

The origins of syntax: from navigation to language

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This article suggests that the parser underlying human syntax may have originally evolved to assist navigation, a claim supported by computational simulations as well as evidence from neuroscience and psychology. We discuss two independent conjectures about the way in which navigation could have supported the emergence of this aspect of the human language faculty: firstly, by promoting the development of a parser; and secondly, by possibly providing a topic of discussion to which this parser could have been applied with minimum effort. The paper summarizes our previously published experiments and provides original results in support of the evolutionary advantages this type of communication can provide, compared with other foraging strategies. Another aspect studied in the experiments is the combination and range of environmental factors that make communication beneficial, focusing on the availability and volatility of resources. We suggest that the parser evolved for navigation might initially have been limited to handling regular languages, and describe a mechanism that may have created selective pressure for a context-free parser.

Keywords: Language faculty; Evolution; Navigation; Computer simulations

1. Introduction

In this article, we present the observation that a crucial feature of language, the ability to perform syntactic analysis and generate sentences from a set of grammar rules, can assist navigation. We suggest that navigation and parsing are two instances of the same abstract computation, performed by a parser that may first have evolved for the purpose of navigation alone. We discuss two ways in which navigation could have supported the emergence of communication bearing some of the defining characteristics of human language: firstly, by promoting the development of a parser; and secondly, by possibly providing a topic of discussion. The two conjectures should be judged independently. Support is provided for the latter by demonstrating that, in a population that has evolved an innate parser to memorize routes as sequences of landmarks, agents can exchange valuable routes (e.g. leading to resources), as long as they can externalize the landmark names in a mutually intelligible way. In other words, all these agents need is a shared lexicon of descriptors. Our previously published experiments are summarized in this paper, and more original results are provided in support

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of the evolutionary advantages this type of communication can provide, compared with other foraging strategies. Another aspect studied in the experiments is the combination and range of environmental factors that make communication beneficial.

One can only speculate whether it was for the purpose of exchanging routes where spoken communication first met syntax, as the benefits of compositional language are much more encompassing. For instance, it has been shown that such languages are more easily passed between generations (Kirby 2002). However, it is clear that a parser evolved for navigation could have benefited the evolution of a human language faculty by lending it its power to handle syntactic structure, regardless of the actual source of selective pressure in favour of such language. The power of this parser is a further issue discussed in the paper. In our model of landmark navigation, the mental map can be seen as a finite state automaton, therefore the parser used for journey planning needs to handle regular languages (RLs). As modern human languages are (at least) context-free, one is tempted to consider circumstances in which navigation could have created selective pressure for a context-free parser. One such hypothesis is proposed in section 7, along with an outline of *in vivo* experiments that could provide support for our theory. The paper also reviews work in neuroscience and psychology that is consistent with the assumption that the handling of syntax for both linguistic and non-linguistic purposes could be grounded in a general-purpose neural circuit performing a certain class of abstract computations applicable across domains.

The rest of the paper proceeds as follows. Firstly, we review the existing literature on the evolution of the language faculty and, in particular, the syntactic aspects of this. We then outline a form of navigational planning that is computationally equivalent to regular language parsing, and from which we believe the latter may have evolved. The relative performance of agents capable of communicating directions is assessed, using this navigationally derived parser, and compared with those unable to do so in an experimental setting and, finally, the implications of our findings are discussed.

2. Neuroscience and psychology on the evolution and nature of language faculty

Language has variously been suggested to emerge in order to provide information about the spatial aspects of the environment (O'Keefe and Nadel 1978) or maintain the social fabric of increasingly large groups of hominids, e.g. to replace grooming and spread gossip (Dunbar 1996, Power 2000). Byrne (1995) shows examples of primates using communication as a deception tool, and it is easy to see how the speakers of a fully fledged language could put it to the same use.

At present, there is a well-known schism in the linguistic community reflecting two general stances: one that human language is, evolutionarily speaking, a relatively recent phenomenon unique to our species that emerged some 100–150 000 years ago as a by-product of the human brain reaching a certain critical level of complexity (Chomsky 1975); alternatively, one can try to explain language as a combination of evolutionary traits, evolved over a much longer period, and possibly for different purposes, when the environment provided selective pressure in their favour. Such theories find support in neurological models grounding essential elements of human language, such as syntax, in parts of the brain that pre-date our species (Lieberman 2002), and that can be shown to play an analogous role in non-linguistic tasks in other species (Aldridge and Berridge 2002).

These two approaches to the evolution of language vary in their vision on the extent to which the human language faculty is innate. Chomsky (1964) claimed that we are born with a language acquisition device (LAD), a complex blueprint, which sets its parameters when

exposed to language. Marcus *et al.* (1999) have reported that 7-month-old infants can learn to discriminate between the sentences of two different grammars, reinforcing the belief that this ability is innate rather than acquired. While the LAD has many supporters, the claim that it is a prerequisite to using language means that the coexistence of the LAD and evolution as leading scientific paradigms is a somewhat uneasy one, as the notion that nature would have to put a potentially very complex tool in place before receiving a pay-off contradicts the common wisdom that evolution usually advances in small steps, delivering immediate benefit. A 'macro-mutation' that would have produced the LAD all at once is extremely unlikely, and so would be a hypothesis that the components of the LAD have been produced as a series of mutations, each amounting to 'genetic drift', that is, to a change that does not affect one's fitness.

