than a diversity-based pattern. On the other hand, as argued by Premack (2010), to encode and generalize an AB pattern as a structure, one should first encode the relation between A and B (different relation) and then make a judgment regarding a relation between relations (i.e., that the relation between AB and CD is the same). However, although children match physically alike objects at an early age, and infants might show rudiments of analogical problem solving (Chen, Sanchez, & Campbell, 1997), they do not seem to successfully match relations until they are about 4 or 5 years of age (Premack, 2010).

Thus, conceivably, encoding structures based on repetitions will be easier for infants than encoding constructs based on diversity. Experimental data from adult studies supports this possibility. Adults can readily learn repetition-based patterns, in contrast, diversity-based patterns or alternations are more difficult and even interfere with performance (Falk & Konold, 1997; Kareev, 1995). When faced with an input containing both repetition-based and diversity-based structures, infants might perceive the latter as "noise" and ignore it, learning only the regularity they can easily process. Alternatively, the overwhelming presence of such noise (50%) might seriously impair learning in general.

However, it is likely that young infants possess powerful mechanisms to detect the salient patterns in a noisy input.

To investigate these issues, we performed a series of experiments, in which, on the one hand, we will expose infants to a noisy speech-like input containing identity-based structures and diversity-based ones. On the other hand, we will ask whether learning adjacent repetition-based patterns are easier than learning nonadjacent ones, and whether such learning is restricted to exact physical identity. We will pit against each other adjacency (adjacent/nonadjacent) and the nature of the identity (physical/phonological identity) using ABA structures (where the two As are physically identical) and AA'B structures (where the two As have a different pitch).

Experiment 1: Learning Simple Patterns Based on Same-different Relations (AA vs. AB)

In Experiment 1 we investigate whether 7- and 12-month-old infants can learn simple structures that are based on identity and diversity (same/different) relations. For instance, the AA patterns have a well-defined structure, namely, they are constituted of words with repeated syllables, as in "vava," whereas the diversity-based AB structures contain words with two diverse syllables, such as "valu."

Presumably these two patterns are maximally different from each other, and thus it should be easy to distinguish and learn them. If infants will learn only one pattern (as it was observed in earlier studies, Kovács & Mehler, 2009; Hochmann, Benavides-Varela, Nespor & Mehler, 2011), for example, AA, it will suggest that repetition-based patterns are computationally easier to process than diversity-based ones, and also support the hypothesis that the presence of 50% "noise" does not impair learning.

Method

Participants

The participants were 16 7-month-old infants (8 girls, mean age = 7.22) aged from seven months 6 days to eight months 3 days; and 16 12-month-olds (7 girls, mean age = 12.22) aged from twelve months 5 days to thirteen months 5 days. Additional 18 infants were excluded (9 twelve-month-olds) because of crying or fussiness ($n = 12$), failing to calibrate the eye tracker ($n = 2$), side bias[1] ($n = 3$), or experimental error ($n = 1$). In all four experiments, participants were monolingual Italian full-term infants recruited from Trieste (Italy), and parents' consent was obtained following the rules of the Ethical Committee of SISSA, the studies complying with the Declaration of Helsinki.

Stimuli

Linguistic stimuli followed two simple patterns. They could have either repeated syllables (as in vava), or two different syllables (as in valu). For the familiarization, we constructed six AA and six AB nonce words from six syllables (va, lu, da, vu, la, du). The two AA and AB structures used for test were constructed from two novel syllables (ke, gi). The items used in familiarization were: vava, lulu, dada, vuvu, lala, dudu, vula, vadu, duva, dalu, lavu, luda; and in test: keke, gigi, gike, kegi. We have chosen similar test phonemes to what was used in earlier studies (Gerken, 2006). The duration of each phoneme was 200 ms, with 250 ms pauses between them and a monotonous pitch of 200Hz. The stimuli were synthesized with MBROLA (Dutoit, 1997), using the soft voice of the German DE7 diphone base. The visual rewards consisted of three colored puppets that appeared inside one of the two white squares on the left or right. The puppets loomed from 4 to 7 cm (visual angle from the infant's position 9.14° to 15.9°) for 2 seconds. The squares had a side-length of 8 cm (18.18°), with a distance between them of 13.5 cm (30.2°). Rewards were randomly paired with the linguistic material.

