Behavioral and Imaging Studies of Infant Artificial Grammar Learning

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Behavioral and imaging studies of infant artificial grammar learning

Judit Gervain[1,2], Irene de la Cruz-Pavía[1,2], LouAnn Gerken[3]

[1]Laboratoire Psychologie de la Perception (Department of Research on Perception), Université Paris Descartes (Paris Descartes University), Paris, France

[2]Laboratoire Psychologie de la Perception (Department of Research on Perception), CNRS, Paris, France

[3] Department of Psychology, University of Arizona

Corresponding author:
Judit Gervain
Laboratoire Psychologie de la Perception (UMR8242)
Université Paris Descartes & CNRS
45 rue des Saints-Pères
75006 Paris
FRANCE

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Abstract

Artificial grammar learning (AGL) paradigms have proven to be productive and useful to investigate how young infants break into the grammar of their native language(s). The question of when infants first show the ability to learn abstract grammatical rules has been central to theoretical debates about the innate vs.

learned nature of grammar. The presence of this ability early in development, i.e., before considerable experience with language, has been argued to provide evidence for a biologically endowed ability to acquire language. AGL tasks also allow infant populations to be readily compared with adults and non-human animals. AGL paradigms with infants have been used to investigate a number of linguistic phenomena and learning tasks, from word segmentation to phonotactics and morphosyntax. In this review, we focus on AGL studies testing infants' ability to learn grammatical / structural properties of language. Specifically, we discuss the results of AGL studies focusing on repetition-based regularities, the categorization of functors, adjacent and non-adjacent dependencies, as well as word order. We discuss the implications of the results for a general theory of language acquisition and we outline some of the open questions and challenges.

Key words: language acquisition; infant artificial grammar learning; morphosyntax; adjacent dependencies; non-adjacent dependencies; word order; functors; repetition-based regularities

1. Introduction

Artificial grammar learning (AGL) paradigms have proven to be productive and useful to investigate how young infants break into the grammar of their native language(s). AGL offers several advantages. It allows for a systematic manipulation of relevant stimulus features (e.g., a particular syllable occurs in both position 1 and position 3 in a 3-syllable string) as well as control over the irrelevant ones (e.g., what occurs in position 2 does not matter, but that is part of what the learner must determine). As novel, unfamiliar linguistic material is typically used, AGL excludes cues from existing natural language knowledge that is not directly under scrutiny, but that participants could nevertheless rely on. Consequently, it also provides a comparable task for verbal (older children, adults) and non-verbal (young infants, animals) participants.

AGL paradigms have been used to investigate a number of linguistic phenomena and learning tasks, from word segmentation to phonotactics and morphosyntax. In this review, we will focus on AGL studies testing infants' ability to learn grammatical / structural properties of language that can be generalized to new strings. The question of when infants first show the ability to learn abstract grammatical rules has been central to theoretical debates about the innate vs. learned nature of grammar. The presence of this ability early in development, i.e., before considerable experience with language, has been argued to provide evidence for a biologically endowed ability to acquire language. Several early AGL studies with infants were originally designed to address this question experimentally (Gómez &

Gerken, 1999; Marcus, Vijayan, Rao, & Vishton, 1999), and as the growing body of literature published since then suggests, this paradigm has proven to be particularly well-suited to answer questions about the development of grammar.

Most infant AGL studies either use a behavioral method, typically a looking time task, such as the headturn preference procedure (HPP, Figure 1A), or an imaging method, such as electroencephalography (EEG, Figure 1B) or near-infrared spectroscopy (NIRS, Figure 1C). Imaging studies allow researchers to measure both the process of learning in real time as well as its results, whereas behavioural studies can usually only target the result of learning. Both behavioral and imaging methods can be used to test what infants bring to the task, such as existing knowledge, cognitive biases, perceptual primitives, etc. In this case, infants' spontaneous preference is typically tested, with no training or learning phase. Alternatively, AGLs can be used to test what infants are able to learn (under laboratory conditions). In this case, a familiarization, habituation or other learning phase is typically provided before infants' responses are tested.

Figure 1

Figure 1. Methods most commonly used in infant AGL studies. (A) The Headturn Preference Procedure (HPP, Kemler Nelson et al., 1995). (B) Electroencephalography (EEG, De Haan, 2013). (C) Near-infrared Spectroscopy (NIRS, Gervain et al., 2011).

As noted above, learning grammar entails being able to generalize beyond the input to more general principles or rules. Section 2 below considers if and how infants generalize over a particular type of structure – repetition. Sections 3 and 4 take on types of generalizations that are more specific to human grammar, which can be described as a set of dependency relations between lexical and phrasal categories. For example, a sentence is composed of a noun phrase and a verb phrase, and a noun phrase can be composed of a determiner and a noun. Section 3 focuses on AGL studies of infants' discerning categories of morphosyntactic elements (e.g., noun vs. verb constituents), and Section 4 focuses on AGL studies of word order and dependency relations among morphosyntactic elements.

