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Current Opinion in Behavioral Sciences

Infants' perception of repetition-based regularities in speech: a look from the perspective of the same/different distinction

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We review the existing evidence, behavioral and neural, of infants' ability to encode repetition- ('same') and diversity- ('different') based regularities in speech. These studies show that, from birth, infants exhibit a robust capacity for learning repetition-based rules from speech (e.g. AAB or ABA, in which A = A). Further, the ability to generalize such repetition-based structures is not strictly language-specific, as infants' extract repetition-based structures from musical tones, animal pictures, abstract geometrical shapes, or faces under some conditions. However, this capacity is strongest when presented with speech or other communicative/meaningful stimuli. Additionally and importantly, recent brain-imaging studies suggest that by six months of age, infants also distinctly encode the notion of difference in speech stimuli. This is the youngest age at which this ability has been shown.

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Current Opinion in Behavioral Sciences 2020, **37**:125–132

This review comes from a themed issue on **Same-different conceptualization**

Edited by **Edward A Wasserman, Jean-Rémy Hochmann** and **Susan Carey**

https://doi.org/10.1016/j.cobeha.2020.11.014

Introduction

Humans' ability to learn linguistic rules is central to debates about the nature of the language faculty. A pivotal question in the nativist versus empiricist debate has been whether humans are biologically endowed with the capacity to learn abstract rules containing symbolic variables. Such rules would apply to any item in a set or category that the variable is a placeholder for, thus guaranteeing a combinatorially productive system. Nativist accounts [1–3] argue that this ability is a species-specific, innate trait, at the core of human language's infinite computational power. Empiricist accounts [4,5], by contrast, claim that while the ability to learn abstract, symbolic rules may be present in adults, it is by no means innate and is learned from the input through experience.

Critical to this debate then is infants' ability to learn abstract rules (see, for example, [6•] for a review). If infants, who have little experience with language, can nevertheless learn rules from language, then this ability must be innate. Probing infants' rule learning abilities, Marcus *et al.* [7•] showed that seven-month-olds extract the identity relationship (A = A), the simplest abstract regularity, from artificial grammars generating three-word sequences in which two words are identical (e.g. ABB, AAB, ABA). A large body of literature followed, exploring the nature and scope of infants' rule-learning abilities.

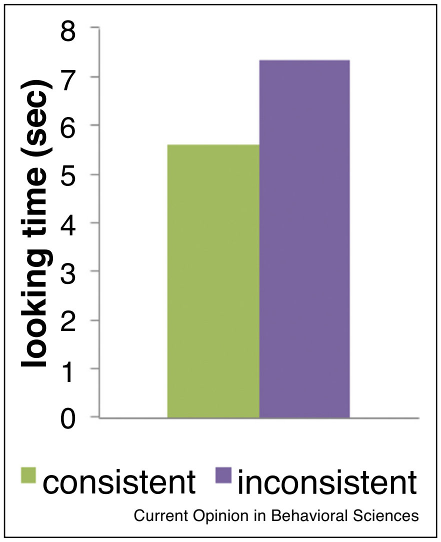
Given the theoretical relevance of these questions, infants have been tested from the youngest age possible, namely birth. The tasks, stimuli and structures tested in this field are often highly similar to the ones used to examine infants' encoding of sameness and difference in the conceptual domain. Infants' ability to learn repetition-based linguistic regularities could, therefore, be relevant for our understanding of how they encode the notions of same and different.

The current paper reviews this empirical evidence, behavioral and neural, and argues that by six months of age, infants can represent not only sameness, but also distinctly encode the notion of difference in speech stimuli. This is the youngest age at which this ability has been shown [8,9].

Behavioral evidence

In their original study using the head-turn preference procedure, Marcus *et al.* [7•] showed that seven-month-old infants exposed to speech sequences rapidly extract and discriminate structures containing adjacent (ABB: *ga ti ti*) and non-adjacent repetitions (ABA: *ga ti ga;* but fail at five months of age [10]), as well as structures containing adjacent repetitions at different positions (i.e. ABB: *ga ti ti* versus AAB: *ga ga ti*). Importantly, rather than memorizing item-based information, infants generalize the underlying structure of the sequences heard during familiarization to novel exemplars presented in test (Figure 1).