Apparatus

Infants' eye gaze was collected with a TOBII 1750 Eye Tracker integrated into a 17-inch TFT monitor, where the stimuli were presented via an Apple Dual G5 computer running PsyScope X (http://psy.ck.sissa.it). Infants were seated on their parent's lap at a 50 cm distance from the monitor. A video camera was mounted above the monitor. A loudspeaker was placed behind the monitor for the presentation of the acoustic stimuli. After the parent put on opaque sunglasses, a five-point calibration was carried out.

Procedure

We used a procedure similar to the one used by Kovács & Mehler (2009). Following calibration the experiment began. Trials started with a display of two white squares on the sides and a central attention getter. The experimenter displayed the linguistic stimuli only if the infant was looking to the screen. If necessary, infants were reoriented toward the screen with tinkling sounds before the onset of the word. The AA or AB word was played while the attention getter

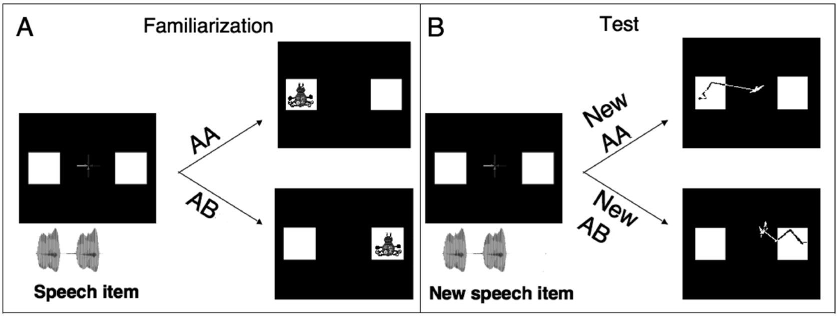

Figure 1 Trial structure in Experiment 1. A. Familiarization phase—participants were presented with linguistic stimuli (AA or AB words) that were followed by visual rewards on the left or right side of the screen, depending on the structure of the word. B. Test phase—infants heard new AA and AB words and no reward followed. On the right, two anticipations of an infant are depicted.

was shown. After the offset of the linguistic stimuli, only the two squares were visible for 1 s. Then a looming puppet (accompanied by a bell-sound) appeared on one side of the screen in one of the white squares (see Figure 1A). During familiarization infants were presented with 36 interleaved trials (6 AA and 6 AB items repeated 3 times) in a pseudo-random order (randomized by 4) so that there were no immediate repetitions of a token, no more than 2 repetitions of a structure, also avoiding alternations more than 2. AA words were paired with puppets on one side of the screen, while AB words with puppets on the other side of the screen. The structure-side pairing and the order of presentation were counterbalanced across infants. During test infants were exposed to another 8 trials (2 AA and 2 AB words, presented twice) in a pseudo-random order described earlier. These were similar to the familiarization trials, except that infants heard new AA and AB items. During this generalization phase no reward puppets were displayed (see Figure 1B). Infants could make anticipatory looks to where they expected the puppet to appear for 2 seconds after the end of the word.

Scoring

The screen was divided into three equal parts, left, middle, and right. We coded the location of the infants' first anticipatory fixation in search of the object after hearing the words. Looks shorter than 80 ms were excluded, to eliminate random noise unlikely to represent true fixations (Bedford et al., 2012).

