

Exploring expressivity: A closer look at the evolution of linguistic structure

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Abstract

Compositionality, a unique and fundamental property of human language, emerges from the pressures placed on language as it is learnt and used by consecutive generations – the pressure for learnability, arising from the transmission process, and a pressure for expressivity imposed by the use of language to convey meaning. This study uses human diffusion chains to explore the contribution that learning and communication make to the cultural evolution of linguistic structure. Languages are exposed to either a learning pressure, a communication pressure, or both. The language in the communication chain became expressive and showed varying degrees of structure, in some cases deliberately introduced as an aid to comprehension. This puts the focus back on the cognitive processes of language users, and emphasises the role of recipient design in the emergence of structure in language. The languages in the learning conditions struggled to maintain a significant degree of structure, contrary to expectations. However, the development of the languages provides clues about the way that language adapts in response to the particular communicative and learning environment.

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CHAPTER ONE

Introduction

From family trees to endangered languages, linguists have long used metaphors from biological evolution to describe the way that language develops and changes. Recently there has been a movement to view the similarities between genetic change and linguistic change as not just metaphorical, but instead arising from the expression of a more general evolutionary process (Hurford, 1999; Croft, 2000; Ritt, 2004).

Both language and natural selection are seen as belonging to a general class of dynamic systems, or *complex adaptive systems* (Ritt, 2004; Lass, 1997), which, because of their inherently replicating nature are able to evolve in a Darwinian way (Ritt, 2004). In such systems if variation between elements leads to a different degree of replication of those elements, then that variation will be selected for or against. As the individual elements which are most suited to the environmental pressures become more prevalent, the system itself adapts and becomes stable in those conditions (Vogt, 2006). Although at this point it may appear that elements in the system, whether words or genes, have been designed for efficiency and successful replication (Kirby, Smith & Brighton, 2004), there is, in fact, no deliberate design or even central control over the system itself. Instead the adaptation is an indirect consequence of ‘massively parallel activities and the interactions of many simpler constituents’ (Ritt, 2004, p.92). Furthermore, as Steels (1997) points out, the feedback from these changes to the system, as well as from individual interactions, becomes part of the new environment that any particular element faces, thus giving rise to higher-order dynamics.

By viewing this kind of Darwinian selection as a more general process, we are freed from the constraints of a framework constructed for biological evolution, leaving us better able to examine linguistic evolution and change on its own terms. For example, the method of linguistic replication and transmission is fundamentally different from the processes seen in biological evolution. Language is arbitrary, both in the forms of signals and in the associations between signals and meanings. This makes it highly flexible also means that it varies widely across time and space. Because of this diversity, most of our linguistic knowledge, but cannot be innately specified (Kirby,

2007). Instead it must be learnt through observing the output of others who have themselves developed their own linguistic knowledge in the same way. This kind of repeated social transmission has its own dynamics, and shapes the language in specific ways. In particular, it has been asserted that it forces language to become more learnable, as variants that are more generalisable or that appeal to the cognitive biases of learners are more likely to be acquired, and thus survive the transmission process (Brighton, Smith & Kirby, 2005; Kirby, 2007; Chater & Christiansen, 2010).

Thus, a language can be seen as an adaptive organism, which evolves on a cultural, or *glossogenetic* timescale (Deacon, 1997; Kirby, 2007; Croft, 2000; Christiansen & Chater, 2008; Wray & Grace, 2007). Empirically, it is well-attested that languages gain and lose words according to their cultural requirements, and that phonological and syntactic rules change over time (e.g. McMahon, 1994). Indeed, a great deal of study within linguistics is dedicated to tracking and explaining these changes at the micro-level, either across cultures (sociolinguistics) or over time (historical linguistics).

However, it is clear that these adjustments occur in the context of individual learning, and that this learning is influenced by the biological makeup of the learner. This has led Kirby and Hurford (2002) to posit that language actually lies at the intersection of three interacting complex adaptive systems: biological evolution of the learning and processing mechanisms of the learner, the course of language acquisition in the individual, and cultural evolution which occurs through the process of social transmission. These systems each work on different time-scales, and interact in non-trivial ways. Biological evolution provides the social, cognitive and anatomical constraints which guide the learning process. Through the process of repeated learning, these preferences come to be reflected in the language. Highly stable or universal features may then alter the selection pressures acting on language users, leading to biological change over time and such change will, in turn, alter the individual learning process. A number of studies suggest that language *can*, in fact, evolve in response to transmission, cognitive, social or functional pressures (see e.g. Kirby, 2001 and Oudeyer & Kaplan, 2007 for evolution in artificial systems; Kirby, Cornish & Smith, 2008; Galuntucci, 2005 and Fay, Garrod & Roberts, 2008 for experiments with human participants; Lupyan & Dale, 2010 for evidence of adaptation in natural languages).

So what does this mean for the study of language evolution? How can we use this framework to reach a deeper understanding of how language changes, and why we have ended up with the kind of languages that we see today? By viewing language as an adaptive system it is possible to explain

language development and change in terms of adaptations to the environment in which language is used and learnt (Chater & Christiansen, 2010). Thus, universal properties of human language can be explained as the result of the selection pressures which apply when human learners repeatedly acquire language (Kirby & Hurford, 2002; Jäger & van Rooij, 2007).

Compositional structure is a universal feature which a number of recent studies have investigated in just such a way. Kirby and Hurford (2002, p.128) define a compositional system as ‘one in which the meaning of a signal is some function of the meaning of the parts of that signal and the way in which they are put together’.

For example, although you may have never seen sentence (1) before, you will have a fairly good idea of what it means.

(1) The teacher kicked the apple.

The meaning of this sentence can be understood even on first exposure because English speakers understand the components of the sentence – the words – and the rules of syntax which assign indicate the relationship between the words. However, there is another level of compositionality at work here. While learners of English must memorise idiosyncratic signals such as *apple* and *kick*, they do not need to learn the word *kicked*. Instead, once they have learnt the meaning of *kick*, learners can generalise from the past tense rule that *-ed* reliably signifies a situation in the past to infer the meaning of *kicked*. Thus, compositionality occurs not only in the grouping of words into sentences, but also in the recombination of phonemes into morphemes, and morphemes into words. It is fundamental to the construction and nature of human languages, and along with recursion, it allows humans to express an almost infinite number of meanings in spite of the limited linguistic resources which are available (Kirby, 1998).

Therefore, understanding how compositionality arose and the forces which influence it are central issues in evolutionary linguistics. Several methodologies have been used to investigate these questions, including computer simulations and experiments using chains of human participants (these studies will be described in further detail in Chapter 2). Results from all paradigms suggest that compositional structure is an emergent property of cultural evolution, arising in response to the data bottleneck during repeated transmission. Most work has focused primarily on this aspect – the pressure for learnability imposed by the bottleneck. However, it is clear that a pressure for

expressivity – an unambiguous one-to-one relationship between meanings and signals – also plays a crucial role (Kirby, Cornish & Smith, 2008; Smith, 2003).

This dissertation will further investigate the relationship of each of these two pressures, and the individual contribution that each makes to the development of compositional structure in language. In Chapter 2 I will describe how the Iterated Learning Model and the diffusion chains of Kirby et al. (2008) have contributed to our understanding of how evolution leads to compositional communication systems. A detailed methodology of the current study is presented in Chapter 3, and in Chapter 4 the results of the three experiments will be explored. Chapter 5 will attempt to explain the outcomes. In particular, this will address the unexpected result that the learning conditions did not develop a significant degree of structure, but the communication condition did. Finally, Chapter 6 will conclude this dissertation by summarising the insights this study has given, and what remains to be explored.

CHAPTER TWO

Background

2.1 Iterated learning and language change

It might be assumed that communicative efficiency would be strongest selection pressure acting on language. After all, communication is the function of language (Jäger & van Rooij, 2007). However, Kirby and Hurford (2002) point out that this is not necessarily the case. In fact, they argue that one of the primary forces acting on language is its mode of reproduction. Language, they argue, is shaped by the need to survive two points of transmission, as it is learnt through observation and then reproduced. At one level, language can be seen as the grammar that exists in the mind of an individual speaker, I-language. Yet it also has an external presence, in the set of utterances that can be observed in the world – this is termed E-language. As there is a continual turn-over of speakers, as people grow old and die, and new babies are born, language is transmitted from speaker to learner by being repeatedly mapped from E-language (the observed utterances) to I-language (the individual's internal grammar), and then back again as the individual produces utterances based on their I-language. This kind of repeated learning, where the output from one generation of learners is used as input for the next is termed *iterated learning* (Kirby & Hurford, 2002). As pointed out earlier, the survival of a linguistic feature depends on it being repeatedly replicated (Kirby, 2001). Therefore the process of transmission itself can have a strong impact on the language, as it develops properties which allow it to be successfully transmitted through the induction and production transformations.

There are two main ways that selection acts on linguistic variants during this learning process. Some variants will be preferred by the cognitive biases or physical makeup of the learner (Chater & Christiansen, 2010; Kirby, Dowman & Griffiths, 2007). These variants will be learnt more easily, so are more likely to survive in to the next generation. Because the next learners have the same genetically-endowed preferences then these variants will be reinforced over time. Eventually, the variants favoured by inherited biases will become wide-spread: the language has adapted to the biases of its speakers through the process of repeated learning.

However, there is another way in which language changes in response to the transmission process. Over time, languages become more intrinsically learnable – that is, more regular and generalisable (Kirby, 1998; Kirby, 2001). This occurs because learners can only ever observe a sub-set of all possible utterances. A linguistic variant which fits in to a regular pattern of associations can be induced by generalisation, even if it is not observed by the learner. Thus, regular signals will build up in the language, while idiosyncratic ones will be lost (Brighton, Smith & Kirby, 2005).

2.2 The Iterated Learning Model

Computer modelling is ideally placed to explore this kind of process, as parameters can be easily manipulated to compare various outcomes. Furthermore, many generations can be run, giving information about changes which occur over long periods of time – or in the computer sense, many iterations of learning. That is, they allow us to see the changes which evolve from the interaction of individual agents, information which may not be intuitively guessable or easily available (Kirby, 1998).

The Iterated Learning Model (ILM) is an agent-based model which was developed to investigate the effect that cultural transmission has on language (see e.g. Kirby, Smith & Brighton, 2004 for an overview), where language is seen as meanings, signals, and the mapping between them (Kirby et al., 2004). In the simplest ILM there will be two agents at any one time: a speaker, or adult, and a learner who observes the speaker's output. In addition, there must be a meaning space and a signal space. The adult will typically be given a set of randomly chosen meanings for which it needs to produce signals. It produces the signals according to the meaning-signal associations in its grammar. The learner then needs to induce its own grammar based on the set of meaning-signal pairs which it has observed. After a certain number of observations, the learner becomes an adult and starts producing signals for the next learner. Note that the agents in most of these models do not evolve – that is, there is no biological variation (Kirby, 2002). Nor is there any selection of agents according to their success at communicating. Therefore, any changes in the structure of the language must occur in response to the pressures imposed by the process of repeated acquisition.

2.2.1 Results from the ILM

The first important finding is that compositional structure does emerge in the ILM model. This result has proved surprisingly robust across different kinds of population structures (Smith & Hurford, 2003; Ferdinand & Zuidema, 2009), meaning-space structures (Brighton & Kirby, 2001; Steels & Belpaeme, 2005), and learning and production methods (e.g. associative neural networks (Smith, 2002), Minimum Descriptive Length ranking of potential hypotheses (Brighton & Kirby, 2001), exemplar-based learning (Batali, 1998), Bayesian learning (Ferdinand & Zuidema, 2008; Schrementi & Gasser, 2010)). These parameters add complexity to the results, but the general findings – that cultural transmission leads to ‘regularisation, an increase in learnability and compositionality’ (Ferdinand & Zuidema, 2008, p. 5) - still hold. This suggests that the increase in structure arises from the process of iteration under bottleneck conditions, rather than to other parameters such as learning mechanisms or population dynamics. Results from Cornish (2010) highlight the fact that bottlenecks occur for several reasons, including constraints on human memory – this will be discussed further in section 2.3.

2.2.2 The bottleneck

So what exactly is the bottleneck, and why is it so crucial to the emergence of structure? The transmission bottleneck refers to the fact that learners can never observe all the potential utterances in a language (Kirby, 2002). If signals are idiosyncratic, then each meaning-signal pair must be memorized by the learner. Because of the bottleneck, any particular meaning-signal pair may not appear in the input data, is not acquired by that learner, and is lost to future generations. In contrast, in a compositional system it is the associations between meaning parts and signal parts that are learnt, allowing a signal to be predicted even if it has never been observed. The ILM models show that over time, linguistic systems become increasingly structured as idiosyncratic signals disappear and random correspondences are exploited by learners, so that systematic pairings are amplified down the generations (Kirby et al., 2004).