Figure 1



The results of Marcus *et al.* [7•]: looking times in the test phase to the test items that were consistent (green) or inconsistent (violet) with the grammar heard during familiarization.

This robust finding, replicated in [11•,12•,13] and a wealth of subsequent work have revealed that learning repetition-based structures is not a language-specific capacity, as infants extract such patterns from a range of stimuli, but it is strongest when presented with speech or other communicative or meaningful stimuli (see Ref. [14•] for a recent meta-analysis). Infants learn ABB and ABA generalizations in musical chords and tones at four months of age, but lose this ability by seven months [15], presumably having learned that speech, but not music, is a suitable input for this type of rule. Interestingly, while seven-month-old infants fail to extract these rules directly from chords, tones, instrument timbres, or animal sounds, they succeed if they are first familiarized with repetition-based structures implemented in speech, transferring the rules across stimuli [12•]. Similarly, 7.5-month-old infants learn repetition-based rules from sine-wave tones only if they are first primed to consider them as communicative signals, and can even transfer the rules to speech sequences [16].

Infants' ability to generalize repetition-based structures is not limited to the auditory domain. At 3–4 months, infants discriminate ABB and ABA patterns implemented over pictures of dogs [17•] and at seven months, they succeed with pictures of dogs, cats [18], and upright, but not inverted faces [19]. Studies using linguistic visual stimuli, that is, sign language, reveal an unclear picture. One study [20] finds that 7.5-month-old infants generalize AAB but not ABB patterns in sign, while another [14•] reports that infants at this age learn ABB and ABA patterns from sign only if previously primed to treat them as communicative. This conclusion needs to be taken with caution, though, as it is supported by planned comparisons but not the study's omnibus statistical test.

Studies examining infants' ability to extract rules from abstract geometric shapes, i.e. non-meaningful and non-communicative visual stimuli, report inconsistent evidence for learning [10,21], supporting the hypothesis that meaningless stimuli hinder infants' rule learning abilities [14•]. However, two recent studies suggest that these variable findings may instead result from differences in stimuli presentation [17•,22]. Indeed, from three months of age, infants generalize ABB and ABA rules over geometric shapes if the sequences are spatially structured, that is, presented left-to-right [17•,22].

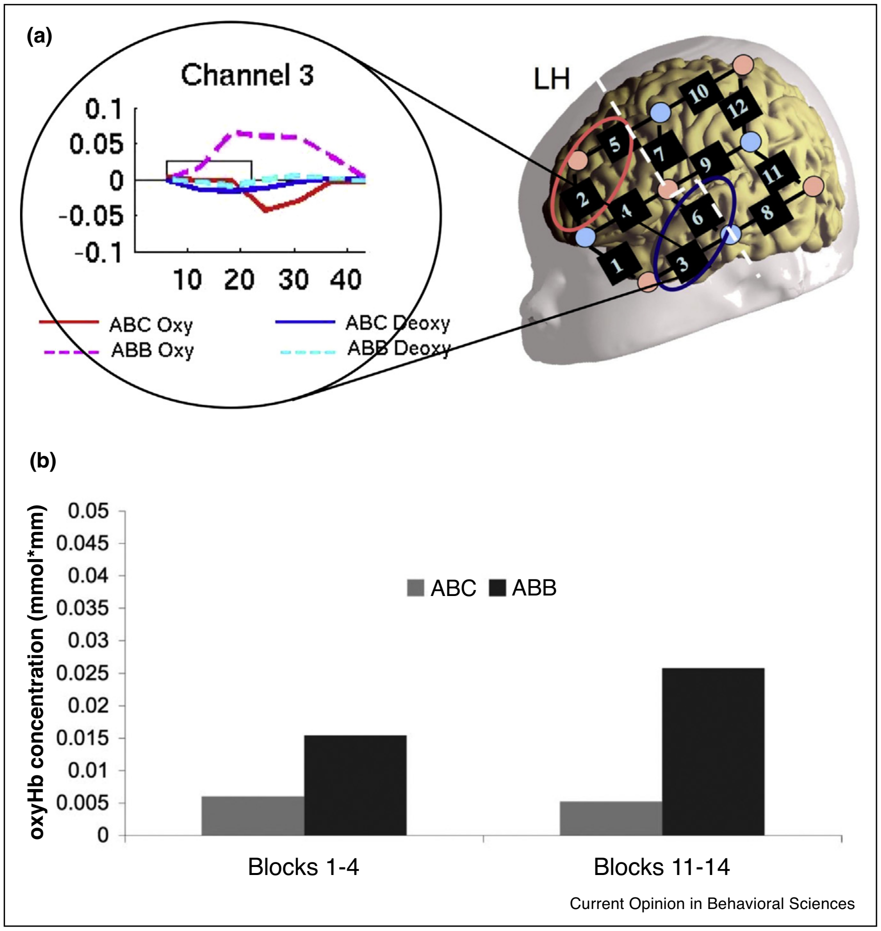
Redundancy within and across modalities also enhances infants' ability to learn repetition-based rules. Thus, five-month-old infants extract ABB and ABA rules from sequences of syllables paired with spatially unstructured geometric shapes, but fail when presented with either modality separately [20,25], and seven-month-old infants' ability to extract these rules from speech is hindered when the input is ambiguous (i.e. when vowels carry the ABA/ABB rule, while consonants carry a contradictory AAA rule: *ba bi ba* versus *ba bi bi*; [13].

