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# Artificial Grammar Learning in children, adults, animals and machines

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## Abstract

Human languages all have a grammar, i.e. rules that determine how symbols in a language can be combined to create complex meaningful expressions. Despite decades of research, the evolutionary, developmental, cognitive and computational bases of grammatical abilities are still not fully understood. “Artificial Grammar Learning” (AGL) studies provide important insights into how rules and structured sequences are learned, the relevance of these processes to language in humans and the evolutionarily conserved cognitive systems that may be shared with other animals. AGL tasks can be used to study how human adults, infants, animals or machines learn artificial grammars of various sorts, consisting of rules defined typically over syllables, sounds or visual items. In this introduction, we distill some lessons from the nine others papers in this special issue, which review the advances made from this growing body of literature. We provide a critical synthesis, identify the questions that remain open, and recognize the challenges that lie ahead. A key observation across the disciplines is that the limits of human, animal and machine capabilities have yet to be reached. Thus, this interdisciplinary area of research firmly rooted in the cognitive sciences has unearthed exciting new questions and venues for research, along the way fostering impactful collaborations between traditionally disconnected disciplines that are breaking scientific ground.

## 1. Introduction

All human languages are characterized by having a grammar, i.e. a series of rules that determine how the items of a language need to be combined in order to create meaningful utterances. These rules may vary among languages, and native speakers of a language acquire them predominantly implicitly, by being exposed to speech (or sign) during their childhood. Yet, the evolutionary, developmental, cognitive and computational bases of grammatical abilities are still poorly understood. Two core questions for cognitive science are how abstract rules are acquired, and whether the learning involves general learning mechanisms or language- or human-specific ones.

Most of the research into these questions examines the natural course of language development and the acquisition of grammar rules. However, here we focus on a scientifically broader approach brought together under the umbrella of "Artificial Grammar Learning" (AGL) studies. AGL is widely used to study the cognitive underpinnings of language using artificial, miniature languages, defined by simple to more complex grammars and exemplified by varying length sequences of auditory or visual items.

AGL studies have led to a wealth of experimental findings for human adults as well as infants. They have also provided insights into similarities and differences with the pattern-recognition abilities of nonhuman animals, including monkeys, great apes, rats and a range of bird species. They are also used to study processes involved in the production of structured behavioral sequences. Furthermore, the empirical findings have given rise to machine learning and computational modeling of the learning mechanisms involved. All these efforts have resulted in the emergence of a vibrant cross-disciplinary community, which applies a range of different AGL tools in psycholinguistic, computational, developmental, evolutionary and neurobiological contexts to understand not just linguistic-related grammar learning, but also more generally cognitive and statistical learning capabilities and systems.

The growing body of empirical evidence and computational models, and the emergence of new interdisciplinary work now warrants a synthesis and a critical assessment of where this field stands and might go from here. The contributions to this special issue present such an overview. In relation to the contributed papers, we next outline the nature and scope of the AGL paradigm and then consider a number of questions and debates concerning the approach and interpretation of its results. We finish the editorial overview with a summary on the state of our understanding and the avenues that lie ahead.

## 2. Nature and scope of AGL studies

Experiments that examine grammar learning will be affected by the individual's prior language and knowledge. Knowledge of the meaning of words or the structure of specific expressions can influence what and how humans learn in experiments aiming to identify principles of grammatical rule learning. It is also challenging to control for the rich complexity of the semantic and syntactic relationships in natural language. AGL paradigms circumvent these problems by focusing purely on rule-based ordering relationships.

In AGL experiments, arbitrary auditory items (spoken nonsense syllables or other sounds) or visual ones (letters, nonsense words or pictures) are used to construct strings that have pre-defined rule-based dependencies between certain items in a sequence. AGL can thus be used to examine the abilities, biases and constraints of the participant to learn some of the properties and patterns in the way that strings are organized over time. With minimal modifications, the tasks can be used as easily with linguistically experienced human adults as with preverbal infants or nonverbal animals with very different prior experiences.