When there is a large bottleneck, so that agents can observe all or almost all of the meaning-signal mappings in a language, then the language reaches a stable state of expressive but idiosyncratic mappings – a random language develops. When the bottleneck is very small, the language becomes

inexpressive and unstable, because the learner can only learn a small section of the language; nor does it have access to enough information to make any generalisations. Thus it must resort to generating or allocating signals randomly, which proves unsuccessful in communication (Kirby & Hurford, 2002).

Note that frequent meaning-signal pairs may be able to survive the bottleneck, even if they are irregular or idiosyncratic (Kirby, 2001) as they are likely to appear in every set of training data. This explains the situation often found in natural languages, where the most common words tend to resist regularisation (Lieberman et al., 2007; Pagel, Atkinson & Meade, 2007). Although Real and Griffith's (2009) model shows a slow but steady regularisation across the language, Kirby's (2001) work suggests that if words are so frequent that they appear early on before the learner has had a chance to make generalisations, then stable irregularity can occur.

2.2.3 The role of learner bias

So, do learning biases play any part in the emergence of structure? Smith (2003, p.9) suggests that compositionality arises in response to two pressures - 'a pressure arising from the poverty of the stimulus, and a pressure arising from the biases of language learners.' He found that learners lacking a particular bias, a preference for one-to-one mappings between meanings and signals, were unable to construct or maintain a compositional system. It is also clear that learners need an ability to generalise in the first place (Smith, 2003; Brighton et al., 2005). That is, learners must be able to deconstruct both signals and meanings into smaller parts, and to track associations between those parts.

2.2.4 The structure of the meaning space

Earlier it was suggested that the formulation of the meaning-space has little effect on the emergence of structure. However, Smith's (2003) point that learners must be able to map subconstituents of both signals and meanings highlights the fact that there must be structure within the meaning space itself for the emerging linguistic structure to hang off. As Brighton & Kirby (2001) point out, 'If the perceptual space of the agent is not broken into multiple features or multiple values, then

compositionality is not possible'. Brighton's (2002) study using meanings represented by feature vectors showed that the number of features (or dimensions) and values is also important. He describes a tension between the complexity of the meaning-space and the ability to observe regularity in the linguistic system. Too little complexity means that it is difficult for compositionality to develop, as associations between signals and whole meanings are observed almost as often as associations between the subparts. However, if there is too much complexity then the feature-values found in the various associations will be spread too widely, and it is therefore more difficult to observe regularities.

2.3 Exploring cultural evolution in the lab

Computer models of language evolution are, by necessity, highly simplified. There is therefore a question about the extent to which they represent real-world processes (Gong, 2005). A complementary method for studying the effects of cultural evolution is to use groups or chains of human participants. For example, Caldwell and Millen (2009, 2010) looked at micro-societies with replacement – small groups of people with a continuous but gradual turn-over of individuals – to explore the impact of various conditions, such as different methods of social learning or cohort size, on the emergence of cumulative culture.

The diffusion chain model, where the output from one learner is given to the next, was first seen in Bartlett's (1932) 'serial reproduction' experiments. More recently, this methodology has been used by Mesoudi, Whiten and Dunbar (2006) to investigate whether a bias towards social content influences the way that information is passed along chains of participants.

These studies show how cultural transmission can result in the accumulation of changes, often in the direction of human biases, but do not directly relate to language evolution. Most studies in the domain of human communication systems have not used iterated learning through diffusion chains, but have used repeated communicative episodes to show how communication adapts to the social environment (e.g. Fay et al., 2008).

The study of cultural evolution in the lab is in its infancy, but these studies show that this is a useful way to examine the emergent properties of cultural evolution using actual human minds, and therefore human cognitive abilities and motivations.

2.3.1 Diffusion chains – the human Iterated Learning Model

To address the question of whether the computer simulation results can be extended to experiments using human participants, an experimental framework was developed which combined the Artificial Language Learning paradigm (e.g. Christiansen, 2000) and the ILM. Essentially, an initially random artificial language was transmitted along chains of human participants (Kirby et al., 2008; Cornish, Tamariz & Kirby, 2009; Cornish, 2010). The initial language consisted of randomly-generated signals and a meaning space consisting of 3 dimensions (shape, colour and movement), with three values in each dimension. Learners were trained and then tested on the language, and the results of the test were used as the training input for the next learner in the chain. There was no communication between individuals, and learners were not even aware that their output would be passed on.

	BLACK	BLUE	RED			BLACK	BLUE	RED	
'horizontal'	wimaku nihepi wikima	miniki wigemi nipikuge	gepinini mahekuki hema	□ ○ △	'horizontal'	tuge tuge tuge	tuge tuge tuge	tuge tuge tuge	□ ○ △
'bounce'	miwiniku kinimapi miwimi	pinipi wikuki nipi	kihemiwi kikumi wige	□ ○ △	'bounce'	tupim miniku tupin	tupim miniku tupin	tupim miniku tupin	□ ○ △
'spiral'	gepihemi pikuhemi mihe	kunige kimaki winige	miki pimikihe kinimage	□ ○ △	'spiral'	poi poi poi	poi poi poi	poi poi poi	□ ○ △

Fig. 2.1 An example of a random language given to the first generation of participants in Kirby et al. (2008) is seen on the right (taken from Cornish (2006)). The table on the left shows how this language changed through the process of iterated learning; by generation 8 the language shows systematic underspecification, so that a single word refers to all objects which share a common value. For example, the word *poi* is used to refer to all spiralling objects.

2.3.2 The importance of expressivity

These experiments confirmed the basic findings of the ILM – structure can develop merely because language is learnt, understood and remembered by a chain of individuals. However, there was a key difference in the *kind* of structure which emerged – while the computer simulations led to compositional structure, Kirby et al. (2008) found that the human chains produced languages which were systematically underspecified – that is, a handful of words were used to represent all the meanings. Usually the words were grouped along one or two of the dimensions, leading to structure in the language.

Kirby et al. attribute this to the fact that learnability is not the only pressure acting on language. Languages must also be expressive; language is used to communicate and communication relies on the fact that meaning-signal mappings are shared. The pressure of language *use* thus drives languages to develop unambiguous one-to-one mappings.

This was clearly illustrated in the diffusion chain experiments mentioned above. With no expressivity pressure, languages became highly structured but underspecified, so that a single signal could represent many meanings. Such a language is easy to learn, as it reduces the number of signals to be memorized, and signals can be generalised to cover novel meanings. However, it is of limited use as a language, because there is no way for the listener to understand the speaker's intended meaning.

Kirby et al. tested what would happen if an expressivity pressure was imposed, by running new experiments with the ambiguous signals filtered out. If a participant produced underspecified output, with a signal that mapped to more than one meaning, then all but one of the meanings were removed from the input data for the next generation. This presumably simulates the pressure imposed by communication, where the need for signals to uniquely identify meanings would ensure that speakers do not produce ambiguous signals – and if they did, presumably communication would be ineffective and the ambiguous signals would not be reproduced in later interactions. Therefore, the filtering of ambiguous signals in Kirby et al. works in a similar way by preventing the transmission of homonyms.

In these new experiments the additional pressure of expressivity led to the development of compositional systems. Although this pressure is not imposed in such a way in computer simulations, Smith (2003) points out that most studies implicitly include a bias against homonymy

(one signal maps to many meanings) and synonymy (many signals are used to represent one meaning). These biases can also be seen as imposing a pressure against expressivity, and when they are present they also lead to compositional systems. Because signals in such systems are composed of smaller parts which map systematically to feature values of the meanings, they are capable of uniquely representing meanings.

This combines with the fact that regularity increases learnability, as regular mappings are more likely to survive transmission. The results of Kirby et al. (2008), as well as a similar experiment by Tamariz and Smith (2008), show that the transmission error does in fact decrease as languages become more structured. In addition, a compositional system helps learning by reducing the memory load placed on learners. Instead of having to learn a large vocabulary of idiosyncratic items, knowledge of the language can be compressed into general rules (Kirby, 2001). Compositional structure is thus an efficient and highly adaptive solution to the problems of learnability and expressivity.

2.3.3 The memory bottleneck

When computer simulations are run with no data bottleneck, languages become or remain holistic and random (Smith, 2003; Kirby & Hurford, 2002). However, when Cornish (2010) ran experiments where chains of human participants were trained on the whole language, she found little difference in the emergence of structure or the rates of transmission error – that is, just as in the experiments where a data bottleneck was imposed, the languages tended to become systematically underspecified. How could this happen? Cornish (2010) believes that the answer lies in the limitations of human memory. Unlike computer agents, who can reproduce meaning-signal pairs perfectly, human memory is unreliable. Because not all signals are remembered, access to the data-set is effectively limited, just as it would be with a data bottleneck. And again, this causes any kind of structure in the language – in this case, systematic underspecification – to be amplified as learners generalise to unremembered meaning-signal pairs.

2.3.4 Learnability – a closer look

Even though the learnability pressure imposed by the data bottleneck and the limits of human memory is not *sufficient* to explain compositional structure, it is assumed that the learnability pressure does play a crucial role. The reason for this becomes clear when we look more closely at how the learnability pressure actually applies. First of all, it refers to the ability of learners to keep a given meaning-signal pair in their memories. This includes the ability to recall the appropriate signal or meaning (given its partner), to recall the correct form of the signal, and also to the limits of the overall vocabulary size. If there is no pressure for the language to change in response to memory or recall issues, any changes that occur to the language must arise as the result of the need for expressivity – that is, a reduction in ambiguity of meaning-signal mappings. If a learner has no upper limit on vocabulary size then the most straight-forward way of achieving an unambiguous meaning-signal mapping system is to have a unique signal for every meaning – a one-to-one mapping.

Learnability also refers to the ability of an individual to acquire a signal even when it is not observed in the input - alternatively viewed as the signal's ability to survive the data bottleneck. If this pressure is removed, then there is no need for the system to become regular and predictable, or for signals to become generalisable. That is, expressivity alone does not impose any pressure for structure to emerge. This was illustrated by manipulating the size of the bottlenecks (Kirby & Hurford, 2002) – where there was no data bottleneck the evolved languages became completely expressive but signals were idiosyncratic.

Note that although the data bottleneck and the memory bottleneck have different causes, they were found to produce similar effects in Cornish's (2010) human diffusion chain experiments. It is merely the fact of having a bottleneck which forces the language to become more generalisable, and in this sense it is irrelevant where in the process of acquisition it occurs. However, this does not rule out the possibility that there may be more subtle differences in the way, or the type of languages that arise, as Cornish (2010, p.124) points out. It also raises the question of how learner preferences for certain meaning types or feature-values, or signals or signal parts, or types of association may shape language transmitted under a memory bottleneck.

It seems, then, that both learnability and expressivity play a role in the emergence of a compositional system. However, as Cornish et al. (2009) acknowledge, there is a certain tension between these two pressures. Compositional structure does not arise from the pressure of learnability alone. A highly

learnable language could consist of a single word for all meanings, or at least a high degree of underspecification (Cornish et al., 2009). That is, as languages become more learnable, underspecification increases. This reduces the expressivity value of the language. So a language that evolves through cultural transmission to be highly learnable will become dysfunctional unless the communicative function of language is also activated.

2.4 Language in use – the communicative aspect

There is an additional factor to consider. The study by Kirby et al. (2008) imposed an expressivity requirement without any actual communication, so that the results could be attributed purely to the fact of cultural transmission. This study will use communicative interaction to impose the expressivity requirement. When language is used in communication, it involves the coordination of the thoughts and behaviour of two individuals. This brings into play informative intentions and the challenge to the speaker of producing a signal that the hearer can map to the correct meaning (Tomasello, Carpenter, Call, Behne, & Moll, 2005). Thus, there is the potential for a signal to change due to the speaker making a deliberate modification for the benefit of the listener. Such modifications reflect an awareness that the listener has a state of knowledge, and will draw on this knowledge to infer the speaker's intended meaning (Sperber & Wilson, 1986). The speaker must therefore attempt to communicate in a way that best appeals to the listener's knowledge and induction strategies. This may be by reproducing the signal as best they can. Or, the communicative attempt may integrate certain biases – for example, particular learning strategies such as an appeal to the structured nature of the meaning space, or particularly salient properties in the meanings. This provides a motivation to develop meaning-signal mappings that are most likely to be shared – i.e. a system of mappings that is most likely to be available to both speaker and listener.