Are all repetition patterns equally easy to learn? In challenging contexts, adjacent repetitions are seemingly more reliably extracted than non-adjacent repetitions. Thus, 7-month-old and 12-month-old monolingual infants learn only the adjacent rule (AAB) when presented simultaneously with a non-adjacent one [23•] (while 12-month-old bilinguals learn both [24]) in an anticipatory eye-tracking task, and so do 7–8-month-olds presented with spatially unstructured shapes (ABB) [21], or with syllables in which the repetition (ABB) is instantiated only in the vowels [13]. However, a recent meta-analysis [14•] does not find evidence of adjacent repetition patterns being easier than patterns containing non-adjacent repetitions. This conclusion is also confirmed empirically in a study [25] that showed that seven-month-old infants discriminate both adjacent *and* non-adjacent repetitions from the diversity-based structure ABC. Furthermore, in the absence of familiarization, infants show no spontaneous preference for repetition-based structures over the diversity-based ones [25].

Other studies suggest that sequence-final repetitions may be easier to learn than sequence-initial ones [21]. This is confirmed by a recent meta-analysis, which reports a larger effect for ABB as compared with AAB patterns [14•].

In sum, very young infants exhibit a robust capacity for learning rules based on the identity relation, that is, the

Figure 2



Newborns' hemodynamic responses to sequence-final adjacent repetition-based and diversity-based structures, adapted from Ref. [26•]. **(a)** The hemodynamic response in the left temporal area. **(b)** The time course of the hemodynamic response in the left frontal area: an immediate advantage for ABB over ABC (Blocks 1-4), which further increases over time (Blocks 11-14).

relation of 'same' from speech and other stimuli. Do infants similarly detect rules based on diversity, that is, the relation 'different'? The behavioral work available doesn't provide evidence for this ability during the first year of life. When familiarized simultaneously with an identity-based (AA: *va va*, or ABA: *du ba du*) and a diversity-based rule (AB: *va lu*, or ABC: *du ba lo*) in speech, in an eye-tracking study measuring anticipation in response to the rules, 7-month-olds and 12-month-olds generalize only the identity-based pattern to novel tokens in test [23•]. A similar pattern emerges with non-speech stimuli. When presented with geometrical shapes, 7-month-old and 12-month-old infants generalize a rule based on identity (AA) but fail to generalize a rule based on diversity (AB) [9].

Neural evidence

The advent of brain imaging, such as near-infrared spectroscopy (NIRS), has made it possible to assess newborns' brain responses to sequence-final adjacent repetitions within trisyllabic sequences (ABB: *mubaba*) and to otherwise matched random controls, that is, diversity-based structures (ABC: *mubage*) [26•]. This paradigm does not include familiarization and test phases, measuring instead infants' responses to stimulus blocks of ABB or ABC sequences. To capture responses to the structure of the sequences rather than to individual items or perceptual properties, a high number of strongly variable items (140 per condition) are presented, with no repetitions, exceeding newborns' memory capacity for rote learning. Under these conditions, newborns showed a greater response to ABB than to ABC patterns (Figure 2a) in the bilateral temporal and left inferior frontal (involving Broca's area) regions, suggesting that newborns already process the repetition-based pattern differently from the diversity-based control in the language network.