Participants in AGL experiments are first exposed, either in passive or active tasks, to strings of items sharing some underlying structural properties established by rules. Next, the obtained (implicit or explicit) knowledge of the grammar is tested by how well the participants can recall the sequences or discriminate novel strings conforming to the training grammar versus those that violate the grammar. When the paradigm was introduced over half a century ago (e.g. Miller, 1958; Reber, 1967), it was used to examine implicit rule learning in human adults. The participants were shown cards with sequences of letters, either sharing or not sharing a particular sequential structure. Next, they had to reproduce these sequences so that the researchers could test whether strings conforming to the structure were better memorized than those not conforming to it. Later on, the paradigm was adapted for examining the learning of grammatical patterns in infants, using behavioral responses such as head turns in a familiarization task (e.g. KemlerNelson et al., 1995), instead of verbal responses.

It was quickly realized that behavioural tests could not only be implemented with human infants, but also with non-human animals, paving the way for comparative studies. The initial animal studies also used a familiarization or habituation/dishabituation task (e.g. Hauser et al., 2001), but many subsequent studies used an operant discrimination task, in which animals are first rewarded to discriminate different (sets of) stimuli (see ten Cate & Okanoya, 2012). Next, in a testing phase, the responses to probe strings is used to gain insights into what knowledge the animals have gained about the structure of the sequences.

Since its introduction, the AGL paradigm has boosted empirical research on rule learning, because of the range of methods that can be used, the questions that can be addressed and the species that can be tested. It has proven to be a useful tool to examine the behavioral and neurobiological mechanisms of rule learning in humans, and whether the cognitive processes involved in grammar learning are language domain-specific or of a more general nature where artificial grammars access similar processes or related ones within a cognitive domain-general system (e.g. Frank et al., 2009 ). The paradigm’s adoption in animal experiments has stimulated the study of homologs and analogs of rule learning processes in animals, which has provided insights into the evolutionary origins of structured sequence learning processes and mechanisms.

However, results obtained in the AGL paradigm have also generated debate about what exactly is being learned and have given rise to new sets of questions, approaches and paradigms. As an example, see Alhama & Zuidema (2019) for a debate concerning the findings and modeling insights following the seminal work of Marcus et al. (1999). These questions go to the heart of cognitive science: Are the rule learning mechanisms shown in AGL experiments the same as those used to acquire natural language grammars? Do animal experiments really demonstrate meaningful rule-learning abilities, or something else, and do they allow direct or only indirect comparisons to human grammar learning? How does the use of different experimental methods and different types of stimuli affect conclusions about learning abilities? At what developmental stages do children learn different properties and how do these relate to the development of language? What are the neural processes and pathways that are involved in rule-based sequence processing and how do these compare across species? What do computational models suggest about the mechanisms involved and how they could evolve?

The above questions call for a critical cross-disciplinary reassessment of the empirical and computational evidence on rule-learning mechanisms both within and beyond AGL studies. One aim of this special issue is to assess and synthesize the insights the AGL approach has provided for understanding the cognitive mechanisms underlying the learning of grammatical structures, their domain and species-specificity, and the development and evolution of these mechanisms. The other one is to evaluate the constraints of the AGL approach and the challenges it is facing from the sometimes contradictory outcomes of the diversity of studies using the paradigm. The AGL paradigm has initially evolved more or less independently in different fields to address different questions. Such divergence in inception is to be expected but the stage is now set for a more cross-disciplinary integrative approach, after having taken stock of the productivity, benefits and pitfalls inherent in its use. Only in so doing can the approach be refined and  used to provide answers to the new sets of questions that can now be conceived.

## 3. Understanding infant linguistic development

Language acquisition in infants takes place at multiple levels simultaneously and over a surprisingly early, yet protracted period of time. The AGL paradigm allows researchers to focus on the learnability of an isolated phenomenon within the limited time-span available for an experiment with infants. Importantly, the AGL paradigm can readily be adapted even for pre-verbal infants, as it assesses the perception and implicit processing, rather than the production, of rule-based strings. Whether infants note differences among different artificial grammars can be measured using behavioral (head-turn, looking time) or neurophysiological measures (e.g. EEG or, recently, fNIRS - Gervain et al., 2011).

The focus of the review by Gervain et al. (this issue) lies on both behavioral and neurophysiological AGL studies that investigate rule and structure learning processes. The paper provides an overview of all the major AGL paradigms used to date with infants to investigate their learning abilities at the level of morpho-phonology and syntax.