2. Learning repetition-based structures **- a symbolic rule, a perceptual bias or both?**

Argued to be the simplest case of abstract symbolic rules, structures based on repetition, i.e., an identity relation, have received considerable attention. In a seminal study, Marcus et al. (1999) showed that 7-month-old infants were able to learn a simple repetition-based structure and discriminate it from another repetition-based structure. For instance, infants familiarized with AAB sequences (Figure 2A) were tested with new AAB sequences, i.e., sequences consistent with the grammar of familiarization, as well as on ABA sequences, inconsistent with the familiarization grammar. Infants showed longer looking times to the inconsistent sequences, indicating that they discriminated them from the consistent ones (Figure 2B). Crucially, infants showed this discrimination ability for sequences made up of elements, i.e., syllables that were not presented during familiarization (e.g., for the familiarization set in Figure 2A, test items were “ba po ba”, “ko ga ko”, “ba ba po”, “ko ko ga”). This was taken as evidence that infants generalize the underlying abstract rule, rather than relying on item-based information, e.g., statistics (frequency of occurrence or co-occurrence, etc.) or the specific position of a given string element.

Figure 2

Figure 2. The stimuli and results used in three experiments on repetition-based structures. A. The stimulus set used for familiarization in Marcus et al. (1999) Experiment 2 (full table), and in Gerken (2006) Experiments 1-3 (encircled column and diagonal), table adapted from Gerken (2006). B. The results of Marcus et al. (1999) Experiment 2. C. The results of Gerken (2006). D. The results of Gervain et al. (2008) Experiment 1, figure adapted from Gervain et al. (2008) and Abboub et al. (2016).

These initial results gave rise to a large body of literature further pursuing different aspects of how infants process, learn and represent repetition-based structures. First, the scope of the generalizations infants make was explored. Most learning sets are potentially compatible with several generalizations. Do infants entertain several possible generalizations? If yes, how do they choose between them? Gerken (2006) addressed these questions by testing infants on two subsets of Marcus et al.’s (1999) original familiarization set. For one subset (diagonal, encircled in Figure 2A), the narrowest generalization was the same as for the entire set, the AAB structure. For the other subset (column, encircled in Figure 2A), however, while the AAB generalization still applied, a narrower one (AA*di* or …*di*) was also possible, as all sequences ended in the same –*di* syllable. When tested on items that conformed to the larger AAB generalization (AAB “ko ko ba” vs. ABA “ba ko ba”), only infants who heard the broader, more variable diagonal subset succeeded (Figure 2C), infants who heard the narrower column subset failed to show discrimination. However, when infants familiarized with this narrower column subset were tested on test items that contained –*di* (“ko ko di” vs. “ko di ko”), they preferred the items consistent with the grammar of familiarization. This suggests that infants converge on the narrowest generalization that is compatible with the learning set.

Second, the interpretation that these simple repetition-based structures are necessarily represented as abstract, symbolic rules was challenged. Some authors have argued that adjacent repetitions are salient, Gestalt-like primitives, which may be detected automatically by the perceptual system without recourse to symbols or abstract representations (Endress, Nespor, & Mehler, 2009). Data from adult and animal AGL studies at least partially supports this claim (e.g., Endress, Scholl, & Mehler, 2005). Importantly, the automatic, perceptual detection of adjacent repetitions may explain infants' ability to discriminate an adjacent repetition based sequence (ABB) from a non-adjacent repetition based one (ABA, as in Marcus et al., 1999) or from a random one (Gervain, Macagno, Cogoi, Pena, & Mehler, 2008; Judit Gervain & Werker, 2012). However, this account is insufficient to explain how infants discriminate between two structures that both contain an adjacent repetition, such as AAB vs. ABB, an ability evidenced in 7-month-olds (Marcus et al., 1999) and newborns (Gervain, Berent, & Werker, 2012). Even if the detection of adjacent repetitions and increased sensitivity to sequence onsets and ends are low-level perceptual biases, discriminating AAB and ABB structures requires the combination of these two primitives, giving rise to a representation that is more abstract than each of the basic primitives. One possibility is that low-level perceptual biases might help infants parse the linguistic input in relevant ways, and over the course of learning the output of this perceptually-based parse feeds into more abstract representations. This hypothesis is supported by NIRS results in newborns (Gervain, Macagno, et al., 2008; Figure 2D), who show increased brain activation to repetition-based trisyllabic sequences over random ones in the bilateral temporal and left frontal cortices immediately upon exposure (Figure 2D, Blocks 1-4), suggesting an early and perceptually-based mechanism. Additionally, this differential response further increases in the left frontal areas (including Broca's area) over time (Figure 2D, Blocks 11-14), implying a more abstract, higher-level mechanism. The debate about the underlying representation of repetition-based structures is not yet resolved and calls for further research.