Marcus *et al.*'s experiments were based on the familiarization of subjects with sequences of syllables from an artificial grammar (e.g. both 'ga na ga' and 'li gi li' are instances of the general pattern ABA). During the test phase, novel spoken sequences, some of which violated the grammar, were played. A strong shift of attention towards the loudspeakers was judged as an acknowledgement of a perceived grammar violation. Importantly, the test sentences consisted entirely of new syllables. The study claims the infants were able to learn to recognize the general ABA pattern as different from ABB. The infants could also discriminate between the patterns AAB and ABB after being familiarized to either. The suggested interpretation of these results is that they are consistent with the infants' being able to 'extract abstract algebra-like rules that represent relationships between placeholders (variables)', and that simple statistical learning relying on transitional probabilities cannot account for the experiments' outcome. The research team also claimed to have experimentally rejected the possibility of replicating the observed behaviour in one of the most common classes of artificial neural network, the simple recurrent network (SRN), but their conclusions on this matter have since been disputed (Altmann and Dienes 1999, McClelland and Plaut 1999, Sirois *et al.* 2000). Recently, many of the assumptions about the uniqueness of the human faculty of language have started to be questioned and tested experimentally (Hauser *et al.* 2002). In an attempt to draw a finer line between what is shared with other animals and what is uniquely human, Hauser, Chomsky and Fitch have focused on *recursion*, and its ability to describe open, potentially infinite sets, be it in the case of numbers or sentences. This statement leaves some apparent room for refinement, as recursion is present in both regular (or *Finite State*) grammars (RGs) and in context-free grammars (CFGs), whereas all human languages are at least context-free.[†] A more recent study (Fitch and Hauser 2004) suggests there is a species (cotton-top tamarin monkeys) that can learn to recognize examples of *spoken* regular languages, but, unlike the human subjects in the studies, failed to learn a context-free language.[‡] The results appear to extend the ground humans share with other species, and to point to the ability to handle CFGs as exclusively human. While putting a considerable effort into eliminating any potentially salient non-grammatical features, Fitch and Hauser's work has been criticized (Lieberman 2004) for the use of different speakers for each of the *A* and *B* classes of symbols (syllables). If pitch were used as a feature, it is claimed, each of the languages studied would collapse to one example (for each grammar and value of *n*), thus reducing the experiment to one 'about memory span and/or sensitivity to statistical deviations'.

A point that is usually made in this context, and readily admitted by the researchers involved, is that any finite language (set of strings) that is generated by a CFG can also be generated by an appropriately constructed RG. Indeed, it could be claimed that the inability to learn to

[†]Cross-serial dependency in some dialects of Swiss German is usually mentioned as a proof that not all languages are context-free (Shieber 1985).

[‡]In the article, CFGs are discussed under the more general category of phrase structure grammars.

recognize sentences of a CFG is indicative only of the inability to represent (e.g. due to lack of memory) the more complex equivalent finite state automaton. On the other hand, it is evident that a human is able to grasp the concept of the $(AB)^n$ pattern for any n , and would be able to establish whether a string belongs to it, if armed with a pen and paper.

3. Computer simulations of the evolution of language

Within the last decade, there has been a large movement towards using computer simulations and models to study the origins and evolution of communication systems, and in particular language. This research can be broadly split into two areas, simulations involving learned communication systems (or language) that change during an agent's lifetime, and those concerned with the evolution of innate communication systems (in which communication is genetically determined). In the case of the former, the objective of the simulation is almost universally to study how the *language* itself changes and evolves, while in the latter setting, it is the evolution of the *mechanisms used by the communication system* that is being studied. In addition to splitting the models by whether the communication system is innate or acquired, simulations can be divided along a second axis into those that study syntactic communication and those in which the object of study are lexical systems, that is, those in which words cannot be meaningfully combined to produce longer utterances.

The most important results in the realm of learned syntactic language come from Kirby (2002). In Kirby's model, language is transmitted through several thousand generations by a process of repeated expression using the language (by an older agent) and induction of this linguistic output (by a younger agent). Compositionality naturally emerges due to the way in which language is transmitted from one generation to the next through a *linguistic bottleneck*, which prevents an individual hearing every possible meaning during its lifetime. Hurford (1998) reported similar findings using a different model to generalize from the linguistic input. In these simulations, while the language itself changed though an implicit form of selection, the mechanisms used by the agents to store, generate and transfer linguistic signals did not. These simulations demonstrated conclusively that linguistic evolution is not necessarily dependent on concurrent biological evolution. Batali (2002) made this point even more explicitly by providing a model in which a population of agents converged on a mutually intelligible syntactic language without the need for any population turnover, even that found in Kirby's model.

It is also possible, however, to produce models in which evolution of the agents, not directly of the language, leads to syntax. These simulations allow issues such as willingness to speak to be addressed. Zuidema and Hogeweg (2000) presented a model in which a population of agents with innate grammars communicate, with fitness being based on the degree to which their grammar is similar to the others in the population. By creating fitness functions that can penalize speaking, but reward understanding, they created a situation in which speech should apparently be selected against. However, speech persists if agents are spatially arranged and interact only with their neighbours. Altruism is often explained through one of two mechanisms, reciprocal altruism (Trivers 1971) or kin selection (Hamilton 1964). In the former, acting altruistically is rewarded by others also doing so, allowing groups of co-operating agents to outperform selfish ones, while in the latter we view individuals as acting not in their own best interest, but in the interests of the genes they possess and that are also present in their relatives. Another theory, costly signalling (Zahavi 1975), seeks to explain how associating costs with the signals produced may also lead to the establishment of 'honest' signalling. The theory predicts that, in situations where interests conflict, it may still be possible to establish truthful signals provided a cost is paid in signalling. This theory has been verified in some

simulations (Smith *et al.* 2001), though others found results that contradicted its predictions (Lachmann *et al.* 2001).

In addition to these models undertaking to explore syntax, there are many simulations that seek to explain how purely lexical languages may evolve. Among the most impressive such studies are the results presented by Steels (1999). In Steels's simulations, agents engage in a series of 'language games' that consist of two agents who are drawn from the population attempting to negotiate a word to describe an object (or a set of words to describe the properties of the object). The agents subsequently update the strength of the association that they make between a particular word and meaning based on the success of the game. Others, such as Oliphant and Batali (1997), explored learned lexical systems that take many generations to converge. In their model, agents learn from the language of the population when they are 'born' in an analogous way to the agents in Kirby's simulations. The details of the learning algorithm ensure that the new agents are better at communicating with the rest of the population on average than the existing agents, and as a result the average communicative accuracy of the population as a whole increases with every added agent.

Finally, researchers have also keenly studied the evolution of genetically specified lexical languages, which are analogous to most kinds of animal signalling in the real world. Cangelosi and Parisi (1998) studied a population of agents based on neural nets, who foraged for mushrooms. In their model, communication between agents was used to inform others of whether particular mushrooms were poisonous. At the same time as evolving the ability to distinguish this information, the agents also converged on a shared language for communicating this information. Werner and Dyer (1991) described an environment with blind, mobile males and static females that had vision and the ability to emit signals that males could hear. Simulations showed that both sexes tended to evolve an inherited behaviour that used females' signalling to guide males towards them in order to mate. The experiment can be seen as proof that an inherited lexicon mapping signals to meanings can evolve in a population of agents where communication comes at no cost. Grim and Kokalis (2004) studied an environment with static agents with fixed behaviour, which could feed on moving 'clouds of food' if their mouths were open at the moment of encounter. An agent was able to emit a signal of limited range that could be triggered by the presence or absence of food. Both opening one's mouth and signalling have an associated cost. The amount consumed in one 'bite' was a parameter of the simulation, but did not depend on the other agents' consumption. Individual behaviour was implemented in one of a number of ways, but in all cases studied, it was periodically updated to copy partially or completely the most successful neighbour's behaviour. In all these models, it has been shown that a population can converge on a common lexical language through a series of decentralized linguistic episodes between pairs of agents: words become associated with meanings without the need for intervention from any central authority.