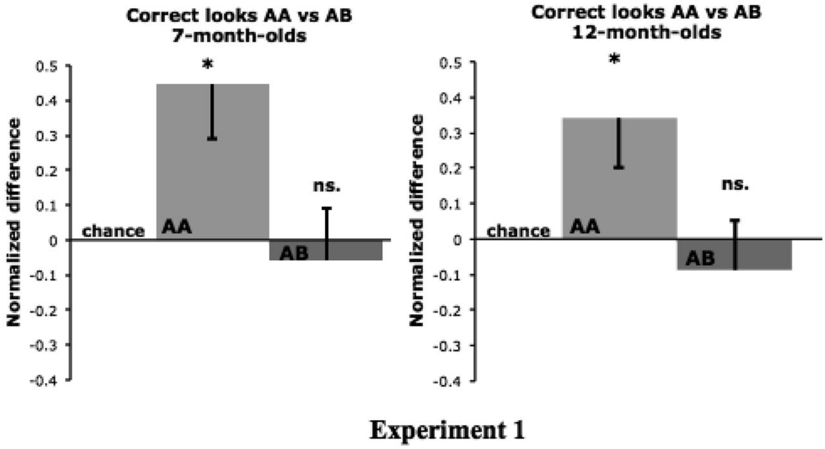

Figure 2 Normalized difference scores (correct looks – wrong looks/correct + wrong) in the test of Experiment 1 for 7-month-olds (left) and 12-month-olds (right). Infants looked more to the correct side for AA but not for the AB structures. Bars depict standard error.

Results and Discussion Experiment 1

As shown in Figure 2, both 7- and 12-month-old infants generalized the AA, but not the AB patterns in the test. Infants looked significantly more than chance to the correct side when the word had the structure AA (t-tests 7-month-olds: $t(15)=2.83$, $p = 0.01$; 12-month-olds: $t(15)=2.84$, $p = 0.01$, two-tailed), but were at chance for the structure AB (t-tests 7-month-olds: $t(15)=0.40$, $p = 0.64$; 12-month-olds: $t(15)=0.78$, $p = 0.44$, two-tailed). Moreover, both groups showed a better performance for the AA than the AB structures (paired one-tailed t-test 12-month-olds: $t(15)=1.98$, $p = 0.02$, 7-month-olds: $t(15)=2.09$, $p = 0.02$). When comparing the performance of the two groups of infants, we found no significant differences.

The results of Experiment 1 show that both age groups generalized and implemented the AA patterns but not the AB ones. The finding that 7- and 12-month-olds failed to learn the AB structures suggests that processing diversity-based structures might be more difficult. The tokens of this structure might have been encoded not as a pattern based on diversity (AB, AB, AB), but rather as random patterns (AB, CD, EF), making learning and generalization impossible.

In the next experiment we investigate whether 7-month-olds could learn adjacent repetition-based patterns that are embedded in a more complex structure (AAB patterns) from an input where two regularities are present (AAB, ABA). In the following experiments we will focus on the younger age group (7-month-olds), because, on the one hand, we did not find any difference between the two groups in Experiment 1. On the other hand, while there is data from 12-month-olds learning tri-syllabic patterns based on adjacent or nonadjacent identity relations (Kovács & Mehler, 2009), evidence that infants as young as 7 months would be able to deal with two regularities, or extract a pattern from a complex input is scarce.

Experiment 2: Learning Adjacent and Nonadjacent Identity Relations (AAB vs. ABA)

In Experiment 1 we have found that 7- and 12-month-olds are able to generalize an adjacent repetition-based structure implemented in bi-syllabic items (AA). In Experiment 2 we ask whether 7-month-old infants can also generalize more complex adjacent identity-based structures based on tri-syllabic items (AAB) in a condition where we also present a nonadjacent structure (ABA).

Method

Participants

The participants were 16 7-month-olds (8 girls, mean age = 7.16) aged from seven months 4 days to seven months 28 days. Additional 7 infants were excluded because of crying or fussiness ($n = 5$), side bias ($n = 1$), or experimental error ($n = 1$).

Stimuli

We used the words that were used by Kovács & Mehler (2009) in Experiment 1. The words had either repeated initial syllables (as in za-za-mo), or identical first and last syllables (as in za-mo-za). For the familiarization, we constructed six AAB and six ABA words from three A (lo, du, za) and three B syllables (mo, ba, vu). The two AAB and ABA words used for test were constructed from two novel syllables (ke, gi). In the familiarization infants heard the following AAB and ABA words: duduba, dudumo, lolovu, loloba, zazamo, zazavu, zavuza, zamoza, dumodu, dubadu, lovulo, lobalo. In the test they heard the following structures: kekegi, gigike, kegike, gikegi. The other characteristics of the stimuli were as described in Experiment 1.