Third, the language-specific nature of the ability to learn repetition-based patterns was investigated. In the auditory domain, when 7-month-old infants were tested on repetition-based sequences made up of non-linguistic sounds (animal vocalizations, environmental sounds, musical instruments, etc.), they were better able to learn if they first heard the repetition-based rules instantiated by speech (Marcus, Fernandes, & Johnson, 2007), suggesting that speech is a privileged input for rule learning. Interestingly, when musical tones were used, 4-month-olds succeeded, but 7-month-olds failed (Dawson & Gerken, 2009), a developmental change the origins of which remain to be clarified. In the visual domain, successful discrimination of different repetition-based structures was found for natural, biologically existing categories, such as dogs, at 7 months (Saffran, Pollak, Seibel, & Shkolnik, 2007). By contrast, when geometric shapes were used, 5-month-olds failed (Frank, Slemmer, Marcus, & Johnson, 2009), while 8- and 11-month-olds succeeded, albeit only partially (Johnson et al., 2009), but even the youngest infants succeeded with multimodal stimuli, coordinated looming visual shapes and speech sounds (Frank et al., 2009). Taken together, these studies thus suggest that repetition-based rule learning is available for a broad set of stimuli from a very young age, but speech and biological categories serve as particularly appropriate input.

While repetition-based patterns do appear in natural language, e.g., in the infant-directed lexicon (French: *dodo* ‘sleep’, Italian: *papà* ‘father’) and in morphology (Tagalog: *mag-isip* ‘to think’, *mag-isip-isip* ‘to think deeply), natural language grammars rely on a large number of other morphosyntactic dependencies, as well.

3. Learning morphosyntactic categories

One of the most important cues to morphosyntactic categories in the input is the small set of function morphemes or functors. Table 1 illustrates this relation.

Category 1 functors						
the	the dog	the house	the shoe	the ball	the doll	the blanket
a	a dog	a house	a shoe	NOT YET ENCOUNTERED	a doll	a blanket

Category 2 functors						
can	can dance	can eat	can drink	can run	can sleep	can fall
will	will dance	will eat	will drink	NOT YET ENCOUNTERED	will sleep	will fall

Table 1. Illustration of how particular sets of functors co-occur with particular categories. The functors *the* and *a* co-occur with one set of content words (e.g., *dog, house,* etc.) and the functors *can* and *will* co-occur with another set of content words. Knowing that *the* and *a* co-occur with the same words allows learners to fill in the forms that have hypothetically not yet been encountered in their input (e.g., “a ball”).

Infants are born with the ability to detect the language-general acoustic differences that set functors and content words apart, functors being phonologically more reduced than content words (Morgan, Shi, & Allopenna, 1996; Shi, Cutler, Werker, & Cruickshank, 2006). They can thus use functors to segment, categorize and learn new words, and learn basic word order. There is abundant evidence of infants’ acute sensitivity to functors. At around 12 months, infants prefer listening to phrases containing real functors over those containing phonetically close nonsense functors (Shi et al., 2006), and show different brain activity when hearing continuous speech compared with a similar stream in which a tone is superimposed on the functors, distorting their acoustic characteristics (Shafer, Shucard, Shucard, & Gerken, 1998). Interestingly, children's first multiword utterances are typically "telegraphic" and lack function words. However, their omission in early production appears to stem from a limitation on production and not on perception or encoding. Indeed, children at this stage understand instructions better if they contain functors rather than being telegraphic (Shipley, Smith, & Gleitman, 1969) and, when imitating sentences, 2- to 3-year-old children tend to omit unstressed monosyllabic morphemes (the equivalents of functors), but not strong, stressed ones (content words), even if they are non-words. Further, they imitate made-up "content words" better when surrounded by real functors than by nonsense functors, and distinguish nonsense functors that follow the usual consonant patterns of the native language's functors from others that do not (Gerken, Landau, & Remez, 1990).

There have been several tests of infants' ability to categorize a novel word based on the native language context in which it occurs (Höhle, Weissenborn, Kiefer, Schulz, & Schmitz, 2004; Shi & Melançon, 2010). For example, French learning 14-month-olds who were familiarized in the HPP with a novel word that occurred in a French noun context (e.g., *des mige, ton mige*) listened longer to (were surprised by) the same novel word when it occurred in a verb context (e.g., *Je mige*) than another noun context (*le mige*; Shi & Melançon, 2010). This study suggests that infants group the set of determiners in their native language (*des, ton, le*) and treat the words that follow this set as another set (i.e., nouns). Another study using an AGL-like paradigm with HPP demonstrated that 17-month-old English-learners could quickly form a category of Russian gendered case markings (masculine *-ya*, *-yem* and feminine *–oj*, *-u*). During familiarization, infants heard a set of masculine and feminine stems, most with the two relevant case markings but some with only one marking (like the unattested forms in Fig. 3). For example, infants heard *pisaryem* (*scribe –masc. instrumental case)* but not *pisarya (scribe – masc. genitive case)* during familiarization. At test, infants distinguished *pisarya* from **pisaroj*, suggesting that they very quickly formed the expectation that words that occur with *–yem* also occur with *–ya* (Gerken, Wilson, & Lewis, 2005). The same Russian gender experiment performed with 12-month-olds revealed no sign of learning. Given the importance of syntactic categories in language acquisition, surprisingly few studies have focused on this issue. The existing studies agree that infants are able to form rudimentary categories (largely from dependencies between functor and content items) early in their second year.