2.5 Motivation

In summary, the results from both computer simulations and human diffusion chains show language adapting under the pressures of transmission and use. A communication system that must be repeatedly learnt under bottleneck conditions will become increasingly learnable – that is,

generalisable. When this is combined with a pressure for unique signal-meaning mappings, then it results in the development of a compositional communication system – each signal is generalisable, due to the regular mappings of the subcomponents, but is also unique, because of the way that those subcomponents are combined.

The studies by Cornish and her colleagues prove that humans can develop compositional communication systems through a process of cultural transmission when an expressivity pressure is imposed. However, the ILM studies have shown that compositional systems arise as a natural result of the process of cultural transmission, with no contribution from human biases or cognitive skills. Of course, natural languages do evolve in real communicative contexts, between individuals with communicative and intentional goals. This study acknowledges that compositionality is an emergent property of cultural evolution, but also places it in the context of human thinking and behaviour, to explore further the precise way in which compositionality emerges in *human* communication.

While the diffusion chain experiments did use human participants, the expressivity pressure was artificially imposed, under the assumption that this is equivalent to a communication pressure. However, human communication is a sophisticated and complex process, and there is clearly a need to explore how exactly the use of signals in communication leads to an expressivity pressure, and what impact this expressivity pressure has on linguistic behaviour.

This study aims to explore the relationship between learnability, expressivity and the emergence of structure as an adaptive property through the process of iterated learning. By comparing the language that emerges over three diffusion chains – one subject only to learnability pressure, one to communication pressure, and one where the pressures are combined, I will test the following hypotheses:

1. If the transmission of a language is subject to learnability pressure, but the communication pressure is removed, then the language will become structured through underspecification (i.e. it will develop identical signals for many meanings along the same dimension).
2. If the transmission of a language is subject to a communication pressure, but the learnability pressure is removed, then the language will develop unique idiosyncratic signals for each meaning.

3. If the transmission of a language is subject to both a learnability and an expressivity pressure, then the language will develop compositional signals.

CHAPTER THREE

Methodology

3.1 Brief overview

This study follows the basic methodology developed by Cornish and her colleagues (Kirby et al., 2008; Cornish, 2010), which combines the iterated learning of computer models with the diffusion chains of experimental work. Participants are taught or given an artificial language, and are asked to reproduce it. The resultant output is then used as the language which is given to the next generation of participants. In her experiments, Cornish artificially imposed the expressivity pressure by removing any ambiguous signals before giving the language to each new generation. Because I wish to separate the effects of the learning pressure and the expressivity pressure, which is driven by language use, I included a communicative aspect instead. The experiment was run with three conditions: LearnOnly, LearnPlusUse, and UseOnly.

- The LearnOnly condition follows the basic arrangement of Cornish's methodology; participants were given 4 rounds of training in a language then tested to see how well they could reproduce the signals.
- The LearnPlusUse participants were also trained on the language, but were then asked to use it in a communicative task.
- Participants in the UseOnly condition performed the same communicative task, using a printed dictionary of the language.

3.2 Participants

Participants were recruited using departmental mailing lists and the University of Edinburgh careers service, and were mostly studying for undergraduate or Masters degrees. Data was collected from 50 subjects (25 male, 25 female; ages ranged from 19 to 40, with a mean age of 24.5). None had studied linguistics, although several studied languages. Non-native speakers and bilingual speakers were

allowed to take part but were not partnered with other speakers of the same language/s. The LearnOnly and LearnPlusUse conditions took approximately one hour, and participants were paid £6. The UseOnly experiments took 30 minutes, and participants received £3.

3.3 The language

The artificial language consisted of a meaning space made up of a small number of visual stimuli, presented on a computer screen or in a printed ‘dictionary’, and a written label for each image.

3.3.1 The meaning space

As Brighton et al. (2005) point out, for compositional structure to arise there needs to be complex structure in the meaning space for linguistic structure to hang off – i.e. meanings must have shared feature values that can be reflected in the signal structure. Therefore, a neatly-structured meaning space was created, with 27 different meanings.

The meaning, or stimuli, consisted of a set of geometric shapes which varied along three dimensions, with three values in each dimension, as shown below. Each meaning consisted of a unique combination of these values.

SHAPE	COLOUR	TEXTURE
circle	blue	block
square	red	check
triangle	yellow	stripe

Table 3.1. The 3-by3 dimensions of the meaning space.

Signals in natural languages do not perfectly reflect structure in meaning spaces, not least because meaning spaces are messy, wide-ranging, and partly created by perceivers themselves in terms of the elements which are noticed, or how the meaning space is broken down (Oudeyer & Kaplan, 2007; Matthews, Kirby & Cornish, 2010). Because I do not wish to presuppose that learners prefer meanings that are defined purely in systematic terms, I also gave each item an idiosyncratic appendage. This allowed the items to be individually identified without referring to any of the

overlapping feature values. As 27 unique appendages were required, they needed to be fairly elaborate to reduce the likelihood of the appendages being perceived as a fourth dimension. Of course, this can never be ruled out, but by increasing the complexity of the appendages it lowers the chance that people will make the same kinds of associations, thereby reducing the probability that another dimension could become entrenched in the language.

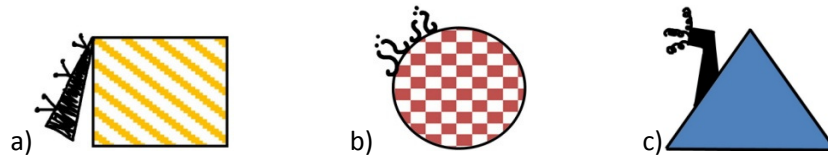


Fig. 3.1. Examples of the meanings. These examples show the variation in colour, shape and texture, as well as the unique appendages.

3.3.2 The signal space

The initial language consisted of 14 randomly-generated words, composed of 2, 3 or 4 syllables. These were drawn from a set of 14 CV syllables, with replacement. In previous experiments the initial participants in each chain were provided with a random language consisting of 27 unique words. Because I am investigating the pressure for expressivity imposed by communication, my initial language needs to be somewhat underspecified – if it were not, then the language would already be perfectly expressive and there would be no need for the language in the UseOnly condition to change at all. I therefore used a randomly-generated language that was only half-expressive – that is, instead of having 27 labels, so that each meaning mapped to a unique signal, the initial language had only 14 labels. This meant that there were a number of homonyms in the language, so that while 5 meanings were represented by a unique signal, 5 shared a signal with another meaning, and 4 shared a signal with two other meanings.

Ideally, because we are starting with a half-expressive language, we should also start with a half-structured language. In a regular, or structured, system, we would expect meanings with shared feature values to be represented by signals that are similar in some way – either wholly identical, which would produce an underspecified system, or with identical segments which more precisely indicate the shared values in the meaning space. To put it another way, there should be a correlation between the distances between signals and the distances between meanings. Therefore, one way of

measuring the degree of structure in a language is to use the Mantel Test, a test of the correlation between two sets of distances.

The first step, then, is to calculate the distance between each pair of signals and each pair of meanings. Distances between meanings can be calculated using the Hamming Distance (HD) (Hamming, 1950), which simply counts the number of differences between two strings of the same length. In this case, each meaning could be seen as a string of dimensions: (COLOUR value)(PATTERN value)(SHAPE value). This can then be compared to other meanings, and the number of dimensions in which the two meanings vary can be counted. For example, (blue)(striped)(square) and (blue)(striped)(triangle) differ in one dimension – shape – and have an edit distance of 1. In contrast, (blue)(striped)(square) and (red)(block)(circle) differ in all dimensions, and so have an edit distance of 3.

For the signals, the distance measure is a little more complicated, as the signal strings are of varying lengths. In this case the Levenshtein Distance (LD) is a more appropriate measure of string similarity (Levenshtein, 1966). As well as substitutions, the LD also counts insertions and deletions when calculating the lowest number of changes required to transform one signal-string into another. For example, even though the two strings ‘lupi’ and ‘likapi’ are different lengths, this is reflected in the number of changes as the additional letters are inserted. In this case, the minimum number of changes is 3: the insertion of ‘i’ and ‘k’, and the substitution of ‘u’ for ‘a’. To allow comparison, the edit distance for each pair of signals needs to be normalised, using the equation given in Fig. 3.2. This returns a value between 0 and 1, so that identical strings will have an edit distance of 0 and strings with no common element will have a value of 1.

$$nLD(s_1, s_2) = \frac{LD(s_1, s_2)}{\max(len(s_1), len(s_2))} \quad (\text{Fig. 3.2})$$

The Mantel test requires the average LD and HD values, which are computed using the following formulas:

$$\begin{aligned} \overline{HD} &= \frac{\sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n HD(m_i, m_j)}{n(n-1)} \\ \overline{LD} &= \frac{\sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n LD(s_i, s_j)}{n(n-1)} \end{aligned} \quad (\text{Fig. 3.3})$$

Once pairwise distances have been calculated for the meanings and signals, the Mantel Test (Fig. 3.4), calculates the correlation between the two sets of distances.

$$E(O) = \frac{\sum_{i=1}^n \sum_{j \neq i}^n (HD(m_i, m_j) - \overline{HD}) (LD(s_i, s_j) - \overline{LD})}{\sqrt{\left(\sum_{i=1}^n \sum_{j \neq i}^n (HD(m_i, m_j) - \overline{HD})^2 \sum_{i=1}^n \sum_{j \neq i}^n (LD(s_i, s_j) - \overline{LD})^2 \right)}} \quad (\text{Fig. 3.4})$$

As this is essentially the Pearson product-moment correlation, it returns an r-value which indicates the degree of correlation. The r-value ranges from -1 to 1, with 1 signifying a perfect correlation between signal elements and the structure of the meaning space – i.e., a compositional system (Smith, 2003). A negative correlation would indicate that similar signals map to dissimilar meanings, while a value of 0 would indicate that signals are scattered randomly over the meaning space.

We then need to determine whether this correlation is significant – that is, given the set of meanings and signals that we have, how likely is it that the associations we see could have occurred through randomly allocating signals to meanings? To do this, the Mantel Test compares the observed correlation with a large Monte Carlo sample, which involves permuting the rows and columns of one of the matrices 999 times and gathering a distribution of the r-values. This allows a z-score to be calculated for the veridical correlation, which gives a measure of confidence that the assignment of signals to meanings in the observed language did not occur randomly.

As stated above, I wished to use an initial language that was half-expressive and half-structured. As a z-score of 1.96 is strongly suggestive of a non-random language, I was looking for a language with 14 labels and a z-score of about 1 – a half-random, half-structured language. Unfortunately, a language was mistakenly chosen which had a z-score of 0.1. This means that the language was half-expressive but essentially random – presumably both in the allocation of homonyms and in the substring patterns. This had implications for the development of the languages, which shall be discussed in Chapter Five.

3.4 Procedures

There were two ways in which the participants were exposed to the language, and two methods for eliciting language from them. These procedures were combined in various ways to form the three conditions.

Input procedures:

Learning – Participants in the LearnOnly and LearnPlusUse conditions underwent 4 rounds of training in the language. All 27 meaning-signal pairs were seen once during each round, making a total of 108 exposures. During the training stage, an image (the *meaning*) appeared on screen, followed one second later by the signal, and both remained for another 5 seconds. After a pause of 3 seconds, the image reappeared, and participants were prompted to type the label in a box below the image. In light of Cornish (2010), it was decided that memory constraints provide a sufficient bottleneck pressure, so this was repeated for all 27 items in the language, followed by a 30-second break before the next round. Items were presented in a different random order in each round, although as the order had to be pre-specified, it was held constant across generations and conditions.

The dictionary – Participants in the UseOnly condition were given a dictionary - a sheet of paper containing all the shape-label pairs.

Output procedures:

Testing – Participants were tested by presenting them with an image and asking them to write the appropriate label in a box on the screen. There was no feedback as to whether the labels were correctly remembered. Again, the items were presented in a random but fixed order. The output from this test was then used as the training input for the next participant.