Interestingly, the advantage for the repetition sequence was present from the beginning of the experiment and increased over its time course (Figure 2b). This suggests two mechanisms involved in processing the repetition structure: one immediately detecting the repetition and one building up knowledge about it over time [26•]. These two neural signatures have also been observed when stimuli were less complex, only 12 items per condition instead of 140, with several repetitions of each item [27]. However, under these less complex, more redundant conditions, the early increased responses to repetitions remained stable over time, while the response to the diversity-based structure increased, likely due to the rote learning of (at least some) individual items.

With NIRS, it is possible to not only compare the two conditions, but also to establish whether a given condition evoked activation, that is, was processed or responded to, at all. Compared to a silent baseline, in this study, activation was significant to the ABB structure in the bilateral temporal and left frontal areas, whereas the ABC pattern elicited only weak responses in a single right temporal channel. These results suggest that while newborns robustly encode the sequence-final adjacent repetition pattern, their ability to represent diversity-based patterns is restricted.

The newborn brain also shows an advantage for sequence-initial adjacent repetitions (AAB: *babamu*) as compared to diversity-based ABC controls, with a pattern of activation similar to the one elicited by sequence-final repetitions [28•].

When ABB and AAB structures are compared directly, that is, when infants are presented with blocks containing only ABB or only AAB sequences, both structures elicit the same increased activation [28•]. But when their discrimination is tested indirectly in an alternating/non-alternating paradigm (Figure 3), newborns respond differentially in the left inferior frontal areas to alternating and non-alternating blocks (i.e. blocks containing tokens of the two structures in strict alternation: ***pepe**na* *ta**lulu*** ***koko**fe* *bi**soso*** . . . versus blocks containing tokens of only one structure: e.g. ***pepe**na* ***koko**fe* ***dudu**zi* . . .) [28•]. Newborns, as seven-month-olds [7•], successfully discriminate then between sequence-initial (e.g. ***pepe**na*) and –final (e.g. *ta**lulu***) adjacent repetitions, which entails encoding not only the repetition itself (*pepe*, *lulu*), but also its serial position (initial: *pepe*– versus final: –*lulu*) in the sequence.

By contrast, newborns' neural responses to non-adjacent repetitions (ABA: *bamuba*) and the diversity-based ABC controls do not differ [26•], suggesting that non-adjacent repetitions are more challenging for the newborn brain than adjacent ones.