Functors' correlated distributional and phonological properties not only help infants form word categories, but they might also provide the basis for learning semantic properties of words. Hochmann (2013) showed that, after being familiarized with a string of frequent and infrequent elements, 17-month-olds associated new objects with infrequent, but not with frequent words, which suggests that infants treat frequent elements as less referential and disprefer them as potential object labels. Furthermore, Lany and

Saffran (2010) found that 22-month-olds can track correlations between distributional and semantic properties of word categories. Infants were first familiarized with a simple artificial language containing two “content word” categories (*X*, *Y*) and two functor-like categories (*a*, *b*). In the first phase, a group of infants listened to a version in which the “content words” were reliably marked by the “functors” (*aX*, *bY*), and a second group listened to a version in which they were not systematically marked (*aX*, *aY*, *bX*, *bY*). In the second phase, the experimenters trained infants on associations between *aX* phrases and pictures of animals, and *bY* phrases and pictures of vehicles. Finally, infants were tested to determine if they treat new *aX* phrases as referring to new animals and new *bY* phrases as referring to new vehicles. Interestingly, only the group of infants who were familiarized with reliable functor-content pairings in the first phase was able to generalize the association between phrases and pictures to novel pairings at test.

In sum, functors appear to act as anchor points to structure that signal morphosyntactic categories. Functors also contribute to the learning of the grammatical rules in which these categories participate, which is the topic of the next section.

4. Learning the ordering and dependency relations among sequences of word-like elements

AGL studies have also explored when infants first show evidence of sensitivity to the order of elements in a sequence and dependency relations among these elements. In natural language, an example of such a dependency relation is the one between *is* and *–ing* in *is VERBing*. Several studies have shown that even very young infants can detect a change in the order of word-like units in AGL-like natural language strings that they had been familiarized with (in newborns: Benavides-Varela & Gervain, 2017; in 2-month-olds: Mandel, Kemler Nelson, & Jusczyk, 1996). More subtle violations of sequential order in complex artificial grammars with test items requiring generalization was observed in older infants (in 12-month-olds: Gómez & Gerken, 1999; in 14-, but not in 11-month-olds: Koulaguina & Shi, 2013).

More recently, AGL tasks have also been used to explore when and how infants start developing some rudimentary, but possibly abstract knowledge of the sequential order of their native grammars. In a series of studies (Gervain, Nespor, Mazuka, Horie, & Mehler, 2008; Gervain et al., 2013) with an artificial grammar in which frequent and infrequent word-like elements alternated, mimicking functors and content words, respectively, infants acquiring languages with opposite word orders such as Italian and Japanese showed evidence of parsing the familiarization stream according to the word order of their native language at 8 months, i.e., before they have a sizeable lexicon. Thus, Italian infants showed a preference for parsing the familiarization stream into units starting with frequent words, reflecting the functor-initial order of Italian (*a Roma* ‘to/in Rome’), whereas their Japanese peers preferred the frequent word final sequences, mirroring functor-final order in Japanese (*Tokyo ni* ‘to Tokyo’). Since Japanese and Italian babies were familiarized and tested with the same artificial, nonsense stimuli, the difference in their preferences during test could only result from their existing linguistic knowledge they brought to the task.

Other work has examined infants' ability to learn dependencies between word- or morpheme-like elements. (We will refer to the nonse elements as "words" here, realizing that they could be construed as one- or two-syllable strings with different phonological properties.) Two types of dependencies have been tracked – adjacent and non-adjacent. Beginning with adjacent dependencies, Gómez & Lakusta (2004) familiarized 12-month-olds with *aX* and *bY* strings, in which there were two functor-like *a* words (both beginning with a vowel), which preceded six monosyllabic content word-like *X* words (always CVC's), and two functor-like *b* words (also beginning with a vowel), which preceded six disyllabic content word-like *Y* words. Infants were able to learn the dependency between specific *a*'s and *X*'s and *b*'s and *Y*'s, as well as the relation between *a*'s and new CVC monosyllables and *b*'s and new disyllables. Thus, adjacent dependencies appear to be learnable at a younger age than morphosyntactic categories, perhaps because the former require only associations between physical stimuli (i.e., 2 specific *a* words associated with CVC words and 2 specific *b* words associated with 2-syllable words), whereas the latter requires a higher order association between groups (categories) of stimuli that are not marked by physical properties such as syllable number. We will return to the question of what infants might have learned in this experiment below.