Apparatus, Procedure, and Scoring

These were identical to the ones used in Experiment 1.

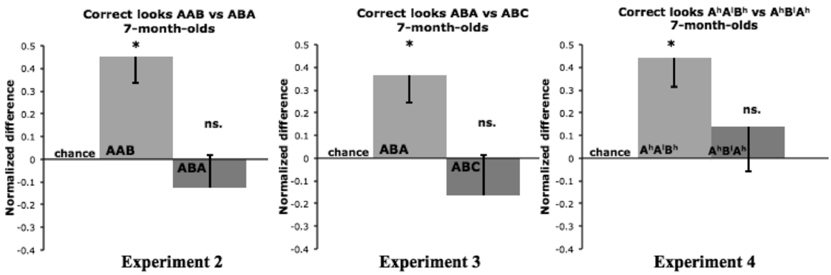

Figure 3 Normalized difference scores in the test (correct looks – wrong looks/correct + wrong) for Experiment 2 (Left), where infants looked more to the correct side for AAB but not for the ABA structures; Experiment 3 (Middle) where infants looked more to the correct side for ABA but not for the ABC structures; and Experiment 4 (Right) where infants looked more to the correct side for the $A^hA^lB^h$ structures where the two A syllables had different pitch (but not for the $A^hB^lA^h$ structures). Bars depict standard error.

Results and Discussion Experiment 2

Similarly to the results observed in Experiment 1, infants seemed to learn only one of the patterns. They looked significantly above chance to the correct side when the test words had the structure AAB (t-tests $t(15)=2.78$, $p = 0.01$, two-tailed), and they were at chance for the structure ABA (t-tests $t(15)=0.68$, $p = 0.50$, two-tailed see Figure 3 Left). They showed a significantly better performance for the AAB than for the ABA structures (paired one-tailed t-tests $t(15)=1.9$, $p = 0.027$).

Thus, even infants as young as seven months could extract a regularity based on adjacent repetitions from a more complex structure. The presence of an ambiguous input (two structures) did not impair learning, however, 7-month-olds, just like 12-months olds in the study of Kovács & Mehler (2009), failed to learn the nonadjacent repetitions. In the next experiment we investigate whether nonadjacent repetitions are learnable when contrasted with "random" patterns. Research suggests that while tracking adjacent repetitions may relay on a simple repetition detector and even newborns are sensitive to such relations, nonadjacent relations seem to be processed in a different manner (Gervain et al., 2009).

Experiment 3: Generalizing Nonadjacent Repetitions (ABA vs. ABC)

In this experiment we ask whether young infants can extract and generalize nonadjacent repetition-based ABA structures when exposed to two patterns simultaneously. Previous studies have targeted this question (Marcus et al., 1999) using a single structure, however, the results may be open to an alternative explanation. In this study, Marcus et al. (1999) familiarized infants with ABA patterns and tested them with new ABA and ABB patterns, finding that infants looked longer to the ABB patterns. The authors have taken this as evidence for learning the ABA patterns, infants thus showing novelty preference for the novel ABB structures. However, one might argue that such results could be observed even if infants were unable to extract the ABA structures from familiarization, and their performance could have been based on a preference for adjacent repetitions in test. Thus, if infants could not extract any structure from familiarization, when they were exposed to ABB structures (that are easy to process) during test, they might have showed a preference toward these patterns, in contrast to the ABA patterns, which they could have considered as noise.

To test whether 7-month-olds can learn nonadjacent identity relations in noisy conditions, in Experiment 3 we exposed infants to ABA patterns (such as, zamoza) and ABC "random" patterns (such as zamodu). Based on the results of Experiment 1, where we found that infants did not learn diversity-based patterns (which were presumably considered as noise and ignored), we conjecture that if infants at this age can track nonadjacent identity relations, they should learn the ABA patterns when exposed to ABA and ABC patterns.