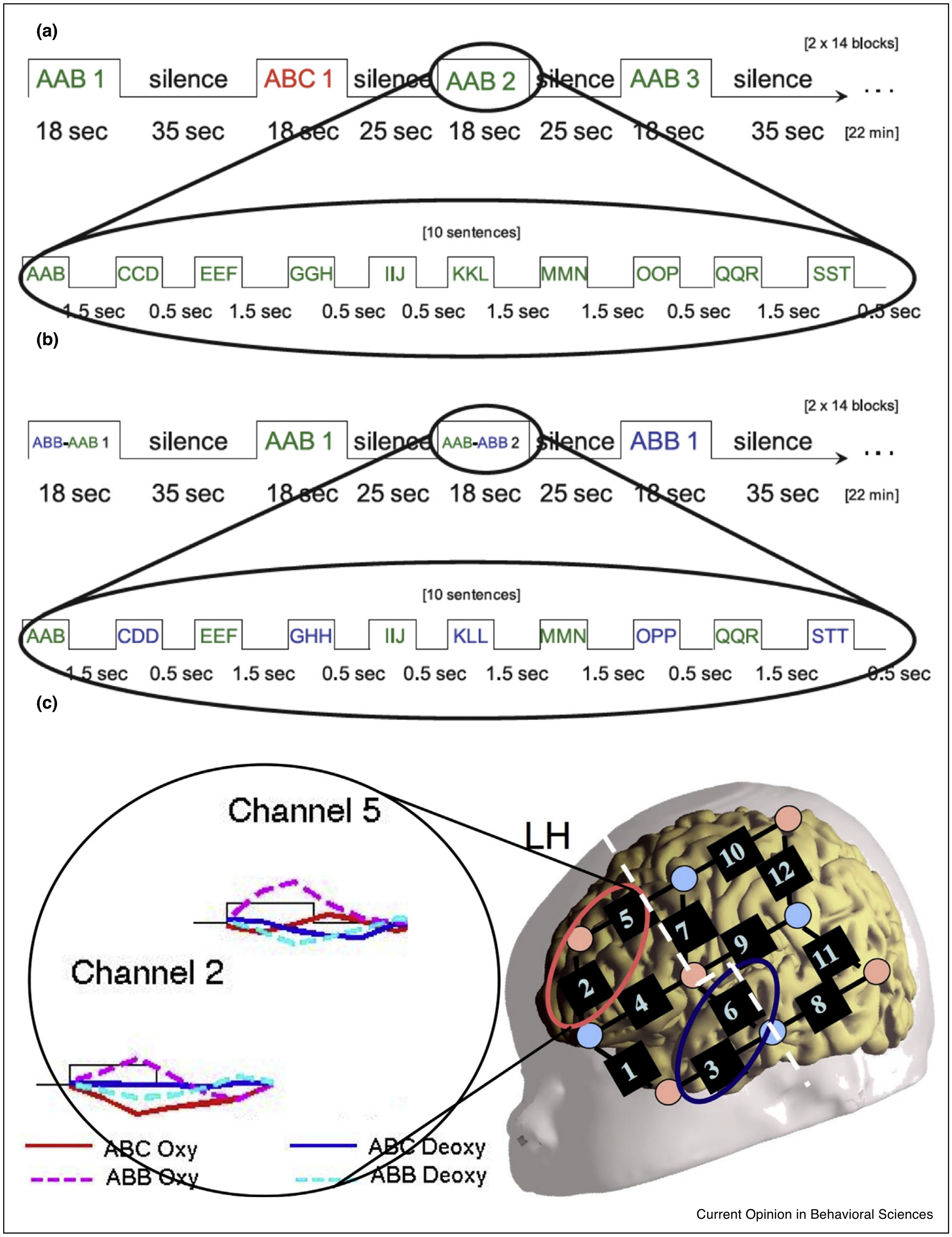
These results establish the earliest possible developmental onset for the sensitivity to repetition, that is, identity-based linguistic rules. The asymmetry between adjacent and non-adjacent repetitions converges with the one observed behaviorally in older infants in some [20,21], although not all studies [14•]. Interestingly, newborns process initial and final repetitions equally well, not demonstrating the advantage some behavioral studies found for sequence-final repetitions [14•]. It remains to be investigated whether these divergences represent developmental changes or are rather attributable to methodological differences.

The handful of NIRS studies investigating older infants point to an interesting developmental change in encoding diversity-based structures. In simple block presentation paradigms similar to those used with newborns, six-month-olds show an increased response, that is, higher than a silent baseline, to simple blocks of both the repetition and the random control, whether trisyllabic [29] or bisyllabic [30•], and as a result, no difference between the two conditions. Nevertheless, when the two structures are presented in an alternating/non-alternating paradigm, six-month-olds can discriminate them [31].

Each of these two results, taken separately, could be explained without positing developmental changes in infants' encoding of diversity-based structures. The similar activation found in the repeated and random conditions, when presented in simple blocks, could result from the low-level auditory processing of the sequences, without the processing of their structure. Independently, infants could discriminate the two structures in the alternating/non-alternating paradigm simply by encoding the repetition-based structures alone, without encoding the fact that the random sequences contain *different* syllables.

However, when the two findings are taken together, these explanations are not sufficient, and the ability to represent difference in syllables needs to be posited. Indeed, if the response to repetitions and random sequences is auditory only, excluding the processing of their structure, then we would predict no discrimination in the alternating/non-alternating paradigm either. But discrimination is actually observed there. Conversely, if we assume, on the basis of the alternating/non-alternating paradigm, that only repetitions, that is, sameness, is encoded, but not difference, then we would expect an advantage for it in the simple block comparison, just like in the case of newborns. But equally high responses are found for both repetitions and random sequences. These findings can only be reconciled, if we assume that six-month-old infants encode diversity-based patterns as well as identity-based ones. This result contrasts with infants' failure to detect diversity-based rules even at 12 months of age in behavioral studies (shapes: [9], syllables: [23•]). However, in these studies infants needed to learn a regularity *and* associate it with a position on the screen. Infants' ability to encode *difference* might be too weak to support such complex tasks.