Turning to non-adjacent dependencies, Gómez (2002) and Gómez & Maye (2005) familiarized 12-, 15-, and 17-month-olds with strings of the form *aXb*, *cYd*, in which there was a dependency relation between *a*'s and *b*'s and between *c*'s and *d*'s; in other words, the middle *X* and *Y* words were irrelevant. Only the older two groups were able to learn the dependencies when tested on previously heard strings vs. ungrammatical (e.g., *aXd*) strings, and only when there were sufficiently many *X*'s and *Y*'s in the familiarization stimuli. An interesting twist on this study was performed by Lany and Gómez (2008), who pre-exposed infants to adjacent (*aX bY*) dependencies (e.g., *erd coomo, ush deech*, where *ong* and *erd* are functor-like *a*-elements and *alt* and *ush* are functor-like *b*-elements. *X*- and *Y*-elements are like content words because there are many of them), after which they were habituated to *acX* and *bcY* strings (e.g., *ong hes coomo, alt hes deech,* with dependencies between *aX* and *bY*). With pre-exposure, 12-month-olds were able to learn the long-distance dependency, suggesting that discerning the adjacent dependency sensitized them to the same dependency at a distance.

One issue to consider about both the adjacent and long distance dependency studies described here is that, although they are similar in format to the category formation studies described earlier, they do not test whether infants treat the *a, b, X,* and *Y* words as abstract classes or categories. To illustrate this point with an English example, a child who has heard *the dog, a dog,* and now hears a new phrase *a goblet* should infer that *the goblet* is a grammatical phrase. Similarly, a child in an AGL experiment who is familiarized with *ong fengle* and *erd fengle* and *erd coomo*, but not *ong coomo* should infer that *ong coomo* is OK and distinguish *ong coomo* from an ungrammatical counterpart (e.g., *ush coomo*, where *ush should be followed by a 1-syllable word*) at test. Yet, this prediction has not been tested, although Lany and Gómez (2008) did withhold some grammatical strings from the pre-exposure set. Therefore, we don't know whether the 12-month-olds who succeeded in learning long distance dependencies after pre-exposure to adjacent dependencies were really learning an *acX bcY* grammar (where a, *c*, *X*, *b*, and *Y* are all classes of lexical elements) or a set of associations between *a1* and *X1*, *a2* and *X1*, *a1* and *X2*, *a2* and *X2*, etc. That is, infants could have learned a set of associations among physical stimuli and not category level associations. The fact that 12-month-olds learned the long distance dependency grammar of Lany and Gómez (2008), but not the Russian gender category grammar of Gerken et al. (2005) suggests that the infants studied by Lany and Gómez (2008) were not learning the same level of abstract categories as the infants studied by Gerken et al (2005). We will also return to this question below.

Let us turn to two studies in which infants must have learned physical, not category level, dependencies. In one such study with 7- and 12-month-olds, Marchetto & Bonatti (2015) familiarized infants with two syllable-based dependencies (e.g., *baXso* and *liXfe*) instead of possible lexical class-based dependencies like *aX* and *bY*. These researchers tested infants on new grammatical and ungrammatical test strings and found that both younger and older infants had been able to discern the syllable-based dependencies (e.g., ***ba***_mu_***so***, ***ba***_ga_***so***, ***li***_mu_***fe***, ***li***_ga_***fe***).

A natural language grammar learning experiment that closely parallels that of Marchetto and Bonatti (2015) was performed with 4-month-olds using ERP's as the dependent measure (Friederici, Mueller, & Oberecker, 2011). German infants listened to the Italian dependencies ***sta*** *VERB-**ando*** and ***puo*** *VERB-**are*** and were tested on grammatical and ungrammatical phrases in an interleaved learning and testing format. ERP's indicated that infants distinguished grammatical from ungrammatical test phrases, suggesting they learned the *sta –ando* and *puo –are* dependencies.

5. Summary and open issues

The AGL studies reviewed above suggest that infants are remarkably well prepared to find regularities in linguistic input. Although it is risky to draw conclusions about development from snapshots of infant performance at various ages, the pattern of successes and failures seen in the AGL and natural language equivalent studies described in Sections 2-4 suggest the following developmental trajectory. Initially, infants (even newborns) notice physical identity relations, probably anchored to string position (e.g., *leledi* vs. *dilele*). Such regularities are probably not specific to language. Nevertheless, it is an open question whether infants are better at finding these regularities in language-like stimuli. Given how early the ability to notice physical identity relations appears, and given that physical identity relations are not specific to language, we might predict that repetition-based patterns would be relatively easily learned by other species.