4. Knowledge representation

Of the many theories suggested as to the origins of language, this paper investigates the proposal that the language faculty (or, more specifically, the syntactic component of it) may have arisen from pre-existing structures in the brain that were used for navigation (O'Keefe and Nadel 1978, Kazakov and Bartlett 2002, Hauser *et al.* 2002): the neural mechanisms used to generate and conceptualize route planning may have been reused in the brain to allow the rise of syntax, a necessary precondition for compositionality of language being able to emerge. In addition to that, the possibility is considered that one of the original purposes of syntactic language may have been to pass navigational instructions to others.

In our experiments, the system that agents use to communicate about the location of resources draws inspiration from the *Songlines* of Australian Aboriginal culture. Songlines reflect a belief that ‘Ancestral Beings roamed once the face of the earth, creating the features of the landscape . . . along the tracks that mark their journeys’. In the grouping of songs into series, ‘the most pervasive is the geographical organisation of songlines, where each “small song” equates with a different site along an ancestral journey, and the series as a whole constitutes a sung map’ (Barwick and Marrett 2003). We abstract away most features of this system, and simplify some of its aspects, to produce an extremely impoverished representation that is used to store the information used to navigate the environment, and gives the minimum amount of information necessary to follow a route. Specifically, an environment is used in which certain objects are known as *landmarks* by all agents and a route between different places can then be described by an ordered list of the landmarks that one sees as that path is travelled. These routes are gathered as agents explore the environment and are stored as rules of the form:

$$\text{goto}(\text{food}) \rightarrow \text{goto}(\text{PosX}) \quad (1)$$

$$\text{goto}(\text{PosX}) \rightarrow \text{goto}(\text{PosY}), L_1, L_2, L_3 \quad (2)$$

$$\text{goto}(\text{PosY}) \rightarrow \text{goto}(\text{PosX}), L_3, L_2, L_1 \quad (3)$$

$$\text{goto}(\text{water}) \rightarrow \text{goto}(\text{PosY}), \quad (4)$$

where rule (1) states that to go to a food resource it is sufficient to go to a *PosX*, rule (2) states that to go to *PosX*, one can go to *PosY* and then pass the mentioned landmarks in order, and rule (3) is an inverse of the second, allowing this path to be traversed in the opposite direction. *PosX* and *PosY* in the above rules are approximate locations internally referenced by a list of landmarks visible from the location in question. The set of rules (1)–(3) are those that would be formed by travelling from *PosY* to *PosX* and discovering food at *PosX*; rule (1) records why *PosX* is significant and the other two rules show how to get to and from this location, respectively. These rules are used procedurally to guide an agent from one location to another using a (very impoverished) map of the environment, very much like the one used to describe public transport routes and the connections between them.

To the experienced eye, rules (1)–(4) are also rules of a regular grammar, in which the start and end points of the route described by each rule play the role of non-terminals (as there may be more than one way to reach and/or leave them), and landmarks are terminals. Therefore, tracing out (or following) a route between two points would amount to generating (respectively parsing) a sentence of a regular grammar. For instance, to find a path to a resource from its current location, an agent would use a rule with the desired type of resource in its left-hand side, and would look for the shortest derivation that results in a sentential form starting with its current location. The remaining part of this sentential form then will constitute a list of landmarks that spell the complete route to the resource. For instance, if the agent is in *PosY* and in the need of food:

$$\text{goto}(\text{food}) \Rightarrow \text{goto}(\text{PosX}) \Rightarrow \text{goto}(\text{PosY}), L_1, L_2, L_3. \quad (5)$$

All that is needed to exchange a route between two agents using ‘songlines’ as their internal representation of the environment is a shared lexicon of landmark descriptors. The speaker then can plan the route as if for its own use, and spell out the landmarks along that route. In the

experiments presented in this paper, we considered the words used to refer to a landmark to have already been fixed in the population by some previous mechanism, such as that used by Steels (1999). In this, we are in agreement with Bickerton (1990) and Jackendoff (1999), both of whom suggested a phase in the evolution of language faculty assuming the use of words in a language with no syntax.

In our setting, every exchange of direction modifies the listener's grammar. Unless this information is already present in its rules, the listener creates a new non-terminal symbol to represent the location where both agents met, and memorizes two new rules to represent: (1) the path from the last location visited to the current meeting point; and (2) the path from this meeting point to the new resource of which it was told.

The types of rule described represent a regular grammar, which can contain recursion, and therefore corresponds to an infinite language, an important feature of human languages. Indeed, even in the minimalist example of rules (1)–(4), the mutual recursion of non-terminals *PosX* and *PosY* describes a closed-loop journey essential for survival, as the agent tries to maintain acceptable levels of food and water. The language described by such rules has another important characteristic, that of compositionality. If landmarks are permitted to have non-unique names, then the landmark referred to by a given token may be different depending on the tokens before and after it, in a way similar to the one in which the parts of a sentence can have their meaning modified by the context in which they appear.

We have demonstrated that memorizing and planning routes by an agent that describes a path as a sequence of landmarks (beacons) amounts to storing the rules of a regular language and generating/parsing its sentences. This is important: *if a regular language parser could help navigation, it may first have evolved for this purpose*. Then a change in the neural connections might have made this parser available to the human brain speech circuitry. This compares favourably with the idea of macro-mutation, as described earlier. The rules proposed herein echo the idea of 'abstract algebra-like rules' proposed by Marcus *et al.* (1999). The idea of separately evolved needs for lexicon and syntax is also consistent with evidence that they are separated in the brain (Ullman 2004). The notion that the same parser (or its replica), originally evolved to serve navigation as a means of internal representation and planning, became involved in communication at a later stage, resembles the idea, proposed by Sloman (2005), of virtual mind machines processing whole classes of computationally homologous tasks.