Communication – For the communicative task there were two participants in each generation; one assigned the role of speaker and the other of receiver. The speaker was shown a set of four shapes, one of which was marked as the target stimulus. The other shapes were confounders, drawn from a pre-specified context set. The context set for each stimulus included two other stimuli that differed from the target in one dimension, two stimuli

that differed in two dimensions, and two randomly chosen stimuli. As each meaning was presented during the communicative task, three confounders were drawn randomly from its context set. The receiver was also given the set of four stimuli, but in this case the target was not marked. The speaker was prompted to write a label for the target stimulus. This then appeared on the screen of the receiver, who was asked to select the shape that they believed to be the target. The receiver's selection was shown to the speaker, and both participants were given feedback, in the form of a happy face or sad face, as well as a score at the bottom of the screen. To ensure that there was no memory pressure on participants in the UseOnly condition, in this condition only a history of the interaction was shown down the side of the screen. For each item, this showed the label produced by the speaker, the receiver's guess, and whether the guess was correct or incorrect. The process was repeated until each image had been targeted. Items were presented in the same order as in the Testing procedure. The labels given by the speaker during the communication task were recorded and used in training or in the dictionary for the next generation.

The four procedures were combined to form the three different conditions in the following way:

UseOnly	input: Dictionary
	output: Communication
LearnPlusUse	input: Learning
	output: Communication
LearnOnly	input: Learning
	output: Testing

(Table 3.2)

Chains of 10 and 11 generations were run for the LearnOnly and LearnPlusUse conditions respectively. In the UseOnly condition, I was mostly interested in how communicators adapted the language for their purpose. Because participants had access to a dictionary, once the language was perfectly expressive then no further changes were required for communication to be successful, so most of the changes occurred in the first few generations. Therefore, in the UseOnly condition three shorter chains were run, of 4, 4 and 1 generations.

CHAPTER FOUR

Results

4.1 Main findings

In Chapter 2 I hypothesized that the absence of a learning pressure would lead to languages with holistic and idiosyncratic signals. In contrast, conditions which include the learning pressure should produce regular languages– the LearnOnly languages, with no reason to be expressive, should become systematically underspecified, while the LearnPlusUse languages should develop compositional structure.

The figures below map the development of structure and expressivity in the three conditions. Clearly, the situation is more complex than hypothesized.

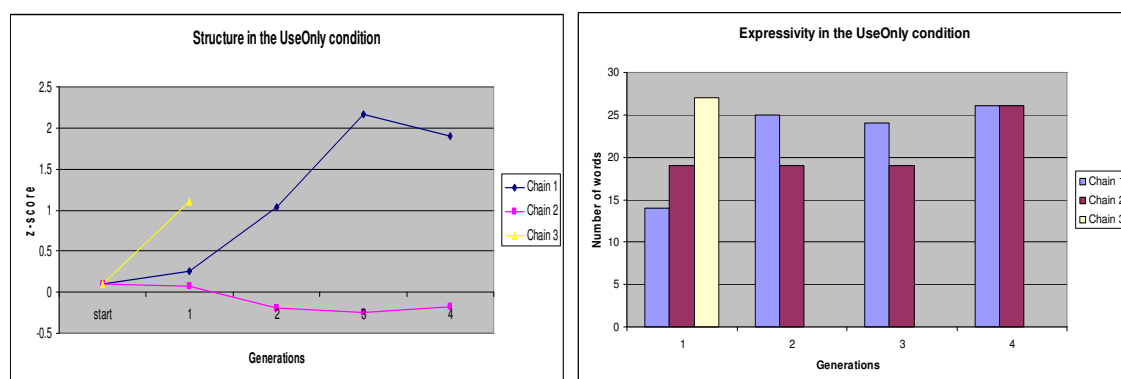


Fig. 4.1 a. Structure in the UseOnly chains. Final z-scores for the three chains are: Chain 1 = -0.179, chain 2 = 1.905, chain 3 = 1.102. b. Expressivity in the three chains. Chains 1 and 2 were somewhat slow to become fully expressive (and in fact, they only reached 26 words).

Although the UseOnly languages (Fig. 4.1) did become highly expressive, they show varying degrees of structure: we see chain 1 exhibiting a negative relationship between signals and meanings, chain 2 showing a degree of structure highly unlikely to occur by chance, and chain 3 showing an increase in systematicity, although within the realms of chance.

This suggests that while structure is not necessary in a functional communicative language, there is no pressure against it. Structure could arise by chance or by design, and this will be discussed in

section 4.3. But as long as all the meanings are disambiguated, once structure is present there is little reason to change the language in any direction.

The results for the LearnOnly and LearnPlusUse conditions are somewhat different than expected. The LearnOnly language (Fig. 4.2) does move in the general direction of systematic underspecification, although the z-score for the final language does not quite reach the 95% confidence interval. In fact, the language becomes significantly systematic at several points, but this is never maintained. Thus, the systematicity appears to be relatively unstable. Furthermore, as shall be seen in section 4.4, the meaning-signal mappings themselves are highly unstable, with major re-organisations of individual mappings and rule systems continuing into the last generation.

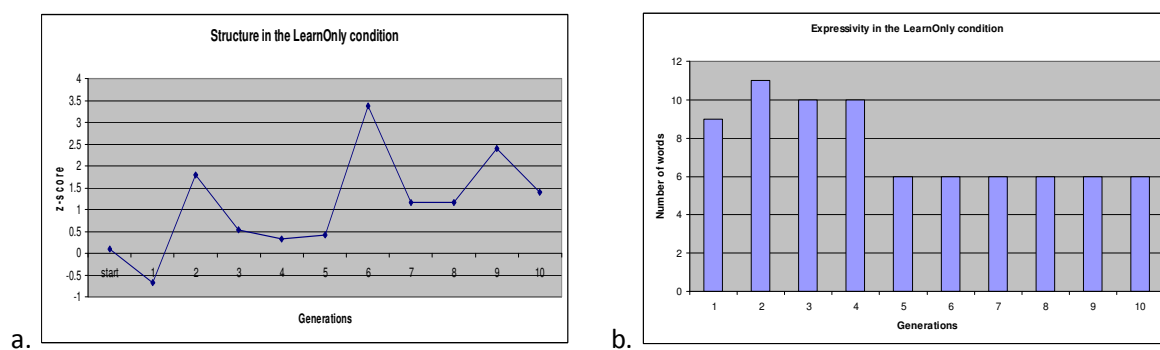


Fig. 4.2 a. Structure in the LearnOnly condition. The final z-score was 1.385, so did reach significance (the 95% confidence interval is 1.96). b. The number of signals in the LearnOnly condition. This fell to six signals and remained stable (although the mappings did not).

While the LearnOnly languages generally moved in the hypothesized direction, the results for the LearnPlusUse condition are completely unexpected. Not only has this chain failed to develop compositionality, but the languages have also become underspecified. The graphs in Fig. 4.3 show that the number of unique words and the z-score as a measure of structure have an inverse relationship in the LearnPlusUse condition. That is, the most structured languages are also the most underspecified, suggesting that the structure is due to systematic underspecification. Conversely, the languages with the greatest number of unique signals are the least structured, suggesting that learners in these generations are memorizing words and meaning-signal mappings individually, without reference to any sort of system.

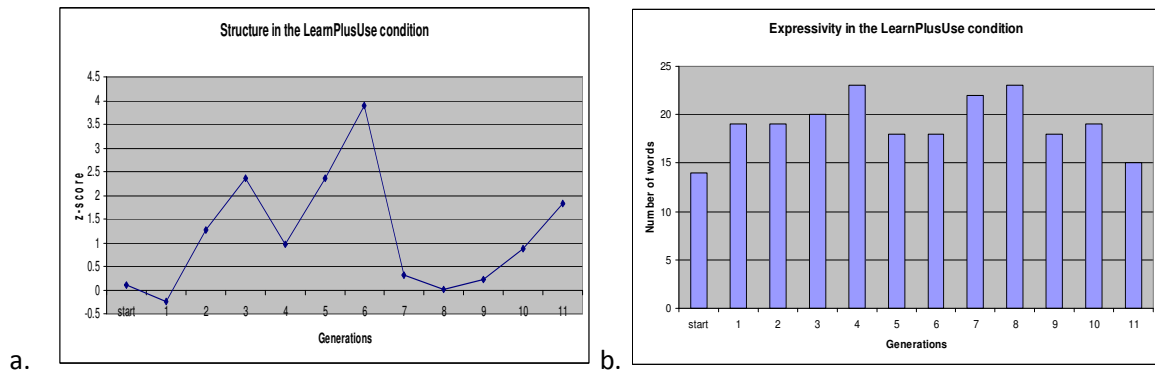


Fig. 4.3 Graphs showing a) the z-score and b) the number of different words in the language by for the LearnPlusUse condition. The highest degree of structure occurred in generation 6 (z-score=3.9), but the structure was lost in the next generation. The degree of structure in the last language did not quite reach significance (the final z-score was 1.8). There are more unique signals in generations where the z-score is low (e.g., generation 4, 7, and 8), suggesting an inverse relationship between number of words and structure in this chain.

4.2 A closer look

Because this is a pilot study, I have run only one chain in each condition. This means that the firm conclusions that I can draw are limited. However, the results of the LearnOnly and LearnPlusUse chains are unexpected, and this needs explaining. A detailed qualitative examination of the data is therefore useful in providing insights into the patterns of language behaviour seen in this study. However, it must be stressed that any generalisations will be tentative and impressionistic.

4.3 The UseOnly condition

4.3.1 Expressivity

All the languages in the UseOnly condition became highly expressive, with 26 or 27 unique labels. Two of the chains took several generations to get to this point (see Fig. 4.1) partly due to an unwillingness to change the input language. In fact, some speakers did not modify the language at all, preferring to take the communicative risk inherent in the status quo. This reluctance possibly stemmed from the formality of the experimental environment, as well as difficulty in formulating a communicative strategy.

4.3.2 Modification strategies

As shown in Fig. 4.4, speakers marked the language in a variety of ways – in fact, with a single exception, every speaker used a different method to differentiate words in the language. This is perhaps not terribly interesting, except that it emphasizes the fact that changes are solely due to the conscious decisions of the individual speakers, rather than being influenced by the dynamics of iteration (in this case, iterated *use*). It also indicates that speakers are not paying a great deal of attention to the language, and do not use any resources already present in the language, including modifications by previous speakers.

	BLUE	RED	YELLOW	
block	kakaluki	nakihulu	lupila	●
	hukipii	nenane	nakihuu (1)	■
	lane	lahumolu	pikalukaa	▲
stripe	pinaku	nehupilu	lahumolu	●
	piku	hukipu (2)	hukipi	■
	molalu	lulaka	pikaluka	▲
check	pinaki (3)	nananee	lulaki	●
	piki	nakihula (4)	kina	■
	kakaluka	nakihu	lulakaa	▲

Fig. 4.4 The language output from generation 4, chain 2. The language shows the different layers of change contributed by the various speakers, including the doubling of final vowels (1), changes to final vowels (2) and the addition of a final syllable (4). One speaker also responded to ambiguity by taking the label from a different meaning, creating underspecification (3). Changes in other chains involved similar strategies.

4.3.3 Communicative strategies

The challenge to the speaker is to make changes that somehow convey to the receiver which meaning is intended, knowing that these changes, in the context of the interaction history and the given language, are the only clues that can help the receiver make his or her choice. This is a significant cognitive challenge, and pairs often took quite some time to complete the task (mean = 19 minutes; min 12m, max 37m, baseline 12m).

It was hypothesized that the languages would become idiosyncratic, but would have no need to become regular. In fact, the results from two speakers show that using signals that make reference to structure in the meaning space can actually benefit comprehension in interaction. Structured signals allow receivers to generalise from existing meaning-signal associations, and so infer the intended meaning on first exposure to a speaker's signal.

The speaker in generation 3, chain 2, pursued a strategy of systematic underspecification. When confronted with the need to disambiguate the target from another meaning, the speaker gave the label for a completely different meaning which shared two values with the target but not with the confounder. For example, given a context set that included both *lupila* (yellow check square) and *lupila* (yellow block circle) and asked to signal the yellow checked square, the speaker wrote *bukipi*, which was the label for the red checked square. However, the receiver was not able to make sense of this strategy, and the speaker did not pursue it.

Another speaker (chain 3) used a system of affixation that reflected the structure of the meaning space, and attempted to use that structure for communication purposes. This speaker started off by adding a three-character suffix to signal CIRCLE-ness. At some stage she needed to distinguish between two circles, so she created a new suffix to represent BLUE-ness, and continued in this way. Unfortunately, because the affix associations were built up over several interactions and in response to particular context sets, there was no consistent pattern to their use, and although the receiver initially did very well, she struggled to understand which feature the affix was marking in the last few cases.

Instead of looking for tools in the language itself, most speakers used strategies based on context – the affixes related to the order in which meanings were targeted, the position of the meaning in the dictionary, or the order of presentation on the screen. These strategies did not prove very successful due to the fact that the receivers were looking for clues within the language itself. Comments in the post-experiment questionnaire indicated that most receivers were trying to make sense of the speakers' strategies in terms of the relationship between the modification and the meaning space. For example, the receiver in generation 2, chain 1 hypothesized that *a* represented triangles and *b* represented squares. In fact, these prefixes marked the order in which the meanings appeared on the computer screen. Thus, in many cases communication failed because of a mismatch between the speakers' context-based strategies and the receivers' hypotheses based on structure.