Somewhat later, infants notice physical dependency relations between syllables or between syllables and stress patterns (4-month-olds in Friederici et al, 2011; 7-month-olds in Marchetto & Bonatti, 2015). It is unclear whether non-adjacent dependencies are more difficult than adjacent dependencies when only physical dependencies are under consideration[1]. A comparison of adjacent and non-adjacent physical dependencies in human infants and animals would almost certainly yield interesting results.

Much later, infants notice higher order dependencies between sets of physical dependencies and can predict as yet unheard strings (e.g., hearing *a dog, the dog, a boy, the boy, a cat* allows the child to predict *the cat*). The Shi & Melaçon (2010) and Gerken et al. (2005) studies show this ability in 14- and 17-month-olds, respectively. The studies of Gómez and colleagues (Gómez & Lakusta, 2004; Gómez & Maye, 2005; Lany & Gómez, 2008) may fall somewhere in between physical and category-based dependencies, since they don't explicitly test infants' ability to predict unheard strings from an abstract category, yet their stimuli do potentially involve dependencies between categories of items as opposed to physical dependencies. Category-based patterns appear to be more specific to human language than are patterns based on physical identity or dependencies among specific physical elements (see Udden et al. in the current Special Issue). Category-based patterns are also only learnable by older infants. Thus, we might predict that such patterns would be particularly difficult for non-humans.

A final point that is related to the forgoing discussion concerns how language-like the AGL stimuli are that have been used with infants. Studies that appear to be very similar on the surface (e.g., long distance dependency relations) can in fact be quite different in both the types of structure infants are asked to find and the basis on which infants are likely to generalize, if they are in fact asked to generalize at all. Using more language-like AGL stimuli (for instance from unfamiliar languages) makes cross-species comparisons harder, but using less language-like stimuli reduces confidence that AGL studies with human infants really approximate anything close to real language learning. As cross-species AGL studies

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[1] One study that can be construed as examining non-category-based adjacent dependencies in an AGL is the word segmentation work of Saffran, Aslin and Newport (1996). The infants tested were 8-month-olds, similar in age to those tested by Marchetto and Bonatti on non-adjacent dependencies. However, the nature of familiarization and test used by Saffran et al. differs from that of most of the AGL experiments described here and aims at investigating segmentation rather than grammar learning. It is therefore not discussed here further.

become more sophisticated, perhaps the best we can do is to become clearer in saying how the stimuli and tasks we are using are like and unlike those encountered by real language learners.

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References

Abboub, N., Nazzi, T., & Gervain, J. (2016). Prosodic grouping at birth. *Brain and Language*, *162*, 46–59.

Benavides-Varela, S., & Gervain, J. (2017). Learning word order at birth: A NIRS study. *Developmental Cognitive Neuroscience*.

Braine, M. D. (1966). Learning the positions of words relative to a marker element. *Journal of Experimental Psychology*, *72*(4), 532–540.

Dawson, C., & Gerken, L. (2009). From domain-generality to domain-sensitivity: 4-Month-olds learn an abstract repetition rule in music that 7-month-olds do not. *Cognition*, *111*(3), 378–382.

De Haan, M. (2013). *Infant EEG and event-related potentials*. Psychology Press.

Endress, A. D., Nespor, M., & Mehler, J. (2009). Perceptual and memory constraints on language acquisition. *Trends in Cognitive Sciences*, *13*(8), 348–353.

Endress, A. D., Scholl, B. J., & Mehler, J. (2005). The role of salience in the extraction of algebraic rules. *Journal of Experimental psychology.General*, *134*(3), 406–419.

Frank, M. C., Slemmer, J. A., Marcus, G. F., & Johnson, S. P. (2009). Information from Multiple Modalities Helps Five-month-olds Learn Abstract Rules. *Developmental Science*, *12*(4), 504–509.

Friederici, A. D., Mueller, J. L., & Oberecker, R. (2011). Precursors to natural grammar learning: preliminary evidence from 4-month-old infants. *PLoS One*, *6*(3), e17920.

Gerken, L. (2006). Decisions, decisions: Infant language learning when multiple generalizations are possible. *Cognition*, *98*(3), B67–B74.

Gerken, L., Landau, B., & Remez, R. (1990). Function morphemes in young children's speech perception and production. *Developmental Psychology*, *26*, 204–216.

Gerken, L., Wilson, R., & Lewis, W. (2005). Infants can use distributional cues to form syntactic categories. *Journal of Child Language, 32*(2), 249–268.

Gervain, J., Berent, I., & Werker, J. F. (2012). Binding at birth: The newborn brain detects identity relations and sequential position in speech. *Journal of Cognitive Neuroscience*, 24(3): 564-574.

Gervain, J., Macagno, F., Cogoi, S., Pena, M., & Mehler, J. (2008). The neonate brain detects speech structure. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(37), 14222–14227.