Let us now consider navigation and language parsing as two instances of the same abstract computation (involving strings of symbols), and enquire whether the way we perform these tasks would reflect that. Anyone interested in this question would be likely to look into existing models of the way in which syntax is grounded in the neural substrate. Ullman's (2004) recent model pinpoints several memory circuits in the brain, 'a network of specific frontal, basal-ganglia, parietal and cerebellar structures', which support 'the learning and execution of motor and cognitive skills, especially those involving sequences'. The model separates, both neurophysiologically and conceptually, this so-called procedural memory from the declarative memory storing information about facts and events, including the mental lexicon. The suggested common basis for the processing of verbal and non-verbal sequences is supported by other authors. Hoen *et al.* (2003) reported that using non-verbal symbols (playing cards) to exercise the ability to reorder sequences in a predefined way (123 → 231) helps patients improve their ability to understand a type of sentence that needs the same transformation to have its constituents rearranged in the default order: 'It was the cat¹ that the dog² chased³' → 'The dog² chased³ the cat¹'. Hauser *et al.* (2002) also drew a link between navigation and language, suggesting that understanding efficient processing of language can help research in other domains, 'such as spatial navigation and foraging, where problems of optimal search are relevant'.

One could conceive two coupled processes through which the link between motor and verbal sequence processing may hold the key to the origins of syntax: (1) the need for 'songline'

navigation providing selective pressure for the evolution of a parser; and (2) the advantages of sharing ‘songlines’ promoting a type of communication that could make natural use of this parser. While our simulations make the possibility of the second process taking place in the past more viable, other theories about the benefits of structured language should be considered as alternative sources of selective pressure promoting syntax. Otherwise, it is not easy to imagine how such a specialized language, possessing only nouns (or noun phrases) and the single verb ‘*to go*’, would have developed other parts of speech as a function of the navigational task.

5. Experimental design

To investigate this theory, we used simulations to compare the performance of a population that was willing and able to communicate the location of resources vital to survival with a population that did not communicate. In both cases, agents navigated as outlined in the previous section, with the communicating population using this same mechanism to speak. Recognizing that this communication is an inherently altruistic act, we also compared the performance of a third population that navigated in the same way as the others, but did not communicate, instead engaging in another altruistic act, namely that of sharing resources with each other. This allows us to compare the potential benefits of two very different types of altruistic behaviour. When handing out actual resource, the agent can carefully measure the amount given to implement a policy, striking a balance between its immediate interests and the benefits that sharing brings to the society of which it is a member. On the other hand, while not incurring an immediate cost, the release of information about a potentially vital resource means the agent loses control over the further spread of this information and the use of the resource it describes. As the relative benefits of any behavioural strategy differ based on the environment in which they are investigated, we also examine the potential role that the environment may play in determining the usefulness of language.

To perform these experiments, we developed an artificial life system (the York Multi-Agent Environment) that allows the study of adaptive and evolutionary agent behaviour in multi-agent settings. In this system, environments consist of two-dimensional, orthogonal grids with squares that may represent different types of terrain and resource. Agents need to consume both food and water regularly, thus forcing them to travel from one resource to another in order to survive.

The agents’ behaviour is based on the notion of *drives*, which describe the level of two internal states: hunger and thirst. The basic behaviour of all the agents used in the simulations is fixed, with the exception of allowing linguistic exchanges or sharing of resources in the appropriate simulations. At the beginning of an agent’s turn, the hunger and thirst drives are increased to represent the cost of living and, if the agent’s drives exceed the maximum allowed, it is considered to have died and is removed. Agents will also die after a period of time (starting at 300 cycles and becoming increasingly likely with each turn in the experiments presented) to reflect the process of ageing. Any agents remaining alive will choose from one of three behaviours depending on whether they are hungry, thirsty or neither. Agents whose hunger and thirst drives are sufficiently low and who share a location with another such agent may reproduce to create an offspring for a one-off outlay of food and water reserves. A new agent created in this way costs both parents a third of their food and water reserves, with the resources subtracted from the parents forming the initial levels of the created offspring. Alternatively, agents whose hunger and thirst levels are above a given threshold will attempt to seek food or water, respectively, using the behaviour shown in algorithm 1. Consumption from a resource reduces the drive level to zero, and removes one ‘meal’ from the resource consumed.

Algorithm 1. Agents' behaviour

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if hunger > drive_threshold then
  if food in current square then
    Eat food;
  else if food in adjacent square then
    Move into square with food;
  else if can generate a route to food then
    Generate a route and follow it on subsequent turns;
  else if in an altruistic population and another agent is present then
    Ask for help;
  else
    Make a random move;
else if thirst > drive_threshold then
  if water in current square then
    Drink water;
  else if water in adjacent square then
    Move into square with water;
  else if can generate a route to water then
    Generate a route and follow it on subsequent turns;
  else if in an altruistic population and another agent is present then
    Ask for help;
  else
    Make a random move;
else
  Attempt to mate;

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In addition to searching for resources, agents in altruistic populations, can also ask those they meet for help. An agent will always help if it can. In the case of the non-linguistic altruistic population, this help consists of a quantity, a , of the resource that the asking agent needs, as defined by the following equation

$$a = \begin{cases} 0 & \text{if } \text{drive_level} \geq \text{drive_threshold} \\ 0.5 \times (\text{drive_threshold} - \text{drive_level}) & \text{if } \text{drive_level} < \text{drive_threshold}, \end{cases}$$

where all quantities are those of the agent assisting and for the drive associated with the resource that is being sought. The requesting agent's drive is reduced by the quantity a , and that of the aider is increased by the same amount. In other words, an agent will always keep a certain amount of resource, and share half of the surplus—see Turner and Kazakov (2002) for a discussion of the merits of such a sharing function.

In the communicating population, the help given will take the form of a list of landmarks that describe a route from the current location to a resource of the type needed by the agent. Rules that an agent gains this way through language from another agent are stored in the same data structure as the rules gained through exploration, and are used in the same way. However, rules (routes) obtained from another agent, but not yet explored, are never passed to another agent (*i.e.* only first-hand information is shared). Also, in foraging, rules obtained through exploration are used in preference to the ones obtained from another agent. These differences were found to be needed in preliminary experiments conducted with the system. Specifically, it was found that if hearsay information was passed between agents, information on resource location was very hard to remove from the population when a resource was exhausted; one agent could inform another of a resource, then later, after deleting this information from its

memory due to finding it had been exhausted, could receive directions to this same resource from the agent that it had informed earlier. Not passing on received information eliminates this cycling of information. The agents use information they have personally gathered as a preference, as this knowledge is reliable: if the resource was there the last time the agent was hungry, it is more likely to be there the next time the agent is hungry than a resource that the agent has never seen and may not have been visited by anyone for a much longer period. This reliability of information is unrelated to the question of trust in the speaker, an issue sometimes studied in agent populations in which lying is possible. Here, all agents truthfully communicate what they know, however this information becomes unreliable over time despite the best intentions of the agents.