4.3.4 Structure

The two speakers who attempted to use the structure of the meaning space (generation 3, chain 2 and generation 1, chain 3) to signal their meanings both produced languages with increased structure, which is to be expected. However, a closer look at chain 2 reveals that much of the increase in structure is due to a few small changes that fortuitously increase the similarity of signals that map to meanings with shared values. In generation 1, by doubling the vowels in situations where there is ambiguity, the speaker has increased the distance between the signals for yellow items (which now include two words ending in *aa*) and the red and blue items, which do not include this combination. Similarly, in generation 2 there were two changes – which actually appear to be mistakes – which left many of the red stimuli associated with signals that start with *na-*. Thus, it appears that a great deal of the increase in structure in chain 2 is due to chance.

4.3.5 Summary

Overall, the UseOnly languages did develop unique signals, although in some cases this took several generations. Although the languages did not necessarily become more structured, this was not ruled out. In fact, several responses showed that the need for receivers to infer intentions when the given language is ambiguous can actually place a pressure on speakers to introduce regularity into their utterances.

4.4 The LearnOnly Condition

4.4.1 The instability of systematicity

As predicted, the language in the LearnOnly condition became underspecified, with a big drop in unique words in the first generation, eventually leading to just 6 different signals by generation 5. The signals remained fairly stable from that point, but it should be noted that several typing mistakes helped create a family of three highly similar variants. Thus, out of the final six signals, three were completely idiosyncratic and three were closely related.

The signals themselves showed little change, but there was a great deal of movement in the meaning-signal mappings over the generations, caused by competition between various systems of associations. The development of structure in generation 6 (Fig. 4.5), and the subsequent loss of structure in generation 7 (Fig. 4.6) illustrates this phenomenon and how it can lead to difficulty in maintaining stable regular systems.

Generation 5					Generation 6				
	BLUE	RED	YELLOW			BLUE	RED	YELLOW	
block	nenane	piki	nenane	●	block	nenane	piki	nenane	●
	nenane	nenane	kipi	■		nenane	nenane	kipi	■
	lane	nenane	nenane	▲		lane	nenane	nenane	▲
stripe	nenane	hikipilu	hikipilu	●	stripe	kipilu	hikipilu	hikipilu	●
	kipi	hikipilu	nenane	■		kipilu	hikipilu	nenane	■
	kipi	nenane	hikipilu	▲		kipi	hikipilu	hikipilu	▲
check	hikipilu	nenane	hikipilu	●	check	kipilu	hikipilu	hikipilu	●
	kipi	hikipilu	nenane	■		kipilu	hikipilu	nenane	■
	kipilu	kipilu	hikipilu	▲		kipi	hikipilu	hikipilu	▲

Fig. 4.5 The language at generation 5 (left) and generation 6 (right) of the LearnOnly chain. The signal-meaning associations in generation 6 have become much more systematic, with *kipilu/kipi* spreading throughout the BLUE meanings and *hikipilu* spreading through the RED meanings. In addition, *nenane* has become highly association with BLOCKS by withdrawing from other meanings.

Inconsistency in the allocation of homonyms in generation 5 meant that the learner in generation 6 could only find some kind of order in the mappings by hypothesizing a complex system of rules. For example, inconsistencies were overcome by having two separate underlying rules. Thus, the language produced by generation 6 can be almost completely learnt using a series of six rules:

1. BLOCK (with some exceptions) = nenane
From the remaining meanings:
2. BLUE TRIANGLE = kipi
3. other BLUE meanings = kipilu
4. all RED meanings = hikipilu
5. YELLOW SQUARES = nenane
6. all other YELLOW meanings = hikipilu

Although this language can be neatly summarised and is almost perfectly predictable from these six rules, the complexity of the rule system made it difficult to discover, and therefore vulnerable to the learning abilities and preferences of the next generation¹. To make sense of the generation 6 language, a learner would need to pay attention first to texture (i.e. whether the meaning is BLOCK or NON-BLOCK), then colour, and then sort the shapes into various groupings. However, the language in generation 7 does not show any recognition of such a system (Fig. 4.6). Instead, we see a preference for assigning words based on patterns to do with shape – for example, the quality of SQUARE-ness seems to override all other considerations, including the salience of block texture². In fact, this learner reported that they looked first for patterns between various signals and the colour values in the meaning space, and then for shape. Because the learner did not notice that texture was the dominant feature in the previous system, he could not make sense of the rule system created by generation 6. Instead, he imposed his own, conflicting rules, and the earlier system was lost.

Generation 7				
	BLUE	RED	YELLOW	
block	nenane	piki	nenane	●
	hikipilu	nenane	lane	■
	lane	nenane	nenane	▲
stripe	nenane	hikiplu	hikipilu	●
	nenane	lane	hikipilu	■
	nenane	piki	nenane	▲
check	piki	hikipilu	piki	●
	lane	hikipilu	hikipiul	■
	hikipilu	hikipilu	hikipilu	▲

Fig. 4.6 The language in generation 7, which has lost a great deal of the systematicity of the previous generation. For example, *nenane* now marks BLUE-ness as well as block texture, and *piki* has spread along two dimensions – to other circles and to another red item.

¹ The impact of individual variation is highlighted by the fact that due to software problems there were in fact two participants who learnt the language produced in generation 6. One of the participants noticed most of the rules, and was able to reproduce this language with a high level of fidelity. However, her data was incomplete, so the language of the second participant was used to continue the chain, and is reported above.

² The block mappings were stable over the whole chain, and were also fairly resilient in the LearnPlusUse condition, so this seems to be a prominent value for learners.

4.4.2 Reliance on idiosyncratic appendages

Several participants reported that after failing to find patterns between the structure in the meaning space and the signals, they resorted to memorization of individual words. When memorizing, the individual appendages proved to be particularly useful to learners, as it enabled them to create a kind of memory trigger based on some connection between the appendage and the signal. For example, one participant commented that he was able to recall the signal for the red striped circle (Fig. 4.7) because both the appendage and the signal, *hikipilu*, reminded him of a caterpillar.

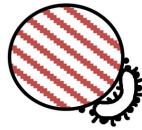


Fig. 4.7 *hikipilu*, the caterpillar.

While this was not the main focus of my study, comments and responses in the exit questionnaire indicate that this is a significant learning strategy, and plays a big part in *remembering*. The graph in Fig. 4.8 shows that unique markers improve the ability of learners to remember more and more accurately.

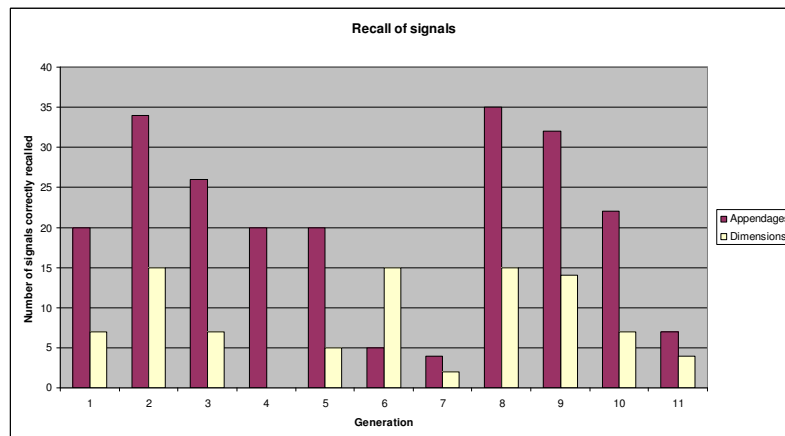


Fig. 4.8 The results of the exit questionnaire. The appendages and the dimension aspect of the meanings (shape, colour, texture) were printed separately, and participants in the LearnOnly and LearnPlusUse conditions were asked to write the word for each image. The Wilcoxon Signed-ranks test confirms that participants were significantly more likely to recall words correctly when shown the appendages ($Z=3.304$, $p=.001$).

4.4.3 Summary

In this condition we can see the language being pulled to and fro in response to individual learning preferences. Competition between systems is apparent, as one learner notices a rule that guides certain associations and extends it to other associations, disrupting the rule systems of previous generations. The inconsistency and complexity of mappings results in weak and unconvincing patterns, making the language vulnerable to the preferences of individual learners. This meant that when structure did emerge it was unable to be maintained.

4.5 The LearnPlusUse Condition

4.5.1 The failure to develop compositionality

A striking result was that the languages in this condition became somewhat underspecified. Furthermore, there is no obvious compositional structure so it appears that the increase in structure in this chain is due to systematicity in the pattern of underspecification, not compositionality. However, it should be noted that these languages do not resemble the languages seen in the LearnOnly condition. The LearnPlusUse languages show a great deal more variety, with a higher total number of words and a number of recurring elements – which could be loosely classified as morphemes – such as *lem-*, *lum-*, *nepa-*, and *-kilo* scattered across the signal space (seen in the language of generation 10, shown in Fig. 4.9). Furthermore, the *forms* of the signals undergo significant change between generations, unlike the signals in the LearnOnly languages.

Generation 10				
	BLUE	RED	YELLOW	
block	lane	lumule	lumuki	●
	nehule	lepaki	nepakiki	■
	nekilo	ne	lupakilo	▲
stripe	lemule	nepaki	nepaki	●
	lemaki	nepaki	nepaki	■
	lupakiki	lumapaki	nehume	▲
check	lamaki	nepikaki	lumaki	●
	lumakiki	nepakiki	nekilo	■
	lumule	nepaki	lumakilo	▲

Fig. 4.9 The output language from generation 10.

It appears that one way that speakers in the LearnPlusUse condition balance the pressures of learning and disambiguation is by creating word ‘families’ – groups of similar words that vary in one or two elements. This is seen in the signals *lemaki*, *lamaki*, *lumuki* and *lumaki* in generation 10. Thus, memory demands are reduced by keeping the words similar, but individuality is maintained by changing one of the letters. Note, however, that this does not necessarily result in structure, either in terms of systematic underspecification or compositionality. In this language, the basic frame *l_m_ki* could possibly refer to CIRCLE-ness, but this is undermined by *lemaki*, which refers to a square. In terms of the differentiating elements, the vowels, there is no clear relationship between a particular vowel and a particular meaning value.

The LearnPlusUse languages face a similar problem as the LearnOnly languages, in that the complexity of the competing patterns seems to make it difficult for compositional structure to be developed or maintained, as seen in generations 5, 6 (Fig. 4.10) and 7 (Fig. 4.11) below.

Generation 5					Generation 6				
	BLUE	RED	YELLOW			BLUE	RED	YELLOW	
block	lane	lapiki	lapiki	●	block	lane	lapiki	lumu	●
	kakaluna	nenane	lumumola	■		lakimo	lapiki	lumunepaki	■
	lane	kakaniko	pikahu	▲		lakilo	ne	lumumu	▲
stripe	lakimulo	kapila	lapiki	●	stripe	lakilumo	pikilomo	lakimulo	●
	piki	ne	pikihulo	■		lakimulo	lipaki	nepake	■
	kakanipiki	lakihi	lumuholu	▲		lakipi	pikilo	lumumu	▲
check	kakaluna	lumumulo	lumumulo	●	check	lakahulo	lumumulo	lumumulo	●
	lakimulo	lumumula	lumumulo	■		lakahulo	pikilomo	lumumulo	■
	lakihi	napiki	lumumulo	▲		lakimulo	napiki	lumumupiki	▲

Fig. 4.10 Generation 5 and 6 of the LearnPlusUse chain. The learner in generation 6 exploited underspecification patterns to introduce the beginnings of a compositional system.

The beginnings of a compositional system are seen in the output of generation 6. The language of generation 5 shows a degree of underspecification, with, for example, *lakimulo* identifying both blue check circles and blue striped squares, and *lumumulo/a* mapping to several different red and yellow meanings. The learner in generation 6 noticed this underspecification, and extended it in a more

systematic fashion. She was then able to lever off this to create a degree of compositionality. For example, the generation 6 learner observed that *lakimulo* referred to two blue objects, and extended the signal to a number of other blue meanings. However, instead of complete underspecification, several of the meanings are differentiated by combining the first part of the signal – *laki* – with different endings, including *-lo*, *-mo*, *-lumo*, *-mulo*, *-pi*, and *-bulo*. It is unclear where these endings come from – although they are present in other parts of the language there is no obvious link to other signals or other meanings. Similarly, this learner noticed an element of systematicity in the underspecification of *lumumulo* in generation 5, and took a part of this word – in this case *lumu-* and *lumumu-* – and extended it to encompass most of the yellow meanings. Thus it appears that while the presence of inconsistent and random underspecified signals may inhibit the development of systematicity by creating confusion, in some cases underspecification can actually act as a launching pad for the development of compositionality.