Gervain, J., Mehler, J., Werker, J. F., Nelson, C. A., Csibra, G., Lloyd-Fox, S., Aslin, R. N. (2011). Near-infrared spectroscopy: A report from the McDonnell infant methodology consortium. *Developmental Cognitive Neuroscience*, *1*(1), 22–46.

Gervain, J., Nespor, M., Mazuka, R., Horie, R., & Mehler, J. (2008). Bootstrapping word order in prelexical infants: A Japanese-Italian cross-linguistic study. *Cognitive Psychology*, *57*(1), 56–74.

Gervain, J., Vines, B. W., Chen, L. M., Seo, R. J., Hensch, T. K., Werker, J. F., & Young, A. H. (2013). Valproate reopens critical-period learning of absolute pitch. *Frontiers in Systems Neuroscience*, *7*.

Gervain, J., & Werker, J. F. (2012). Learning Non-Adjacent Regularities at Age 0;7. *Journal of Child Language*, 40(4): 860-872.

Gomez, R. L. (2002). Variability and detection of invariant structure. *Psychological Science*, *13*(5), 431–436.

Gomez, R. L., & Gerken, L. (1999). Artificial grammar learning by 1-year-olds leads to specific and abstract knowledge. *Cognition*, *70*(2), 109–135.

Gómez, R. L., & Lakusta, L. (2004). A first step in form-based category abstraction by 12-month-old infants. *Developmental Science*, *7*(5), 567–580.

Gómez, R., & Maye, J. (2005). The developmental trajectory of nonadjacent dependency learning. *Infancy*, *7*(2), 183–206.

Green, T. (1979). The necessity of syntax markers. *Journal of Verbal Learning and Verbal Behavior*, *18*, 481–496.

Hochmann, J.-R. (2013). Word frequency, function words and the second gavagai problem. *Cognition*, *128*(1), 13–25.

Höhle, B., Weissenborn, J., Kiefer, D., Schulz, A., & Schmitz, M. (2004). Functional elements in infants' speech processing: The role of determiners in the syntactic categorization of lexical elements. *Infancy*, *5*(3), 341–353.

Johnson, S. P., Fernandes, K. J., Frank, M. C., Kirkham, N., Marcus, G., Rabagliati, H., & Slemmer, J. A. (2009). Abstract rule learning for visual sequences in 8-and 11-month-olds. *Infancy*, *14*(1), 2–18.

KemlerNelson, D. G., Jusczyk, P. W., Mandel, D. R., Myers, J., Turk, A. E., & Gerken, L. (1995). The head-turn preference procedure for testing auditory perception. *Infant Behavior and Development*, *18*, 111–116.

Koulaguina, E., & Shi, R. (2013). Abstract Rule Learning in 11- and 14-Month-Old Infants. *Journal of Psycholinguistic Research*, *42*(1), 71–80.

Lany, J., & Gómez, R. L. (2008). Twelve-month-old infants benefit from prior experience in statistical learning. *Psychological Science*, *19*(12), 1247–1252.

Lany, J., & Saffran, J. R. (2010). From statistics to meaning: Infants' acquisition of lexical categories. *Psychological Science*, *21*(2), 284–291.

Mandel, D. R., KemlerNelson, D. G., & Jusczyk, P. W. (1996). Infants remember the order of words in a spoken sentence. *Cognitive Development*, *11*, 181–196.

Marchetto, E., & Bonatti, L. L. (2015). Finding words and word structure in artificial speech: The development of infants' sensitivity to morphosyntactic regularities. *Journal of Child Language*, *42*(4), 873–902.

Marcus, G. F., Fernandes, K. J., & Johnson, S. P. (2007). Infant rule learning facilitated by speech. *Psychological Science*, *18*(5), 387.

Marcus, G. F., Vijayan, S., Rao, S. B., & Vishton, P. M. (1999). Rule learning by seven-month-old infants. *Science*, *283*(5398), 77–80.

Morgan, J. L., Meier, R. P., & Newport, E. L. (1987). Structural packaging in the input to language learning: Contributions of intonational and morphological marking of phrases to the acquistion of language. *Cognitive Psychology*, *19*, 498–550.

Morgan, J. L., Shi, R., & Allopenna, P. (1996). Perceptual Bases of Rudimentary grammatical categories: toward a broader conceptualization of bootstrapping. In *Signal to Syntax* (pp. 263–283). Hillsdale, NJ: Lawrence Erlbaum Associates.

Saffran, J. R., Aslin, R. N., & Newport, E. (1996). Statistical learning by 8-month-old infants. *Science*, *274,* 1926-1928.

Saffran, J. R., Pollak, S. D., Seibel, R. L., & Shkolnik, A. (2007). Dog is a dog is a dog: Infant rule learning is not specific to language. *Cognition*, *105*(3), 669–680.