Figure 3



Newborns discriminate sequence-initial and sequence-final adjacent repetitions. **(a)** The simple block and **(b)** the alternating/non-alternating designs used in [28•]. **(c)** The differential response to non-alternating blocks in the left inferior frontal region.

Potential support for infants' emerging ability to represent difference, at least in linguistic sequences, comes from the finding that by nine months infants show stronger activation to diversity-based sequences than to repetition-based ones [32]. This pattern of results could suggest a complete developmental shift. However, this result has to be taken with great caution, due to its small sample size, and needs to be replicated, especially because it contrasts with behavioral findings (shapes: [9], syllables: [23•]), which show a repetition-advantage at that age. To what extent methodological differences (imaging versus behavioral methods) plays a role also requires further investigation.

Older infants' neural ability to detect repetition-based regularities in visual input has been investigated only for linguistic signs and their non-linguistic visual controls [33]. At 6 months, hearing infants never exposed to sign language show an advantage for repetition-based sequences of two nonsense signs (AA) over random sequences (AB) in bilateral fronto-temporal brain areas overlapping with what is identified in adults as the language network, unlike their age-matched peers' equal response to repetition-based and diversity-based regularities in speech, but similarly to newborns' repetition advantage response. This suggests that in language, experience modulates how regularities are processed.

Interestingly, non-linguistic visual controls, matched in spatio-temporal dynamics and shape to the signs but represented as a cartoon tree, triggered greater responses to the diversity-based than to the repetition-based structure, pointing to mechanisms that process repetitions differently as a function of their relevance in a given cognitive domain.

Discussion and conclusion

Taken together, the behavioral and neuroimaging studies provide firm evidence for young infants' ability to encode regularities predicated over identical elements in speech from birth, and stimulus-dependent, more variable abilities for other stimuli from 3 to 5 months.

Is this ability an abstract, symbolic rule-learning mechanism, as initially conceptualized [7•], or could repetition-based structures (ABB, AAB, ABA etc.) be learned relying on lower level perceptual and memory mechanisms [34]? Adjacent repetitions have been argued to be Gestalts automatically detected by the perceptual system, without relying on abstract symbols, since different animals are also sensitive to immediate repetition [35]. Furthermore, while from a symbolic perspective identity is a two-place predicate similar to the 'greater/smaller than' ordinal relationship, adults are better at learning identity-based than ordinal relations [36]. Also, in the tested structures, repetitions always appear at sequence edges, a position known from the memory literature to be special (primacy/recency effects). Indeed, adults are better at detecting repetitions at the edges of 5-syllable-long or 7-syllable-long sequences than in medial positions [37,38]. However, to distinguish sequence-initial and –final repetitions [7•,28•], even if the repetition is detected by a perceptual Gestalt and the edges as memory primitives, the two need to be combined into a joint representation. This representation is, therefore, at least one level more abstract than the two low-level mechanisms that feed into it.

It is, therefore, reasonable to conclude that young infants have the ability to encode repetitions, that is, identity or sameness, from birth, at least in language. The evidence is less conclusive about the representation of difference. Many results can be explained by assuming that infants can represent sameness only and develop strategies to choose or avoid it (for a detailed discussion, see Ref. [9]). This is because many studies use methods that cannot establish an absolute measure of infants' preference, but rather compare measures between conditions. In illustration, looking time for a stimulus type is not in itself interpretable. Rule learning is inferred from looking time data, if there is a difference in looking times between two relevant conditions, for example, repetition versus non-repetition.

A few studies, however, used methods that establish a measure of infants' processing of a single condition compared to some baseline. Anticipatory looking assessed by eye-tracking is one such paradigm. Using this design, 7-month-olds and 12-month-olds have been found to correctly learn to anticipate when hearing a repetition- but not a diversity-based regularity [23•]. This result suggests that the representation of diversity may not be in place in the first year of life. This task, however, is complex – infants need to learn the regularity and its association with a position on the screen to anticipate correctly. The ability to encode diversity could be present, but too weak to support this task. The NIRS data indeed suggests this to be the case. While the response to ABC patterns is not distinguishable from baseline at birth [26•], by six months, it becomes significant, reaching amplitudes similar to the responses to repetitions [29,30•].