In AGL experiments, infants are typically familiarized with or habituated to auditory or visual stimuli arranged in a simple pattern, such as the repetition pattern ABB or ABA (e.g. Marcus et al., 1999). During testing, infants are presented with novel stimuli, arranged in either the pattern they were familiarized with (i.e. a consistent/grammatical pattern) or a different (i.e. inconsistent/ungrammatical) pattern. It is remarkable how infants as young as 4 months of age are already able to extract a pattern from the input in just 2 minutes of familiarization, and can show a differential response to consistent vs. inconsistent  sequences. Behavioral AGL studies have tested many levels of linguistic description, charting young infants’ learning abilities and native language knowledge at the level of phonotactics, phonology, morpho-phonology, syntax and the lexicon.

Imaging studies have shown that newborns already show sensitivity to auditorily presented patterns, and specifically do so in brain areas classically associated with speech and language processing in adults, indicating that some processing mechanisms are already present before birth. Other imaging AGL studies with older infants have started exploring infants' earliest acquisition of their native language as well as learning mechanisms that emerge throughout early cognitive development.

Infants are also sensitive to regularities carried by non-speech auditory stimuli as well as visual stimuli, suggesting that some rule learning mechanisms are not language-specific. However, it remains to be seen whether infants use these same mechanisms to acquire the grammatical structure of their native language(s) and relatedly, whether the mechanisms identified in the laboratory scale up to explain language development in the real world.

## 4. Insights from comparative AGL studies

In a wide range of mammal and bird species one can find long and complex vocalization sequences, consisting of various sound elements. Such vocalizations are characterized by species-specific structural regularities, suggestive but not necessarily indicative of grammatical rules. In several species the sound sequences and the units from which they are constructed show very little if any evidence of having been learned during development and once developed they show little, if any, plasticity. In these species there is currently little reason to postulate a grammar or a rule-learning mechanism to explain the structure of the vocalizations.

In other species (e.g. songbirds, parrots, dolphins and whales) vocal learning plays a prominent role in the development and variation in their vocalizations. A range of studies examined the structural properties of such vocalizations and compared them to those present in human languages. This revealed that most sequences can be formally described by a relatively simple finite state grammar, with little evidence of greater complexity (Berwick et al., 2011).

This finding has led some researchers to conclude that a fundamental gap separates animal and human rule learning abilities (e.g. Berwick & Chomsky, 2015). However, the absence of more complex rules than finite state grammars in animal vocalizations need not imply that animals cannot detect and learn complex rules (ten Cate, 2017). Nonhuman animals may well have cognitive abilities to detect rules of higher complexity, but simply not use them to structure vocalizations. For instance, the ability to detect and learn complexity and principles that give rise to dependencies in the structure of the world is advantageous in many other contexts. The AGL paradigm provides an excellent tool to examine these 'hidden' relational knowledge and cognitive abilities experimentally. Presenting animals with problems, tasks and stimuli comparable or identical to what is presented to human subjects in AGL experiments, might reveal similarities and differences in sequence processing or rule learning abilities between humans and various non-human animal species.

Petkov & ten Cate (this issue) pit the seminal studies in humans with corresponding ones in nonhuman animals. They provide a synopsis and critical overview of the findings from AGL studies in non-human animals that were directly inspired by studies in human adults and infants. They remark on the rich variety of different types of AGL patterns, which they use to organize AGL tasks into a multidimensional ‘sequencing complexity space’. Comparing human and nonhuman experiments drawn from portions of this space shows that many species are capable of detecting at least some types of regularities and dependencies among items in structured sequences. In particular, many animals can learn highly predictable relationships between items immediately following each other (adjacent dependencies) and when the items share physical similarities that provide cues on the sequencing dependencies. However, it remains to be seen whether any animal can learn more complex dependencies, including hierarchical ones, although some recent experiments suggest that we have yet to understand the full limits of animal sequence learning capabilities (Jiang et al., 2018). The currently available data are still too limited to arrive at conclusions concerning the limits of animal processing capacities or evolutionary patterns and new approaches are needed to better assess animal learning of complex rules.

Wilson et al. (this issue) focus on one particular class of AGL tasks, which concerns detecting non-adjacent dependencies (NADs) among items. This is arguably more cognitively demanding than detecting adjacent dependencies because it taxes working memory. It is also a requirement for detecting more complex hierarchical patterns where several items might form NADs. Whereas in natural languages non-adjacent dependencies can be detected by human adults at various levels, such as subject-verb agreement, detecting them in AGL tasks is remarkably difficult for adults.