Shafer, V. L., Shucard, D. W., Shucard, J. L., & Gerken, L. (1998). An electrophysiological study of infants' sensitivity to the sound patterns of English speech. *Journal of Speech, Language, and Hearing Research*, *41*(4), 874–886.

Shipley, E. F., Smith, C. S., & Gleitman, L. R. (1969). A study in the acquisition of language: Free responses to commands. *Language*, *45*, 322–342.

Shi, R., Cutler, A., Werker, J., & Cruickshank, M. (2006). Frequency and form as determinants of functor sensitivity in English-acquiring infants. *The Journal of the Acoustical Society of America*, *119*(6), EL61–7.

Shi, R., & Melançon, A. (2010). Syntactic Categorization in French-Learning Infants. *Infancy*, *15*(5), 517–533.

Valian, V., & Coulson, S. (1988). Anchor points in language learning: The role of marker frequency. *Journal of Memory and Language*, *27*, 71–86.

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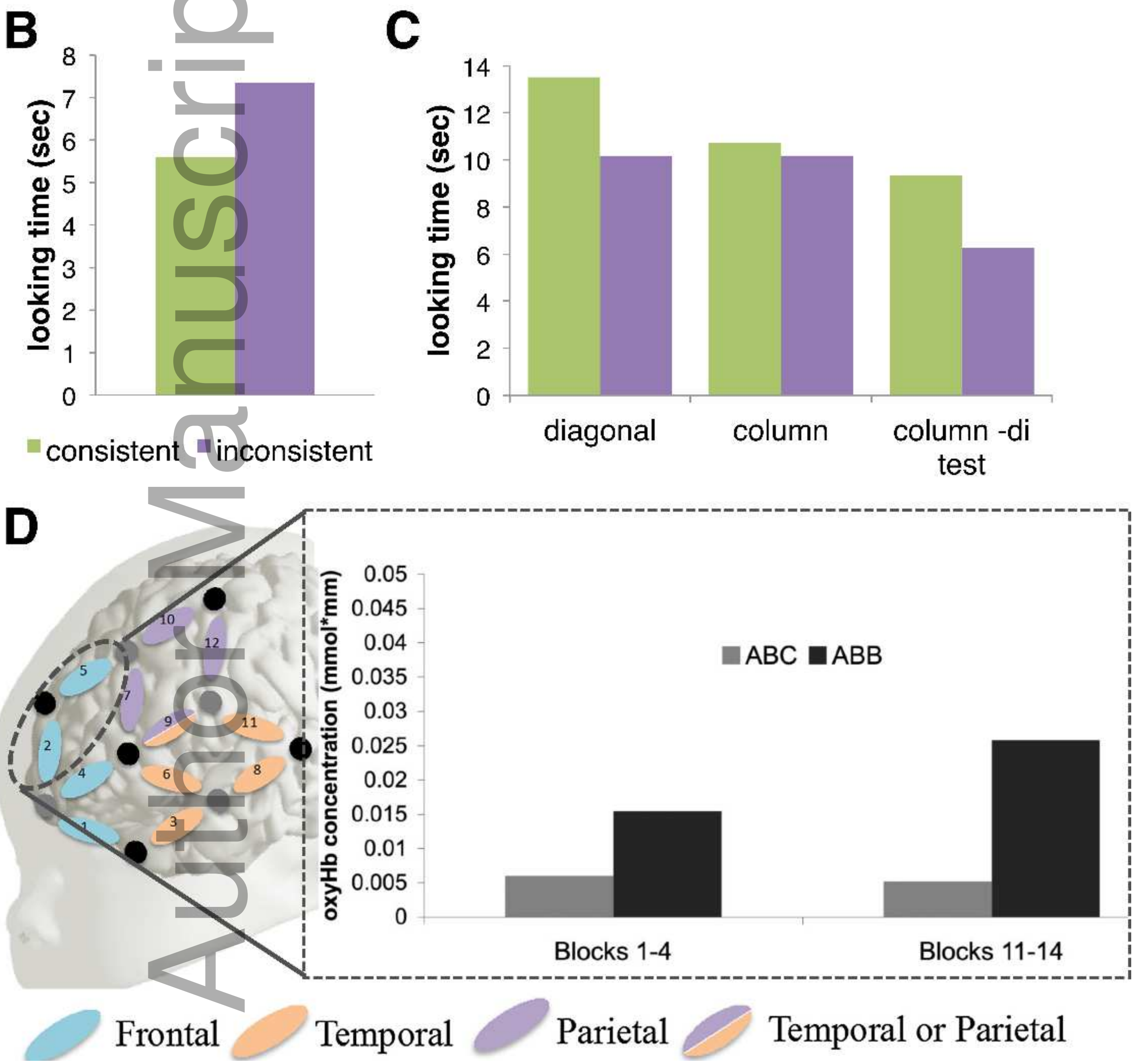

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