While this pattern is fairly extensive, it still comes down to two rules; one which maps *laki-* to (most) blue meanings³, and one which (mostly) maps *lumu-* to yellow meanings. Apart from these two rules, there is not a great deal of regularity in the language. Furthermore, there is little consistency in the way that these ‘prefixes’ are combined with other elements. This combination of underspecification and half-efficient compositionality, combined with some exceptions that disrupt general rules means that it is still difficult for learners to uncover patterns. The fragility of the system can be seen as the next participant introduces new rules which destroy the systematic colour mappings of generation 6. Instead of referring to YELLOW, *lumu-* has spread across to another red striped item. Similarly, the fact that *lakimulo* refers to the yellow striped circle, which made it an exception in generation 6’s system, has been noted by the learner in generation 7 and has perhaps caused him to extend this signal to the yellow block circle. This signal now shows a close relationship to that of the other yellow circles, *lakimulo* and *lumumule*. However, it means that the *laki-* and *lumu-* elements are spread throughout the language. Any potential for the compositional elements which emerged in generation 6 to be clarified and extended has been lost.

³ However, it should be noted that English segmentation patterns may have lead to difficulty in recognising compositional aspects for the learner in generation 7, as words like *lakilo* may be read as *la-kilo* instead of *laki-lo*.

Generation 7				
	BLUE	RED	YELLOW	
block	lane	lupaki	lakimule	●
	nepiki	lepaki	lumupakiki	■
	lakilo	ne	lumu	▲
stripe	lakilule	lumapiki	lakimulo	●
	lumaki	lepaki	nepaki	■
	lakipi	pikilo	lumu	▲
check	lakahula	lumumu	lumumule	●
	lakahule	lumumule	pikilo	■
	lumule	nepaki	nepakiki	▲

(Fig. 4.11)

4.5.2 The unusual distribution of underspecification

A final point that needs explanation is the rise of underspecification in this chain. Surely the communicative task should provide a pressure for signals to be distinctive – that is capable of identifying the speaker’s intended meaning? Furthermore, if we look at the *distribution* of homonyms across the languages, we see an odd pattern starting to develop. While the initial, randomly-generated language has a fairly even distribution of unique words and signals mapping to two or three meanings, the distribution in the final generations is quite different – languages in the later stages of the chain are mostly idiosyncratic, with a few large groups of homonyms (Fig. 4.12). There are very few words with two or three homonyms, but by generation 11 there are two groups of homonyms with five items each. What can explain this pattern?

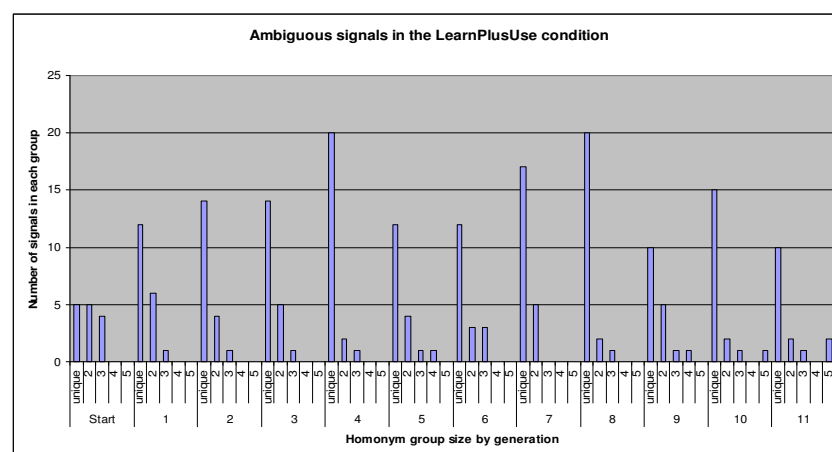


Fig. 4.12 The distribution of homonyms in the LearnPlusUse languages. The x-axis shows the size of the groups; the y-axis shows the number of signals in each group-size.

Here it is important to remember that the confounders that appear with each target are drawn from a pre-specified and fixed context set. That is, when a meaning is targeted, it will only ever appear with a small selection of the meanings with which it shares feature values - although the meaning may, of course, be a confounder for other meanings. Nevertheless, the situations in which ambiguity is an issue are restricted and constant. Perhaps then, it is not surprising if the language adapts to the specific but stable environment in which it is used.

For example, one of the dominant homonyms in generations 10 and 11 is *nepaki* (see Fig. 4.9) which first arose in generation 7. An examination of the context sets for the *nepaki* signal reveals that in most cases, the ambiguous meanings did not co-occur, and there was thus no need to differentiate between them. This meant that the signals were able to spread to these meanings in an underspecified fashion. It appears, then, that the language may actually be adapting to the context sets which make up the environment in which it is used, by avoiding homonyms when meanings need to be distinguished from each other, but allowing ambiguity when there is no such pressure. However, it should be emphasized that this is based more on my impressions than any hard data, and it is certainly not true that users never used underspecified signals when there was ambiguity in the context. The possibility therefore remains that what I have seen as a tendency is mere coincidence.

4.5.3 Summary

The LearnPlusUse chain is plagued by the same problems of inconsistency and competition that were seen in the LearnOnly condition. This has made it difficult for compositional structure to develop, and where it did emerge, it was quickly lost. However, the language did adapt to be easier to learn by taking advantage of gaps in the context sets, and becoming systematically underspecified.

CHAPTER FIVE

General Discussion

To review the situation, it is theorized that compositionality arises because of the interacting pressures for language to be learnable, as it must survive the transmission process, and to be expressive so that it can reliably convey the speaker's meaning during communication, perhaps aided by a genetically specified preference for one-to-one mappings. Results from computer simulations and human diffusion chains provide good evidence for the importance of the learnability pressure, showing that compositionality reliably emerges when the learner does not have perfect access to the entire language at any stage during the learning and production process. However, less is known about the expressivity pressure and exactly how it manifests through communication. In fact, no studies have actually used a communicative situation between human participants to confirm that it is, in fact, the interaction of learning and the drive to specify intentions that leads, through cultural evolution, to compositionality.

Previous experiments have shown that compositionality does arise when the expressivity pressure is artificially imposed. This study aimed to show that it also arises under a more realistic communication condition which involves the coordination of intentions between a speaker and receiver. Although the LearnPlusUse language showed an increase in overall structure, and although compositional elements emerged sporadically and briefly, the experiment failed to produce a stable compositional language.

However, I do not believe that this negates the basic assumption that one of the main causes of compositionality is expressivity, and that the expressivity pressure is, in turn, driven by the need to reliably identify meanings in communication. Rather, I suggest that a number of factors in the experimental design may have led to the unusual development of the LearnPlusUse language.

5.1 Factors which contribute to the lack of compositionality

The most significant factor appears to be the state of the initial language, as this inhibited the exploitation of regularities in mapping and therefore made it difficult for any kind of system to get off the ground. Although the initial language was random, it also contained homonyms, which made it different from the random languages used in other experiments. Because the Mantel Test is a blunt measure of structure, it is unable to distinguish between compositionality and systematic underspecification. It is therefore unclear how the z-score of 0.1 for the initial language related to the distribution of homonyms (Fig. 5.1). In fact, it is evident that there was a degree of randomness in the allocation of homonyms to meanings. Although there was certainly some overlap in meanings represented by the same signal, there were also odd pairings or pairings which disrupted potential patterns. This meant that although there were some regularities in the language, these patterns were inconsistent and complex, and therefore less noticeable and/or vulnerable to counter-evidence. In languages where structure arises through cultural evolution, this kind of inconsistency is less prevalent, and patterns are more easily accessible to observers.

		initial language			
		BLUE	RED	YELLOW	
block		kakaluka	piki	lupila	●
		hukipi	nenane	nakihu	■
		lane	lahumolu	pikaluka	▲
stripe		pinaki	nehupilu	lahumolu	●
		piki	hukipi	lupila	■
		molalu	<i>lulaka</i>	pikaluka	▲
check		lupila	nenane	<i>lulaka</i>	●
		piki	nakihu	kina	■
		kakaluka	nakihu	<i>lulaka</i>	▲

Fig. 5.1 The initial language. There are a number of homonyms in the language. All the mappings to *lulaka* are shown in italics; while the use of *lulaka* to represent the yellow check circle and the yellow check triangle shows a tentative pattern, the association of *lulaka* with the red striped triangle is inconsistent.

By giving the participants an initial language with homonyms that were randomly allocated to meanings, it seemed to be very confusing for learners who were trying to find patterns. Because it is unlikely that two words should randomly occur in exactly the same form, learners often assumed that there was a reason for this similarity. They therefore had an *a priori* expectation that there was regularity between the allocation of homonyms and the structure in the meaning space. Thus, any inconsistency in these allocations made it difficult for the learner to find an adequate hypothesis, as the inconsistency provided counter-evidence to any patterns that they noted. In contrast, where a language is random but has no homonyms, the randomness must refer to substring mappings – particularly the distribution of single phonemes or characters across the language. It is reasonable to assume that in such languages inconsistency in phonemes is likely to be seen as random, rather than providing counter-evidence to the learners' hypotheses. Thus, it is asserted that inconsistency in the allocation of homonyms to meanings impeded the development of structure as it discouraged learners from taking advantage of any regular patterns.

While it is true that competition between signals, rules or perceptual categories is prevalent in studies of cultural evolution (Brighton et al. (2005); Cornish et al., 2009; Matthews et al., 2010), I believe that the problem was exacerbated in this study by the high degree of inconsistency. That is, it is not a new problem, it is just more extreme. Furthermore, it actually seemed to be aggravated by the iterated learning process. Because the patterns were so weak, even when learners made the language more systematic this regularity was rarely strong enough to become highly salient and override other patterns. Therefore, each learner created their own system to make sense of the input, which added additional layers to the rule systems. The complexity of the mappings both encouraged and was exacerbated by individual differences, as learners showed preferences for rules relating to particular dimensions, or even different learning strategies.

The population structure – a single parent and single learner – may have contributed to the complexity of the language, as it made the systems more vulnerable to the preferences of individuals. It is tempting to speculate that languages may become more structured when learners are exposed to output from several parents, as it may iron out inconsistencies and help the language to converge more rapidly to systems based on general preferences. However, it is also possible that increasing the number of parents would only make the input more complex and more difficult for the learner to find regularities.

A number of other experimental conditions varied slightly between this and the experiments run by Cornish (2010), all of which may have affected the outcome. For example, my participants learnt the language by re-typing each label, whereas in Cornish's studies they were merely presented with label-image pairs. This may have led my participants to reproduce more accurate signal forms. On the other hand, my participants were exposed to each meaning-signal pair just four times during training, in contrast to Cornish's six times.

Finally, there is the possibility that there were just not enough iterations for compositionality to emerge. There was a slight increase in structure over time, so perhaps if the experiment were continued the language would eventually have reached a point where there was enough structure for one system of rules to dominate.

These issues do not affect the development of underspecification, but they do affect the development of structure. The final languages in the LearnOnly chain and the LearnPlusUse chain are both moving towards systematic underspecification. In the case of the LearnPlusUse chain, this underspecification appears in response to the particular way that the expressivity pressure is manifested – that is, signals mostly spread to new meanings that did not need to be distinguished because they never appeared in the same context. When differentiation was required, learners often addressed this need by changing single letters or inconsistently combining a limited number of morphemes.

So why did underspecified structure emerge rather than compositional structure? One possibility is that it is easier for regularity to arise from underspecification. Underspecification involves a process of simplification, and this simplification is likely to remove at least some inconsistent mappings. Thus, regular mappings are more likely to gain a toe-hold in an underspecified system. Interestingly, in the few cases where compositional elements did arise it appeared that underspecification actually provided a pathway to compositional systems. It seems that the underspecified rules may have drawn the learner's attention to some similarity in the meanings that the learner was then able to take advantage of.

5.2 Appendages and learning strategies

Earlier I noted that variation in individual preferences and abilities inhibited the development of structure, as each learner tended to pull the language in a new direction instead of extending the regular patterns already present in the language. In this respect, the addition of idiosyncratic appendages had a strong impact on the way that languages developed.