In their paper, Wilson et al. (this issue) provide a typology of the different types of non-adjacent dependencies in natural languages and how the AGL community have aimed to study analogous dependencies in AGL tasks. They show that a range of cues affect non-adjacent dependency learning, ranging from the variability and number of intervening elements to the presence of shared prosodic cues between the dependent items, which help in detecting NADs. Without such cues, even humans can experience difficulties in discovering non-adjacent dependencies. Nevertheless, the same cues that facilitate learning non-adjacent dependencies in humans are also found to facilitate learning in some nonhuman animal species.

A similar conclusion on human and animal processes is also reached in the paper by Mueller et al. (this issue) on the role of acoustic cues in detecting language structure more generally. Across languages, there are clear links between acoustic cues and syntactic structure. Acoustic cues can, for instance, disambiguate category-crossing homographs, such as between the noun ‘PREsent’ and the verb ‘preSENT’. AGL experiments implementing analogous dependencies show that prosodic cues, as well as various auditory biases, can greatly facilitate the learning of structural rules. Here also, cross-species comparisons suggest that some of these biases, e.g. for auditory grouping, are also present in other species.

What the above papers show is that processes beyond rule learning can be studied with AGL experiments: at least some basic learning mechanisms, as well as several auditory biases, are not uniquely human or specific for language learning. This suggests that such biases predate the evolution of grammatical structure learning, and may have served to bootstrap its evolution. At the same time, the overviews reveal species differences in rule learning abilities and strategies, as well as in the specific nature of auditory biases. Given the wide variety of cognitive challenges that different species have to face daily, it would be surprising not to find interspecies variation in both the nature and extent of cognitive strategies.

While it is not surprising that humans are superior in several tasks it remains difficult to evaluate whether observed species differences between humans and other animals are really based on inabilities to learn particular rules. Often, they may be due to the experimental tasks and the dearth of direct cross-species comparisons. In some tasks, animals may fail because of inadequate methodologies or memory constraints. Or the animals can solve the tasks by reverting to simpler strategies and narrower generalizations (which also occurs in human infant studies – (Gervain et al., this issue)).

Then again, this rich variability also provides opportunities for exploring the impact of methods, grammars and stimuli on the outcome of AGL experiments. This is demonstrated by an intriguing meta-analysis of a selected subset of studies by Trotter et al. (this issue). The range of studies available for a more complete meta-analysis is still both too varied in nature as well as too limited in species diversity to arrive at definite conclusions, but the authors note some interesting patterns that future meta-analyses could seek to test. Such approaches could tease apart in ways not possible with individual studies, whether differences in results among studies are due to variation in design features, in stimulus characteristics or to genuine species differences.

Altogether, the reviews of comparative work show the value of these studies, but also call for a broader range of species to be tested and more attention to using comparable designs and stimulus sets to allow for a more robust assessment of how and why species diverge in rule learning abilities.

The above mentioned studies focus on the abilities for detecting and discriminating structural patterns using some kind of perceptual discrimination task. A different comparative approach is taken by Lipkind et al. (this issue). They focus on development of sequences in sound production in human infants and songbirds. Early in development, the vocalizations of both infants and songbirds vary along continuous acoustic parameters. Discrete vocal categories and structured vocalizations only emerge gradually from an initially highly variable and unstructured performance. The way in which these vocal units emerge shows remarkable similarities between infants and zebra finches (a much used model species for examining vocal learning), and these observations indicate an important role for motor variability in both species. In contrast to what is commonly assumed, Lipkind et al. (this issue) suggest that songbird subsong and its development into more structured song is more comparable to the phonation stage in infants than to human babbling. Observational and experimental data on the development of vocal unit combinations shows more parallels between the species, like the transitioning from a repetitive to a diverse production of units. Finally, Lipkind et al. (this issue) argue that the idea that words and song motifs are not directly comparable (Yip, 2013) should be reappraised, based on observed similarities between the development of these fixed sequences of units in birds and infants.

## 5. Computational modeling and theoretical strengthening of the AGL paradigm

The previous sections illustrate that AGL studies vary widely in their design and approach. The conclusions on what they tell us about the presence of specific rule learning capabilities also vary and are sometimes contentious, giving rise to debates on what constitute proper or suitable ways to test the presence of specific grammatical abilities. Especially contentious is the issue of hierarchical structures and their representation. These are thought to play a key role in human language and some other domains, such as music, while the presence of hierarchical processing abilities in animals is disputed (e.g. Berwick et al., 2011).