Method

Participants
The participants were 16 7-month-olds (7 girls, mean age = 7.16) aged from seven months 5 days to seven months 25 days. Additional 8 infants were excluded because of crying or fussiness ($n = 5$), failing to calibrate the eye tracker ($n = 1$), or side bias ($n = 2$).

Stimuli
Linguistic stimuli followed two simple patterns. They could have either the first and the last syllable identical (as in dubadu), or three different syllables (as in dubalo). For the familiarization, we constructed six ABA and six ABC nonce words from six syllables (du, lo, za, ba, mo, vu). The two ABA and two ABC structures used for test were constructed from four novel syllables (ke, gi, te, ti). The items used in familiarization were: dubadu, dumodu, lobalo, lovulo, zamoza, zavuza, dubalo, dumoza, lobaza, lovudu, zamodu, zavulo; and

the ones used for test: ketigi, gitike, ketike, gitegi. Phonemes were synthesized as previously described.

Apparatus, Procedure, and Scoring

These were identical to the ones used in Experiment 1.

Results and Discussion Experiment 3

As shown in Figure 3 (middle) 7-month-olds generalized the ABA patterns to new tokens in test, but they had a random response to the ABC patterns. Infants looked more than chance to the correct side when the word had the structure ABA (t-test $t(15)=3.28$, $p = 0.0005$, two-tailed), but were at chance for the structure ABC (t-test $t(15)=0.87$, $p = 0.39$, two-tailed). Infants looked significantly more often to the correct side when the word had ABA structure than when it had an ABC structure (paired one-tailed t-test $t(15)=2.12$ $p = 0.02$).

Seemingly, infants generalized the ABA patterns to new exemplars performing anticipatory looks to what would have been the correct side for that structure. Thus, infants at seven months are able to extract nonadjacent relations when faced with a noisy input (ABA and ABC structures). They successfully manage to encode both adjacent (Experiment 1 and 2) and nonadjacent repetition-based regularities (Experiment 3) and make predictions based on them, by looking to the side where the reward used to appear after hearing new patterns that follow the same structure. Together the results of these experiments suggest that although infants are able to learn nonadjacent identity relations, adjacent identity relations are favored. In Experiment 4 we investigate whether repetition-based learning is restricted to exact physical identity and explore the level of generalization on which such mechanisms might operate.

Experiment 4: Physical Identity vs. Adjacency in Repetition Detection ($A^hB^lA^h$ vs. $A^hA^lB^h$)

In this study we explore the nature of the mechanisms involved in repetition-based learning, by asking whether such learning is restricted to exact physical identity, pitting against each other adjacency and physical identity. We thus had patterns containing adjacent repetitions that were non-identical (differed in pitch), and nonadjacent repetitions that were identical. We exposed 7-month-old infants to $A^hB^lA^h$ and $A^hA^lB^h$ structures where the superscript depicts differences in the pitch of syllables inside the word (^{h} stands for high pitch and ^{l} for low pitch). If identity detection is not restricted to physical identity, given the results of Experiments 2 (preference for adjacent repetitions), infants should learn the $A^hA^lB^h$ regularity also here. In this case, infants would use the same processes to generalize over physically identical repetitions (AAB, e.g., ZO-ZO-MO) and over non-exact identity relations ($A^hA^lB^h$, e.g., ZO^h-ZO^l-MO^h) and learn the structure based on adjacent repetitions. In contrast, if identity detection is restricted to physical identity, infants might perceive the $A^hA^lB^h$ pattern as three "different" (non-identical) syllables (ACB) and in this case they should learn the other pattern ($A^hB^lA^h$) as they did in Experiment 3, since in this pattern the nonadjacent repeated A syllables are physically identical.

Method

Participants

The participants were 15 7-month-old monolinguals (8 girls, mean age = 7.20) aged from seven months 6 days to eight months 2 days. Additional 7 infants were excluded because of crying or fussiness ($n = 4$), side bias ($n = 3$).