Language learning can be seen as an inductive problem (Chater & Christiansen, 2008), where each learner examines the input and generates hypotheses about the underlying systems of the language. By making generalisations, learners can condense the language and reduce the number of rules they need to remember. However, it appears that in this study the addition of appendages provided learners with the opportunity to follow a different learning strategy based on strict associative learning⁴ (Paivio, 1969). That is, the appendages acted as a memory aid in a process of memorization of word forms and individual mappings. Comments in the exit questionnaire indicate that people are using appendages in many ways, and often these were complementary to more systematic approaches – for example learners might use the appendages to help remember particular signal forms which they then started to spread systematically, or they might prefer a systematic strategy but use appendages to memorize inconsistent mappings. It is hard to make generalizations because there seemed to be a great deal of variation. However, it appears to be an important strategy for learners, and is definitely worth further investigation.

While this may be beneficial for individual learners, it hinders the accumulation of regularity through iterated learning. When learning is based on the structured aspect of the meaning space, each generation of learners is likely to make the same associations and see the same patterns (thereby strengthening the patterns of associations). In contrast, associative learning is highly subjective and the associations each learner makes are likely to be unique. Thus, as the language changes to reflect these associations, it may actually become more difficult for the next learner, as it draws the language away from a regular system. Another reason that associative learning might inhibit the development of structure is because it is too efficient – if it helps learners remember more accurately then it may reduce the chance of regularity arising because of random changes to letters or morphemes, or

⁴ Much of the literature uses the term associative learning in a broad sense. Here I use it to refer strictly to associations in the immediate context (i.e. the visual stimuli) that help learners memorize signals and mappings.

because of subconscious processes during recall. This also means that exceptions and inconsistencies can be highly stable, which makes other patterns weaker.

In addition, it is unclear how relevant this kind of learning is to the evolution of compositionality, given that child learners face a greater task than that seen here; that is, not only must they remember the signals and mappings of the language, but they must also determine the exact referent of a particular signal (Smith, Smith & Blythe, 2011; Quine, 1960). Because of this, and because of the huge number of words and meanings to be learnt in the real world, it is unlikely that children can rely on a simple memorization process. Instead, they appear to use some kind of guessing strategy when learning vocabulary, using past experiences to generate ideas about how the language fits together, and then evaluating the accumulated knowledge at each learning step to fine-tune their linguistic understanding (Yu et al., 2007). However, there is still a great deal to be learnt about how children learn language, and work by Rowland (2007) does suggest that the memorization of high-frequency chunks of language ‘protect(s) the child from error’ (Vogt & Lieven, 2010, p.23), as well as boot-strapping them into further linguistic development. So it is possible that such a learning strategy does play a role in language acquisition and therefore in the development of language overall.

5.3 Compositionality and expressivity

We already know that expressivity is a crucial element in the emergence of compositionality (Kirby et al., 2008), so what extra insights have been gained by separating out the communication aspect in the UseOnly condition? First of all, communication is often framed as a pressure *against* ambiguity, whereas this study reveals that it can also be seen as a pressure *for* compositionality because it enhances comprehension. In an ostensive-inferential communication system, such as human language (Grice, 1975), speakers must design their utterances in a way that will allow the particular audience, in the given context, to recognise the speaker’s meaning. This is termed ‘recipient design’ (de Ruiter et al., 2010). When the speakers in the UseOnly task were confronted with ambiguous signals, the only way that they could achieve immediate communicative success was by using the

given signal-meaning mappings to refer to particular dimensions of the intended meaning – that is, by using some sort of structure.

Just as compositionality benefits learners because it allows them to make generalisations about meaning-signal associations that they have not observed, so too does it allow receivers to make generalisations about the novel meaning-signal associations presented by the speaker. For example, imagine that a speaker is presented with the context shown in Fig. 5.2. The speaker must somehow signal that the blue striped triangle is the target. The dictionary label for the blue striped triangle is *kakaluka*, but unfortunately this also refers to the blue block circle. The two meanings are therefore the same colour, but differ in shape and texture.

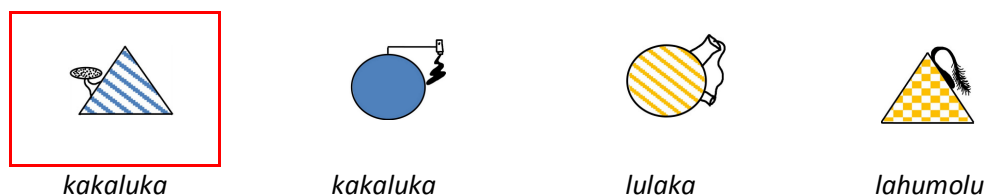


Fig. 5.2 An example of a context set that shows ambiguity.

To signal the target, the speaker could add a suffix to the actual signal, *kakaluka*. If the suffix is taken from the signal for a meaning that is similar in shape and texture, such as the red striped triangle, then this new signal would potentially allow the receiver to identify the target.

However speakers showed a limited motivation to use such strategies. Instead, most speakers created a linguistic system that referred to the context of the interaction, such as the order of presentation of the stimuli. This was mostly unsuccessful because the receivers tended to interpret the linguistic modifications of the speakers in relation to the structure of the meaning space – that is, they were expecting a compositional, or at least systematic, strategy. Speakers who did refer to the structure of the meaning space were unable to come up with an efficient method of creating signals that would allow the receiver to guess the target correctly, suggesting that it is a significant cognitive challenge to design an effective compositional system.

Although speakers in the UseOnly condition did not appeal to compositionality in their utterances, this is because the speakers misjudged the receivers' interpretation strategies, not because generalisation would not be beneficial. It would be interesting to see what would happen in a situation of two-way interaction, where the receiver has the opportunity to take on the role of speaker. In the Results section, I suggested that one of the reasons that speakers did not use the structure of the meaning space was because they were not paying a great deal of attention to the language. In contrast, the comments of the receivers indicate that the inferential process had made them more aware of the meaning-space in general, and encouraged them to think about ways of exploiting structure in the meaning-space to disambiguate signals. Thus, while *use* is not enough to prompt compositionality, the swapping of roles in two-way *interaction* may encourage speakers to develop an element of compositionality as a way of better aligning to the receiver's inferential strategies.

The results of the UseOnly condition highlight the role of recipient design in the communicative process and show how it generally fails to produce compositionality. This prompts us to think more carefully about how exactly generalisation occurs under the combined pressures of transmission and communication, and how it relates to the cognitive processes of the individuals involved. Recipient design alone did not lead to compositionality, but it clearly does play a part in the LearnPlusUse condition, because otherwise the language would have become underspecified (I am ignoring here the underspecification which arose where there was no pressure to disambiguate signals). So when compositionality arises in such situations, is it because the challenge of learning draws speakers' attention to structure in the mappings or in the meaning space, which the speaker is then willing to utilise when producing output for the receiver? Or is it just that the speaker restricts their tendency to underspecify, which allows other regularities to arise by chance? For example, in the LearnPlusUse condition in my study the language resisted underspecification in ambiguous contexts, but did reduce the number of morphemes under the learning pressure. Because of the problems in this chain, as outlined above, there was never enough of a system for these morphemes to be regularised by the next learners, but in a more stable, consistent language presumably this could happen.

5.4 Future directions

The tentative conclusions that I have drawn here provide ample opportunity for further research. For example, I believe that the random allocation of homonyms had an inhibitory effect on the emergence of regularity. The effects of homonym allocation could be investigated by running an experiment which maintains the three-way learning/testing/communication distinction, but has two chains in each condition. The chains would be seeded with a language with nine signals that map to three meanings each. One chain in each condition would have a language where these homonyms were allocated systematically, so that they mapped to meanings with two shared values. In the other chain, the homonyms would have an inconsistent distribution, so that the two of the identical words would map to a meaning with a shared value, but the third word would be allocated to a meaning with no shared values. I anticipate that the language with systematic distributions would reach stable regularity fairly quickly in the learning conditions, while the inconsistent language would struggle or never become stable.

As outlined above, I also believe that an interaction condition would provide valuable information about the effect of recipient design on the evolution of structure. The interactive condition would be run alongside the three conditions detailed in this study. Participants would take part in the communicative task, with the dictionary, but they would then swap roles, so that the receiver becomes the new speaker. The language for the next generation would be taken from the output of the second speaker.

CHAPTER SIX

Conclusion

The aim of this study was to explain a key feature of human language, compositional structure. While previous work has tended to focus on compositionality as an emergent property of iterated transmission, I wished to explore the role of the expressivity pressure by placing language in a communicative context. While the ILM has shown that compositionality can arise even when pragmatics and individual psychology are removed (Jäger & van Rooij, 2007), it cannot be denied that human cognition and the requirements of communication play a significant part in learning and production. Therefore I believe that it is also important to look at the way that real humans learn, and how they respond to the need to communicate successfully and unambiguously. By including an element of communication, this study has put the spot-light back on human behaviour, which has revealed some subtle and interesting details about the way that learning and expressivity pressures affect language.

This study looked at how language changed in response to three different conditions. In the first condition the language was used to convey meaning; in the second it had to be learnt. The language in the third condition was placed under both these pressures. The UseOnly condition led to the development of languages with unique signals, as expected. Unexpectedly, this condition also saw the emergence of some compositional strategies on the part of the speaker, highlighting the fact that compositionality is useful in any situation which requires generalisation. While the language in the LearnOnly and LearnPlusUse conditions did not develop as predicted, some interesting points have emerged from these results.

- The importance of the initial conditions is emphasized, as the state of the initial language proved to be a barrier to the development of structure in the languages.
- This points to a need for a deeper understanding of randomness and structure in language. In particular, the random allocation of homonyms seemed to have an unusual effect on the language.

- The emergence of compositionality through cultural evolution relies, both theoretically and in actuality, on an inductive process of language learning. However, my study suggests that there are alternative strategies open to language learners, which may influence the way that the language develops.

These findings leave us with many questions about how aspects of human cognition, such as human learning preferences, influence the way in which structure emerges in human communication systems. For example, the extent to which children might use associative learning, and under what conditions, is unclear. Furthermore, little is known about how the associative and hypothesis-based strategies interact and what implications this would have on the degree of systematicity, idiosyncrasy and irregularity in the language.

By framing compositionality as a response to a need for generalisation, this brings the focus back to questions about where exactly this occurs in the process of transmission from the E-language to the I-language and back. A pressure to generalise can occur for several different reasons:

- 1) When learners are presented with incomplete data they can use generalisation to recover mappings that were not observed.
- 2) When confronted with a great deal of linguistic data, generalisation can make learning easier by reducing the number of rules to be remembered.
- 3) During production a speaker may find that they are unable to remember the language accurately and may generalise from forms, meanings and mappings that they *can* remember.
- 4) Finally, generalisation is also useful in communication, as it allows a listener to reconstruct the speaker's meaning in the face of ambiguity in signal-meaning mappings.

Therefore, we need to know more about how the various linguistic, learning, and communicative environments apply pressure for generalisation at the various points, how they interact together, and what specific effects they may have on language.

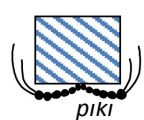
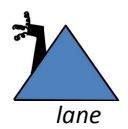
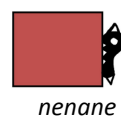
Finally, languages in the learning conditions were characterised by an extremely high degree of competition, leading to their instability. However, as Brighton et al. (2005) point out, competing systems of regularity are, in fact, common in natural languages. How, then, do learners of natural language cope with this competition? Perhaps children are better at reconciling inconsistent rules, or

perhaps it is just because they are exposed to a far greater set of input data, which allows them to notice and track different systems.

As a pilot, this study has perhaps raised more questions than it has answered. However, it confirms that the attempt to identify meanings in communication does lead to the development of expressivity in language, even if communication is not always successful. This brings attention to the role of the speaker in developing compositionality through the process of recipient design. Furthermore, this study affirms the power of evolutionary processes in shaping language, as the languages in this study have responded in particular ways to the specific pressures and constraints placed upon them.

APPENDIX A

The initial language



APPENDIX B

Instructions to subjects

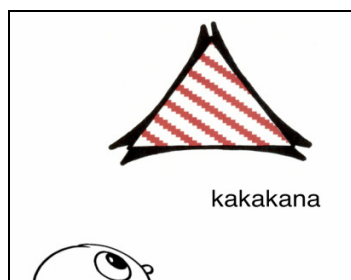
The following pages were given to the participants in the relevant conditions.