An important methodological issue is that demonstrating and examining hierarchical operations is challenging. Linguistic input and output, i.e. spoken language, always consists of a linear sequence of units, from which the existence of particular underlying hierarchical processing mechanisms is inferred. Udden et al. (this issue) use graph theory to provide an unambiguous and explicit framework for describing the possible structural relationships that may underlie a linear output sequence. They make clear how being more explicit in defining different structures can help to identify and test their presence in carefully designed AGL experiments – in this case the detection of hierarchical structures as opposed to sequential ones. They illustrate this by showing how behavioral (see also Levelt, this issue) as well as neuroimaging methods and data can reveal signatures of hierarchical processing in humans. If combined with a model comparison approach the framework provided by Udden et al. (this issue) holds much promise for future progress in demonstrating and understanding hierarchical processing.

Being more explicit about assumptions and theoretical considerations is also the theme of the contributions by Zuidema et al. (this issue) and Levelt (this issue). Zuidema et al. illustrate how empirical AGL studies can benefit from computational models and techniques. Like Udden et al. (this issue), they argue that computational techniques can help to clarify and formalize theories, and thus result in a sharper delineation of research questions. In particular they show how computational modeling can be integrated with empirical AGL approaches. They present some examples demonstrating how such modeling can facilitate experimental design and stimulus generation, as well as how analyzing results using model selection can indicate the most likely model to explain the data.

In the final contribution to the special issue, Levelt distills decades of hard fought experience with empirical linguistic research to advise the AGL community. He considers the value of AGL from a psycholinguistic perspective and remarks on the various gaps and overlooked venues. He draws attention to the fact that whether participants in AGL experiments are only exposed to grammar conforming (legal) strings or also receive information on which structures are illegal has a dramatic effect on the learnability of grammatical structures. From this, he suggests how several currently used experimental AGL designs might be improved. He also raises the more fundamental question on whether artificial (and natural) grammar learning is about detecting ‘rules’, as is commonly assumed. He illustrates that an alternative, and maybe more parsimonious approach is that the learning process involves the detection of a set of constraints. He also cautions the community not to ignore ‘semantics’. While currently enjoying the benefit of AGL tasks devoid of such meaningful complexity, less artificial tasks can enhance learning abilities and seem to be needed for learning more complex rules by human or nonhuman animals.

Together, the above contributions not only provide strong arguments to make the assumptions and questions in AGL experiments much more explicit but also provide the modeling tools to do so. The stage is thus set to revamp and modernize the AGL field as it seeks to understand more complex rule learning and its limits in human and nonhuman animals.

## 6. Conclusions and ways forward

The inspiring papers brought together in this issue demonstrate the richness of insights that systematic AGL studies provide into the nature of rule learning mechanisms that may underlie grammar and sequence learning. While the tasks and stimuli used to date in AGL experiments with infants may be viewed as somewhat limited, the available evidence suggests they can tap into similar or shared mechanisms as those involved in natural language learning and processing. And while the abilities of humans to deal with a variety of grammatical structures clearly exceeds those of nonhuman animal species, evidence is accumulating that the same or similar cues and biases that facilitate rule learning in humans are also present in nonhuman animals. These results suggest that the gap separating humans and animals might be one of degree rather than kind.

This special issue also shows that AGL tasks can provide insights on perceptual and cognitive abilities that go beyond ‘rule learning’, something that they were not originally designed to do but comes with the nature of using richly informative sequences of strings for the human or nonhuman animal. The papers also illustrate how useful meta-analysis and computational modeling tools can be for the community seeking to modernize their approach. These tools also provide scope for improvement in comparative studies that may help to assess the limits of animal abilities, which interestingly have yet to be found.

Comparative studies will also benefit from testing more species with a wider range of experimental techniques, applicable to more species. At the same time, such studies have already proven to be a powerful tool to gain insight in the cognitive abilities underlying sequence learning and rule abstraction in various animal species and have demonstrated interesting, presumably evolutionarily conserved, parallels between species as well as potentially derived inter-species differences. Hence, expanding these studies can provide insights on evolutionary pathways towards more complex sequence and grammar learning mechanisms.

We thus hope that the reader will be inspired by the papers in this issue, which provide insights on the nature, variation, development, and evolutionary origins of sequence and grammar learning in humans, other animals and machines. They point the way to new empirical, theoretical and computational endeavors that will lead to the next step change in scientific knowledge in this field.

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