Stimuli

The stimuli were identical to the ones used in Experiment 2, except that the middle syllable of each word ($A^hB^lA^h$ and $A^hA^lB^h$) was synthesized with a pitch of 100Hz instead of 200Hz used in the previous experiments and for the first and third syllables here.

Apparatus, Procedure, and Scoring

These were identical to the ones used in Experiment 1.

Results and Discussion Experiment 4

As shown in Figure 3 (right), 7-month-olds generalized the $A^hA^lB^h$ pattern to new tokens, but not the $A^hB^lA^h$ patterns, even though in the first pattern the two A syllables were not physically identical. Infants looked more than chance to the correct side when the word had the structure $A^hA^lB^h$ (t-test $t(14)=3.18$, $p = 0.006$, two-tailed), but were at chance for the structure $A^hB^lA^h$ (t-test $t(14)=1.06$, $p = 0.31$, two-tailed).

The results show that infants generalized the $A^hA^lB^h$ patterns and not the $A^hB^lA^h$ ones, suggesting that adjacent repetition-based generalizations are not restricted to exact physical identity and may involve computations that operate not only on primary perceptual features, but possibly on a more abstract level. While further studies implementing different stimulus sets should confirm

Table 1 Overview of the four experiments reflecting a possible hierarchy in encoding

Age	Experiment	Fam & Test	Results (Test)
7-month-olds	1. AA & AB	36 familiarization and 8 new test trials	Learn AA over AB
	2. AAB & ABA		Learn AAB over ABA
	3. ABA & ABC		Learn ABA over ABC
	4. $A^hB^lA^h$ & $A^hA^lB^h$ (pitch variation)		Learn $A^hA^lB^h$ over $A^hB^lA^h$
12-month-olds	1. AA & AB		Learn AA over AB

such a possibility, the present results suggest that adjacent relations based on phonological identity are computationally preferred over nonadjacent, but physically identical repetitions.

General Discussion

Taken together, the results of four experiments suggest that infants employ powerful learning mechanisms to extract regularities from a complex input that contains multiple patterns, readily learning structures based on identity relations (see Table 1). They showed successful generalizations for immediate syllable repetitions (e.g., AA, when faced with AA and AB) and for nonadjacent repetitions (ABA, when faced with ABA and ABC), however, failing to extract diversity-based patterns. While in Experiments 1 and 3 infants were exposed to a well-defined pattern (AA or ABA) and a random pattern (AB or ABC, respectively), in Experiment 2 infants heard two repetition-based regularities (AAB and ABA structures). In this case, infants generalized the adjacent identity relations (AAB), and showed no learning for the nonadjacent identity patterns (ABA). This suggests that close identity relations are more salient and easier to learn than distant identity relations. In Experiment 4 we exposed infants to $A^hB^lA^h$ and $A^hA^lB^h$ words where the middle syllables of both structures had a lower pitch compared to the other two syllables. Infants generalized the $A^hA^lB^h$ patterns but not the $A^hB^lA^h$ ones, suggesting that such generalizations are not restricted to exact physical identity and that adjacent non-identical syllable repetitions are favored over identical nonadjacent repetitions.

Given the pattern of results we observed in these studies, in the following part we will address three possible implications. First, we will discuss why diversity-based patterns are not learned and how they might be encoded. Second, we will focus on the mechanisms involved in adjacent-repetition learning and their level of abstraction, and third, we will speculate on the possible constraints of language learners that might lead them to focus on a single regularity when faced with multiple patterns.

Regarding the first issue, the results of Experiments 1 and 3 show that infants readily extract bi-syllabic or tri-syllabic identity-based patterns (AA, AAB or ABA), but they fail to extract diversity-based patterns (AB or ABC). This suggests that “same” and “different” relations based on syllable identity and diversity are differentially learned, at least with linguistic stimuli. Given various evidence from animals studies suggesting that even bees or rats can successfully learn “different” relations after training (Giurfa et al., 2001; Murphy et al., 2008), one might have expected infants to learn here, as well. However, while training involving animals usually consists of hundreds of trials, in our study infants were exposed to only 12 trials repeated 3 times. While other studies have used similar numbers of trials (Marcus et al., 1999), it is possible that with more trials in a different procedure infants could also learn the more difficult “different” relations. To the minimum, our data suggest that infants extract easier identity-based structures than diversity-based structures with a 36 trial familiarization. Such a possibility is also supported by evidence from adult studies suggesting that diversity-based patterns are more difficult to learn for adults, as well (Falk & Konold, 1997; Kareev, 1995). However, our data do not provide evidence that infants have perceived the diversity-based patterns as a structure. In fact, the tokens of this structure might have been encoded not as a pattern based on diversity (AB, AB, AB), but rather as random patterns (AB, CD, EF).