This is the earliest evidence available to suggest that infants can represent not only sameness, but also difference – at least for speech stimuli. Given that at the same age, infants show a repetition-advantage for sign, their emerging ability to encode diversity in speech is likely linked to their experience and the developmental trajectory of language learning. It remains an open question whether, tested using brain imaging, infants show evidence of encoding difference in other domains, and if yes, whether and how this may be linked to developmental changes and learning constraints characteristic of these domains, for instance how spatial structure versus meaningfulness play a role in extracting regularities from visual stimuli.

Conflict of interest statement

Nothing declared.

Acknowledgements

This work was supported by the ERC Consolidator Grant “BabyRhythm” nr. 773202 to JG, and the Basque Foundation for Science Ikerbasque and the Spanish Ministry of Science and Innovation [Grant nr. PID2019-105100RJ-I00] to IdlCP.

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This review discusses the literature testing infants' ability to learn grammatical properties of language, focusing on studies that use the Artificial Grammar Learning paradigm.

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This pioneering study uncovered young infants' abilities to encode and discriminate structures containing adjacent and non-adjacent repetition-based regularities.

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The author investigates the information in which infants focus to generalize a repetition-based rule to new stimuli. She presents infants with sequences from an artificial language containing two logically possible generalizations. The results of two studies show that infants made the generalization most statistically consistent with the input they had received, rather than making the more abstract generalization.

12. • Marcus GF, Fernandes KJ, Johnson SP: **Infant rule learning facilitated by speech**. *Psychol Sci* 2007, **18**:387-391

The authors show that young infants fail to encode repetition-based regularities directly from a number of non-linguistic auditory stimuli such as musical tones or animal sounds. Strikingly, infants succeed if they are first familiarized with these regularities in speech sequences.

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14. • Rabagliati H, Ferguson B, Lew-Williams C: **The profile of abstract rule learning in infancy: Meta-analytic and experimental evidence**. *Dev Sci* 2019, **22** e12704

This recent meta-analysis examines 20 previous reports on infants' learning of repetition-based regularities. It additionally contains an experiment testing young infants' ability to extract rules from sign in different communicative contexts. The authors argue that the ability to encode repetition-based structures is facilitated when the signal is 'meaningful' to the infant.

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This study shows that infants as young as 3–4 months of age learn repetition-based rules implemented over abstract geometrical shapes when the visual sequences are presented spatially structured, namely, left-to-right and showing all elements in a sequence simultaneously. This result evidences the different requirements of the auditory and visual systems in rule learning.

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Using eye-tracking, the author investigates whether young infants encode repetition-based and diversity-based structures, and use them to anticipate the occurrence of a visual stimulus in a given position on a screen. This research shows that infants generalized repetition-based but not diversity-based regularities.

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26. • Gervain J, Macagno F, Cogoi S, Pena M, Mehler J: **The neonate brain detects speech structure**. *Proc Natl Acad Sci U S A* 2008, **105**:14222-14227

Using near-infrared spectroscopy (NIRS), the authors show that newborn infants encode adjacent repetitions from speech input (ABB), and discriminate them from random sequences (ABC). In contrast, newborns do not discriminate random sequences from sequences containing non-adjacent repetitions (ABA).

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28. • Gervain J, Berent I, Werker JF: **Binding at birth: the newborn brain detects identity relations and sequential position in speech**. *J Cogn Neurosci* 2012, **24**:564-574

Using near-infrared spectroscopy (NIRS), the authors show that newborn infants discriminate speech sequences containing adjacent repetitions at the initial and final edges (i.e. AAB versus ABB). This result evidences a certain level of abstraction, as infants need to detect the repetition as well as its position within the sequence.

29. Radulescu S, Wijnen F, Avrutin S, Gervain J: *Same processing costs for encoding sameness and difference in the developing brain: An fNIRS study with 6-7-month-olds*. . In preparation 2020.

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This work shows that young infants never exposed to sign language nonetheless extract repetition-based structures (AA) from dynamic signs, as well as from visual analogs. Interestingly, infants' brain activation measured using NIRS is greater for repetitions in sign language, but for random sequences (AB) in visual analogs. When presented with speech stimuli, infants exhibit a similar degree of activation to repeated and random sequences.

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