A comparison with Grim and Kokalis's (2004) work shows that they implemented a fixed cost of communication, whereas in our simulation that cost could vary greatly with the content of the message, as disclosing the location of food to other agents affected the amount available to the speaker, something not present in Grim and Kokalis's simulation. In both simulations, the agents' individual speech acts did not bring immediate reward, hence could be seen as altruistic. However, Grim and Kokalis's agents co-evolved this altruistic behaviour while always interacting with the same neighbours, which was not the case with the mobile agents in our simulations. The importance of this can be seen in the following analysis of Grim and Kokalis's environment. A 'free rider', responding to food warning signals with an open mouth, but never emitting a warning itself, could survive if moving through a population containing signalling agents, but would become a victim of its own success in a static setting, as it would make its neighbours copy its behaviour, yet eradicate in this way the signalling neighbours, on the presence of which its survival depends.

6. Results and evaluation

In order to evaluate any possible benefit to a population of communicating or sharing resources in dynamic environments, experimentation is conducted in which a population of agents is placed into an environment and the simulation is run for a period of several generations. The quality of a particular strategy in an artificial life environment can be measured by the performance of the agents at their most fundamental task: remaining alive and reproducing.

We have published a number of experiments with our environment aimed at studying the potential effects of sharing directions, the specific environmental conditions when this type of communication is beneficial, and some of the specific side-effects that could have an impact on the agents' ability to evolve and use language.

Our first simulations (Kazakov and Bartlett 2004) looked at the relative benefits of communication, with the results showing that communicating societies of agents outperform those without communication in the circumstances studied. The results also show that this type of communication creates relatively stable clusters of agents sharing a set of paths/rules. In other words, sharing information about resources makes future communication more likely, which leads to the formation of relatively stable agent neighbourhoods. This should, in turn, promote a more coherent language in a variety of evolutionary settings, e.g. by reducing the negative impact an influx of outsiders has on the evolution of a lexicon shared by the group of agents (Steels 1999). These experiments also show a link between the distribution of resources and the number of clusters of agents: the more and the farther apart the resources, the greater the number of clusters.

We have studied further the impact the distance between individual resources has on the benefits of communication (Bartlett and Kazakov 2005). In an environment with two types of

resource (food and water, both needed for survival), the experiments focus on two parameters, d_{same} , the distance between resources of the same kind, and d_{diff} , that between resources of a different kind. The former represents the minimum exploration needed to find an alternative resource when the current becomes depleted; the latter, the shortest journey an agent has to make repeatedly in order to survive. The experiments are also extended with a comparison between three mutually exclusive strategies, where agents are alternatively allowed to share paths to a resource, share some of the already harvested resource, or not share at all. With respect to the population size, the results show that sharing in kind is the least effective strategy, and sharing information, the best, with the benefit becoming more pronounced as d_{diff} becomes greater. There is a similar, although less pronounced, trend in the case of d_{same} .

The fact that in these experiments sharing resources is not beneficial comes to prove that the benefits of communication are not just down to the resulting altruistic behaviour. Communication seems to reduce the need of offspring for initial exploration, as they query parents immediately after birth. Another positive side-effect of communication is that, at any time, agents are clustered around a subset of the resources, increasing in this way the chances of mating.

In this paper, the effectiveness of communication in an environment in which resources are volatile is explored. To do this, two parameters involved in affecting the volatility of resources are varied: the time they take to decay and the number of ‘meals’ they can provide before being exhausted. In the experiments presented, food resources were volatile: they were both depleted by use and decay over time. When a food source was exhausted, another appeared at a predetermined location. Water resources were static and inexhaustible.

The procedure of the experiments was as follows. The environment of figure 1 was populated with agents as shown and the simulation was run for 1000 cycles, a period equivalent to at least three generations of agents. The agents in the simulations were programmed with one of

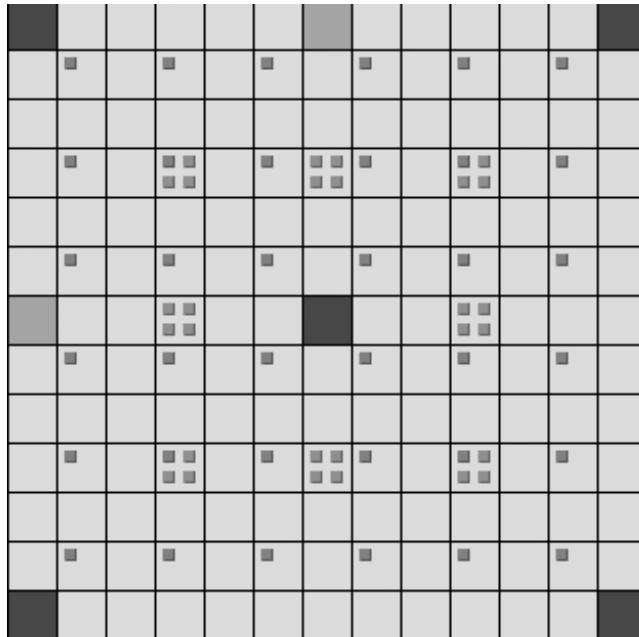


Figure 1. Artificial life environment used in all experiments. Landmarks are spaced out at regular intervals of two squares; agents are shown in groups of four. Water is present in the four corners and centre, and two sources of food are placed in the centre of two adjacent sides.

three possible strategies: they could share resources if asked to do so by another agent; they could share knowledge in the form of paths to reach resources; or they had an entirely selfish behaviour and helped no one. The food resources shown in the environment were also altered along two dimensions between experiments. Both the amount of food that each resource contained and the period of time after which its gradual (linear) decay made it disappear (if not exhausted faster due to agents' consumption) were set to one of eight values each. Both these factors influence how dynamic the resources are. When one food resource disappeared, another was programmed to appear at the diametrically opposite position in the environment. Water resources were inexhaustible and static. The size of a resource and the time after which it is exhausted were both increased logarithmically across experiments in order to allow us to explore a large parameter space, while still being able to observe changes at the lower end of our space. Experiments were carried out for all possible combinations of resource size, volatility and agent strategy.