Second, targeting the mechanisms involved in repetition-based learning, the results of Experiment 4 suggest that repetition-based generalizations involve computations that operate not only on primary perceptual features (exact physical identity), but possibly on a more abstract level. These results also suggest that infants in Experiment 2 did attend to the structure of the speech stimuli and did not only learn a general rhythmic pattern that might arise from the exact physical repetition of the syllables (e.g., AAB, identical, identical, different). In Experiment 4 such a rhythm was disrupted by the pitch differences of the syllables, as the two A syllables had different pitch. While in this case both structures ($A^hB^lA^h$ and $A^hA^lB^h$) had a high-low-high pitch pattern, infants generalized the $A^hA^lB^h$ pattern, although in this structure the two A syllables were only phonologically identical (but not physically). This is a rather surprising finding with 7-month-olds as earlier studies suggest that not until around their 10 months of age infants manage to equate words despite of changes in talker gender, fundamental frequency, or vocal affect (Houston & Jusczyk, 2000; Singh et al., 2004). Furthermore, such findings might be difficult to explain with an automatic repetition detector, which detects repeated tokens, as it is unclear why such a basic perceptual mechanism should be sensitive to perceptually non-identical repetitions ($A^hA^lB^h$).

Finally, one might wonder why infants learned one regularity only, independently whether the signal contained two structures or a structure and a random or diversity-based pattern. Infants extracted only one structure and presumably considered other evidence (e.g., the other pattern) as noise. This finding that was consistent across four experiments opens the field for an interesting speculation. It is possible that infants extracted only one pattern because in their natural environment they are exposed to a monolingual language input, and they expect all speech input to contain a single coherent set of regularities (in contrast to a bilingual input). Of course, the monolingual input also contains multiple regularities, and monolingual infants tested here seem to be prepared to deal with multiple patterns. However, the input infants are exposed to might be important, as even a short exposure to specific kind of patterns (e.g., bi-syllabic units) in a laboratory setting seems to shape infants' expectations (Lew-Williams & Saffran, 2012). Expectations, however, would be different in infants exposed to a bilingual input, as such experience could result in being tuned to multiple sets of regularities in the speech signal. In a paradigm similar to the one used here, it was found that infants exposed simultaneously to two languages from birth extracted two regularities (AAB and ABA), while monolinguals only one (AAB, Kovács & Mehler, 2009). Developing specific expectations regarding the speech input would aid rapid language acquisition, as it would permit considering as noise all other evidence, which does not fit with the specific "conjecture" of the learner.

Alternatively, one might argue that extracting first the simplest possible pattern from multiple patterns could reflect a hierarchy in encoding and a possible feature of the cognitive apparatus that would ensure the efficiency of learning. Across four experiments infants selectively learned what was easier in a given context following a specific hierarchy (i.e., adjacent regularities were favored over nonadjacent patterns; and identity-based patterns over diversity-based patterns).

In sum, our results point to powerful abilities of young infants to extract repetition-based structures from an input that contains 50% "noise." To better understand the nature and the constraints of such learning and its role in language acquisition, it will be important to uncover whether such findings are restricted to language-like stimuli, and whether young infants would be able to learn non-identity relations with stimuli in the visual or other modalities.

Note

1 Side bias was established based on the familiarization phase. If an infant looked more than 75% of the time to one side of the screen after the offset of the word and before the onset of the reward during the 36 trials of the familiarization phase, the infant was excluded from the analyses.

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