While it may appear that the amount of resources placed in each environment differed (due to differing volatilities) and hence the experiments were not immediately comparable, this was not the case. Owing to the fact that a fixed number of agents could occupy the location of a resource at one time and the fact that two food resources were always available, the maximum amount of food potentially available to agents in all experiments was actually constant throughout and across the experiments conducted, with the only factor varying being the rate at which resources changed position.

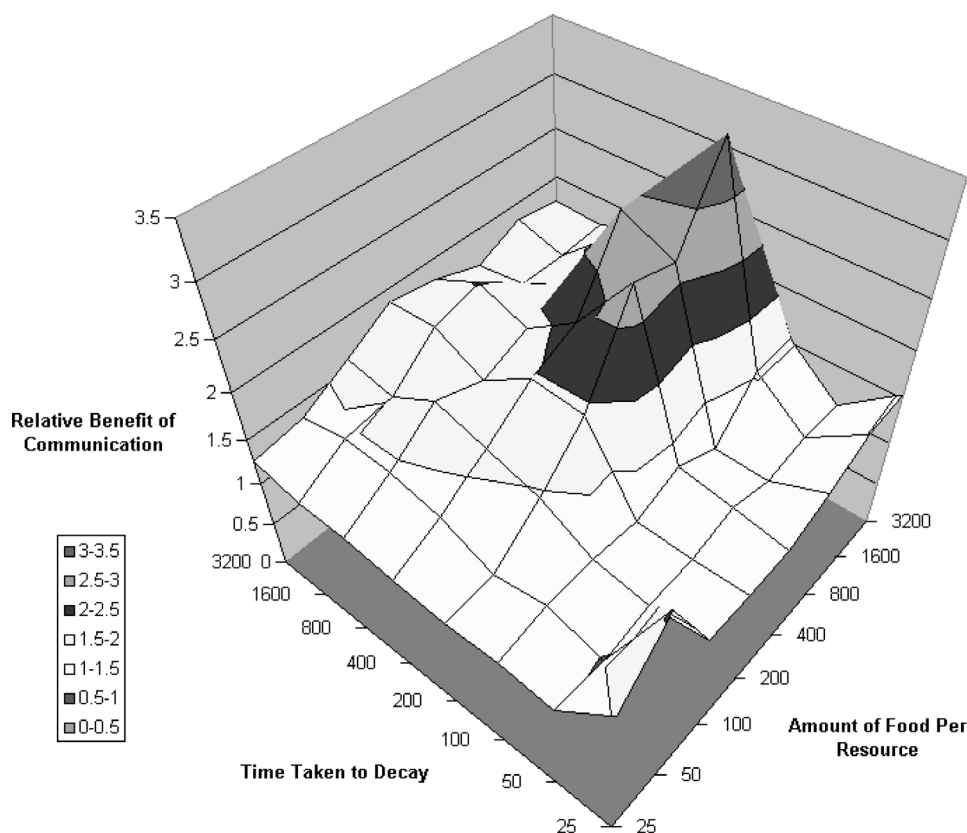


Figure 2. The relative advantage of using language depending on volatility of resources. The x -axis shows the amount of food present at each resource, the y -axis shows the time taken for the resources to decay, and the z -axis shows the relative average population size.

Figure 2 shows how the relative benefits of communication varied with the two parameters of volatility. The relative benefit figures shown were calculated as the average population size of the communicating population over the period of the experiment as a percentage of the average population size for the non-altruistic population. As periodic increases and decreases existed in the population size (due to the movement of resources), we took average size instead of final size as a more reliable figure to indicate the success of a policy. These figures are reported relative to the selfish population's size as we wished to see how beneficial communication is compared to this baseline behaviour, not how large the population becomes in absolute terms. Figure 3 shows equivalent figures for the population that engaged in non-linguistic altruism. Figure 4 shows a comparison of the figures for linguistic and non-linguistic altruism.

These results show immediately that linguistic sharing seems to be at least as good a policy as either selfishness or non-linguistic sharing in all situations. Indeed, of all combinations of parameters studied, in only one case did language use perform worse than selfish behaviour, and by only 1%, within what might be expected due to random variance. In contrast, the non-linguistic altruistic populations seemed to perform very similarly to the selfish populations, seldom deviating by more than 10% from this baseline size. The most interesting cases, from our perspective, occurred in the region where resources were not extremely volatile but still moved quite often. In these situations, language use proved to be a distinctly more effective policy than the other two: the population seemed to benefit most from communication when

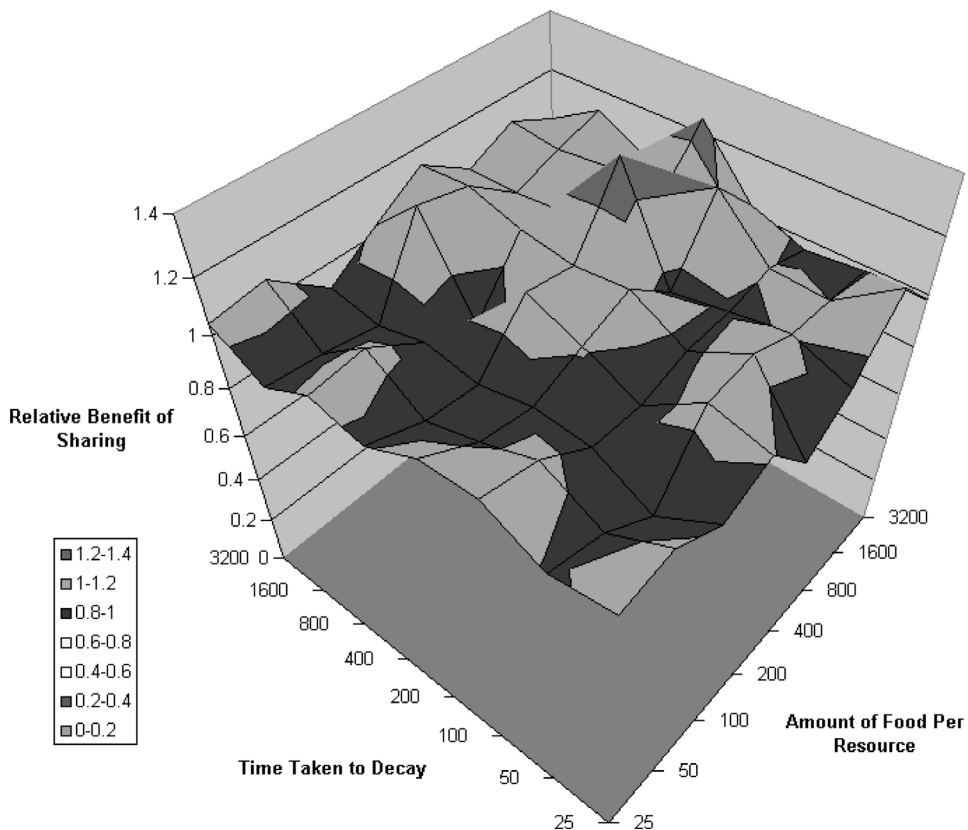


Figure 3. The relative advantage of acting altruistically depending on volatility of resources. The *x*-axis shows the amount of food present at each resource, the *y*-axis shows the time taken for the resources to decay, and the *z*-axis shows the relative average population size.

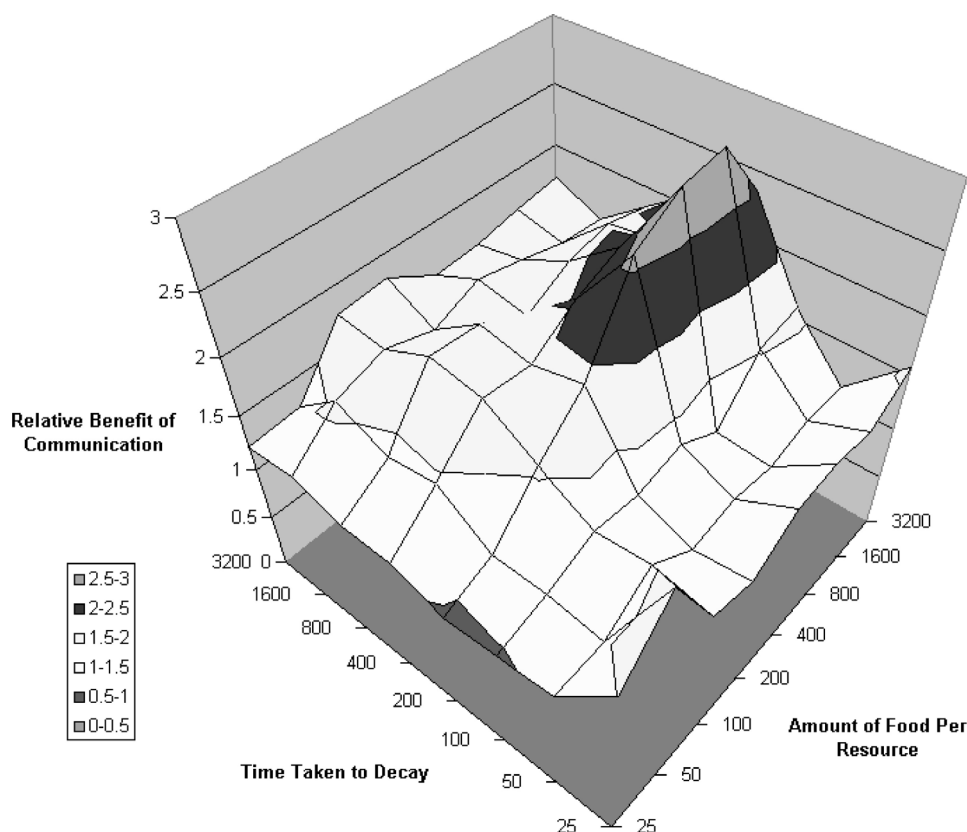


Figure 4. Comparison of the advantages of linguistic and non-linguistic altruism. The x-axis shows the amount of food present at each resource, the y-axis shows the time taken for the resources to decay, and the z-axis shows the relative benefit of linguistic altruism as a proportion of that of non-linguistic altruism.

either food was sparse but decayed slowly or when the environment contained large food resources that decayed rapidly.

We can also study the data from the experiments in another way. For each combination of resource size and decay rate studied, it is possible to plot the population size against the number of cycles elapsed. This allows us to study the population dynamics at a point in a way that was impossible with the three-dimensional graphs. In particular, we can view the cases at which resources were most volatile, least volatile and at the point at which communication provided the greatest relative benefit (figure 5). The first of these graphs shows what is typical behaviour for a point with very volatile resources, a small initial increase in population size followed by a gradual but inevitable decline to extinction. The second graph is also typical of the region it is taken from, showing a continual increase in population size towards the carrying capacity of the environment. In both these cases, we see the effect that language use has on a population clearly. The net effect of communication appears to be an increase in the chance of survival of an agent. In the first case, this was manifested as a longer period for the population to become extinct, while in the second case the communicating population was able to grow faster as more children survived to have children of their own.

The most interesting graph, from the perspective of this work, is the graph from the point at which communication provided the greatest benefit. From this graph, we can observe two

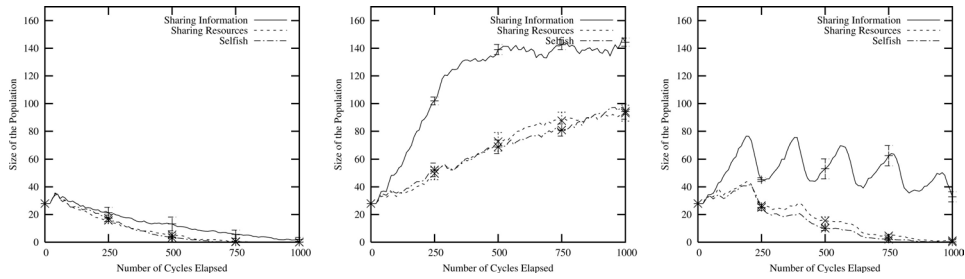


Figure 5. Comparison of sharing information/food and selfish behaviour. Graphs show results for the region with the most volatility, least volatility and most advantageous use of communication respectively. All results were averaged over 10 runs.

things. Perhaps most obviously, the graph exhibits a periodic behaviour, as mentioned above. This is most probably due to a fall in the population size when a resource moves to a new location and many agents starve before they manage to find the new resource. After the resource has been located again by sufficient agents, the population size begins to increase, as fit agents are again able to meet and breed. Secondly, we observe that in non-communicating populations the number of agents falls slowly but steadily towards extinction, whereas the number of agents in the population using communication seems to have all but stabilized (except for the increases and decreases due to resource volatility). This illustrates that communication may not just be a factor that can increase a population's fitness, but might make the difference between life and death.

7. Discussion

If it appears that language could emerge from a set of navigational systems already present in animals, we are forced to ask why language has occurred only in humans. One possible answer is that humans were the only species that found itself in a situation favouring the use of language, with all aspects of readiness for language already present. We have established some of the conditions under which we would expect communication of the kind described in this paper to be of most use, such as when resources are volatile. It is tempting to compare this result with the conditions in which language use first began in humans. It is thought that primitive humans first evolved in the area around the Serengeti plains in Africa at a time when densely forested areas had given way to more open plains. This tallies with the form of navigation that we propose: open areas with clear lines of sight would allow navigation by landmark far more readily than before. Both an increased volatility and scarcity of resources, due to sparser vegetation and a shift towards hunting, would increase the selective pressure for language, according to the experimental results shown here. It may have been in these circumstances that exchange of directions introduced a syntactic component to human language.

So far, we have only seen how navigation could have created the need to represent and process regular languages. As modern human languages are at least context-free, this would still leave a step to be explained in the evolution of language faculty. This step could have come about to benefit an already existing, simpler type of communication, or, again, one could look for its origins elsewhere. Here we repeat our suggestion (Kazakov and Bartlett 2005) that navigation may have provided the original need for context-free parsing.

One can use a regular language to plan navigation between a number of important locations, but no regular language can describe the seemingly simple task of going somewhere and

returning using the same way if there are alternative routes available. The need to return to one's dwelling between feedings is shared by many animals. Often, the return is guided by local cues, such as smell and trails on the ground or in the foliage. Here, landmark-based navigation could be employed to provide redundancy, or, in some cases, where the above mentioned cues would be of less use, it may be the only alternative, e.g. frequent rains may destroy pheromone trails, hard terrain and sparse vegetation may not be marked by the passing of an animal, and a bird or an upright-walking hominid may be better placed to use visual rather than olfactory cues. As to the reasons for taking the same way back home, these could include, for instance, the need to reduce the risk of encountering unexpected dangers or help estimate the time needed to return.

In terms of 'songlines', the landmarks passed on the round trip would spell out a palindrome (e.g. **Hull–York–Leeds–York–Hull**). It is known that a context-free (CF) parser is needed to recognize an arbitrary palindrome. A context free language parser is usually modelled as a push-down automaton, consisting of a finite state automaton (FSA) (*i.e.* a RL parser) and memory (stack). This means that a CFL parser could have evolved from an existing FSA with the addition of last-in, first-out memory. Such a scenario, in which navigation provides the selective pressure for both regular and CF parsing, assumes shared purpose, which makes functional dependency of the latter on the former more plausible.

The fact that palindromes are rare in human languages, at the level of both word and sentence syntax, does not constitute a problem. Unlike the previously discussed case of regular languages, we do not suggest that human communication had ever had to spell out palindromes of landmarks explicitly in order to describe a round journey, only that such navigation could have provided the need for a CF parser to evolve. Indeed, the combined evolutionary pressure of limited short-term memory and cost associated with the message length would favour the implicit use of the CF parser to trace the return path, once the outward directions have been given.

Regardless of whether the need to make a round journey using the same path in both directions created the original need for CF parsing or not, it could be used in an experiment involving navigation, rather than responses to speech, to test the ability of a species to perform this type of abstract computation, while avoiding the criticism of Fitch and Hauser's (2004) work. One could consider two classes of tasks. In the first, the subject would have to learn to navigate between two locations, collecting a reward on reaching the destination and a second one upon returning to the starting position. Assuming landmarks are used to memorize the paths, successful navigation would amount to learning a RG. The second experiment modified the above setting by extending the reward given upon returning to a more significant one, provided the subject went to the destination and back using the same path. Navigation based on a RG with alternative routes will fail to collect the extended reward most of the time, however, we have shown that a simple CFG will suffice (Kazakov and Bartlett 2005).

Using another string of salient features, such as turns and distances or cardinal directions, will not change the need to reverse that string to navigate back, but will assume the ability to transform a left turn to a right one (or North to South, West to East, respectively) and vice versa. One can use obstacles to guarantee that no complete path used in training is available in the test phase and vice versa, or replace the maze altogether, in order to mirror Marcus *et al.*'s (1999) use of different syllables for training and testing.

In a final remark, it is interesting to note for any finite alphabet that the grammars needed to describe palindromes, while being CF, belong to the class of 'linear' grammars, *i.e.* the ones containing at most one non-terminal in the right-hand side of their rules. All regular (finite-state) grammars are linear, and the ones that are CF represent the simplest class of CFGs in a hierarchy that has 'correct bracketing' grammars at the other end (Berstel 1979).

8. Summary

The main ideas in this article can be summarised as follows.

- (1) The ability to handle RG, a critical step on the road to human language, may originally have evolved to assist navigation.
- (2) Navigation and language parsing are two instances of the same abstract computation, and the way they are grounded may reflect that.
- (3) Provided an innate parser serving navigation and the ability to develop a shared lexicon have evolved in a population of agents, the step combining the two existing abilities for the purposes of sharing directions appears evolutionarily plausible, and is supported by the results of the simulations described in this paper.
- (4) The availability and volatility of resources are two important environmental factors influencing the relative benefits of sharing information about resource location, with the environments most beneficial for language striking a trade-off between the two.
- (5) The need for CFGs, typical for human languages, could have originated in navigation.

9. Future work

Building on the results obtained through the use of simulation in this paper, we intend to carry out further experiments to investigate factors beyond the scope of the current enquiry. Specifically, we shall address the issues of willingness-to-speak and the emergence of lexical communication, both of which have been assumed as prerequisites here. By implementing the agents' willingness to act altruistically as an inherited feature subject to natural selection, our simulation will permit the study of the benefits of communication at an individual level, in a population where altruism and selfishness coexist and compete. Incorporating language games into our simulations may help to provide evidence of whether a comprehensive common lexicon needs to be established before sharing routes becomes evolutionarily beneficial, or whether indeed this type of communication may actually promote faster convergence of the lexicon.

The range of indirect evidence for the link between navigation and parsing also suggests the idea of using neuroimaging to compare the brain activity between tasks corresponding to regular and context-free languages for navigation, on one hand, and language, on the other hand. An exciting, but yet unconfirmed possibility is that the patterns of activation for navigation and language would be similar for the same class of languages, but processing a different class of language would result in distinguishable differences even for the same type of task.

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