Condition 1 Instructions

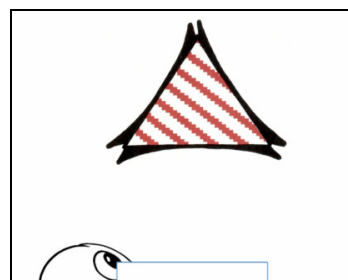
Scientists at the University of Edinburgh have recently discovered intelligent alien life-forms from the distant galaxy of Centaurus A. The aliens seem friendly and interested in making contact with humans, but do not speak any human languages. We are offering you the opportunity to learn something about the aliens' own language so that you can communicate with them.

You will be shown some images, and the words that the aliens use to describe those images. When the label disappears, you will need to write the word, as you remember it, in the box on the screen.

Step 1. A picture and the alien label.



Step 2. Write the alien label in the box.



You will have four training rounds, during which you need to learn the labels as best you can. The aliens will then give you a test to see how you are getting on. In the test, you will be shown an image and asked for the label that you think the aliens would use to describe it. Write the label in the box.

Don't worry if this is very difficult. Just make sure you answer every question. The aliens are very friendly and understanding, and they don't mind if you make a mistake as long as they can see that you are making an effort.

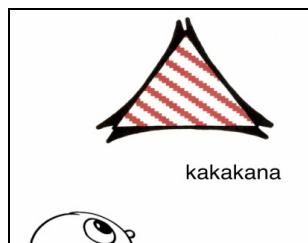
Good luck and have fun!

Condition 2A Instructions

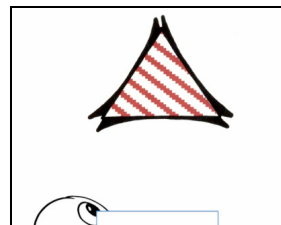
Scientists at the University of Edinburgh have recently discovered intelligent alien life-forms from the distant galaxy of Centaurus A. The aliens seem friendly and interested in making contact with humans, but do not speak any human languages. We are offering you the opportunity to learn something about the aliens' own language so that you can communicate with them.

You will be shown some images, and the words that the aliens use to describe those images. When the label disappears, you will need to write the word, as you remember it, in the box on the screen.

Step 1. A picture and the alien label.

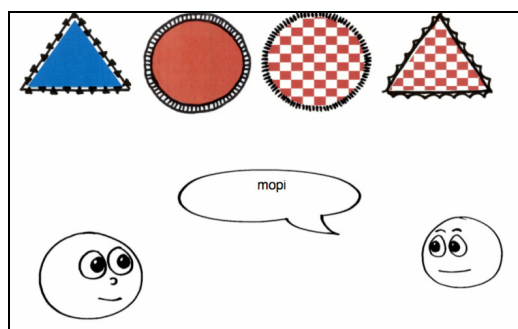


Step 2. Write the alien label in the box.



You will have four training rounds. You will then have the opportunity to communicate with an alien through the computer. This time, you will see four images on the screen, and the alien will write a word. You have to click on the image that you think the alien is describing. If you choose the correct image, you will see a smiley face. If you choose the wrong image, you will see a sad face.

Step 3. Choose the correct image



Don't worry if this is very difficult. The aliens are very friendly and understanding, and they don't mind if you make a mistake as long as they can see that you are making an effort.

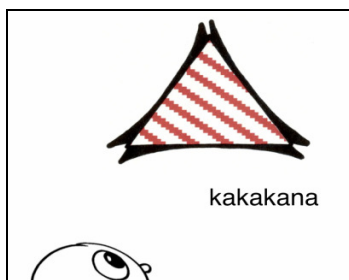
Good luck and have fun!

Condition 2B Instructions

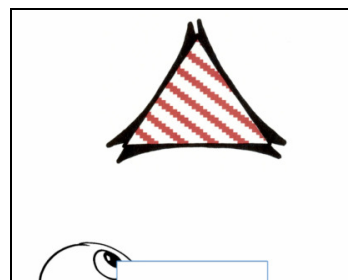
Scientists at the University of Edinburgh have recently discovered intelligent alien life-forms from the distant galaxy of Centaurus A. The aliens seem friendly and interested in making contact with humans, but do not speak any human languages. We are offering you the opportunity to learn something about the aliens' own language so that you can communicate with them.

You will be shown some images, and the words that the aliens use to describe those images. When the label disappears, you will need to write the word, as you remember it, in the box on the screen.

Step 1. A picture and the alien label.

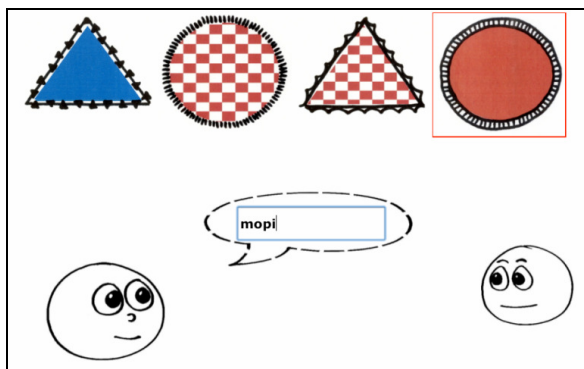


Step 2. Write the alien label in the box.



You will have four training rounds. You will then have the opportunity to communicate with an alien through the computer. This time, you will see four images on the screen. One of the images will have a box around it. The alien will also see these four images, but doesn't know which one is selected. You need to write the word describing this image so that the alien can choose the best one. If the alien chooses the correct image, you will see a smiley face. If the alien chooses the wrong image, you will see a sad face.

Step 3. Write the label in the box.



Don't worry if this is very difficult. The aliens are very friendly and they will do their best to understand you.

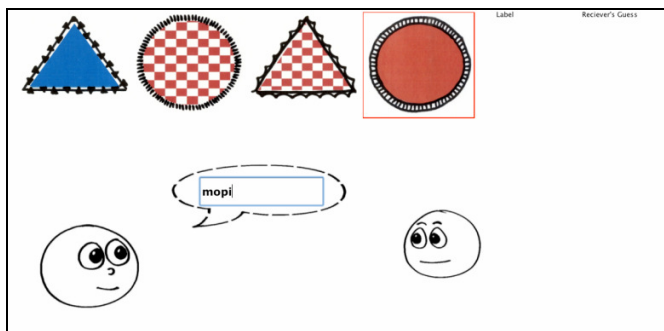
Good luck and have fun!

Condition 3A Instructions

Scientists at the University of Edinburgh have recently discovered intelligent alien life-forms from the distant galaxy of Centaurus A. The aliens seem friendly and interested in making contact with humans, but **do not speak any human languages**. Luckily, we have already started making a dictionary for some of the words in the alien's language.

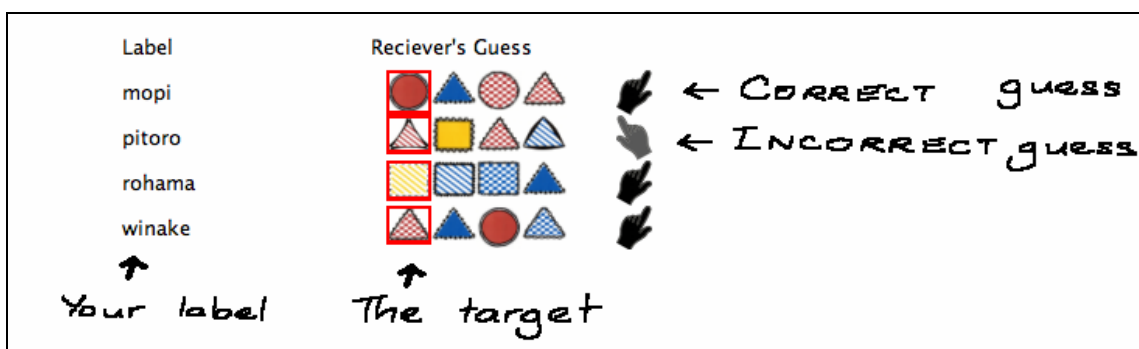
You will have the opportunity to communicate with an alien, using the information in the dictionary. You will see four images on the screen, and one of the images will have a box around it. The alien will also see these four images, but it doesn't know which one is selected. You need to write the word describing this image so that the alien can choose the correct one. If the alien chooses the correct image, you will see a smiley face. If it chooses the wrong image, you will see a sad face.

Step 1. Write the label in the box.



To help you remember which words you have used and what the alien guessed, you will be able to see a history of your interaction. This includes a list of the words you have written, the target image with a box around it, and whether the alien's response was correct.

Close-up of the interaction history



If you wish to make changes to the dictionary, we just ask you to update your dictionary using the pencil provided.

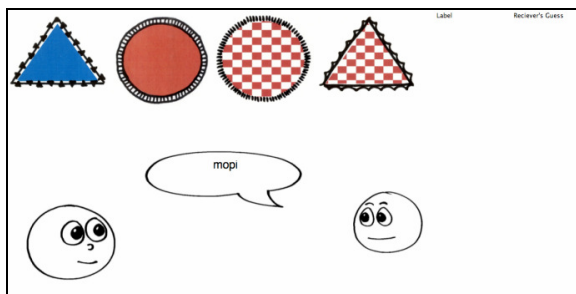
Good luck and have fun!

Condition 3B Instructions

Scientists at the University of Edinburgh have recently discovered intelligent alien life-forms from the distant galaxy of Centaurus A. The aliens seem friendly and interested in making contact with humans, but **do not speak any human languages**. Luckily, we have already started making a dictionary for some of the words in the alien's language.

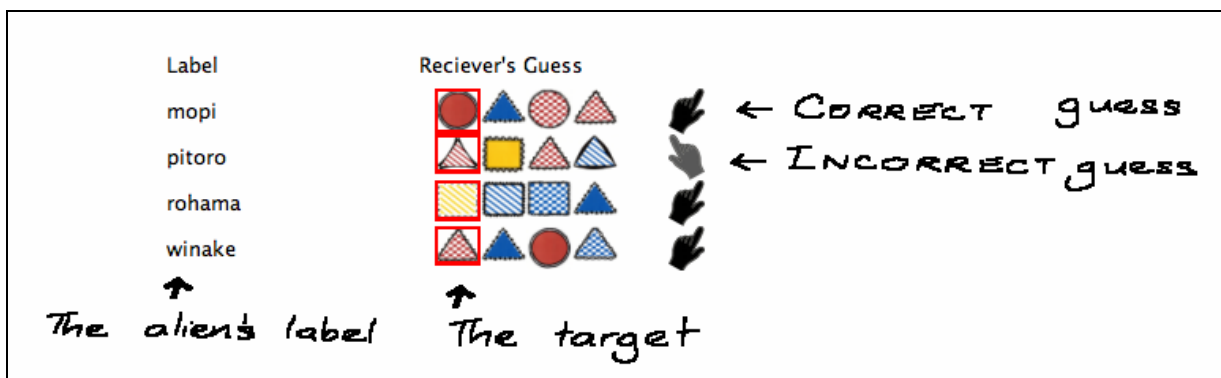
You will have the opportunity to communicate with an alien, using the information in the dictionary. You will see four images on the screen, and the alien will write a word. You have to click on the image that you think the alien is describing. If you choose the correct image, you will see a smiley face. If you choose the wrong image, you will see a sad face.

Step 1. Choose the correct image



To help you remember which of your guesses were correct, you will be able to see a history of your interaction. This includes a list of the words you have seen, the target image with a box around it, and whether your response was correct.

Close-up of the interaction history.



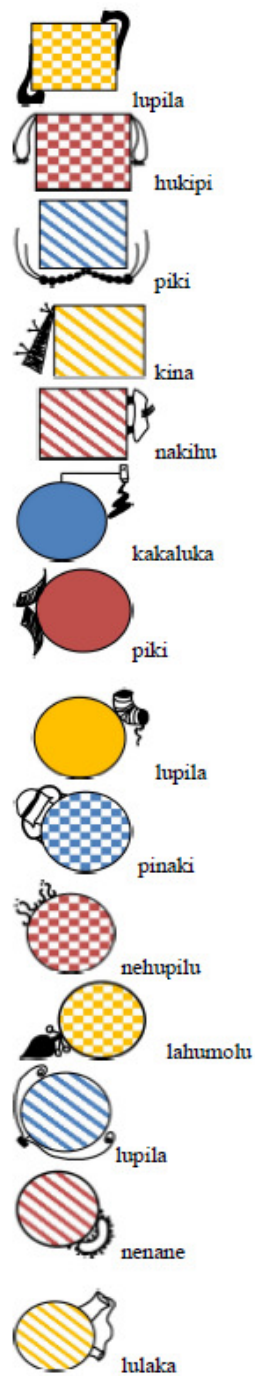
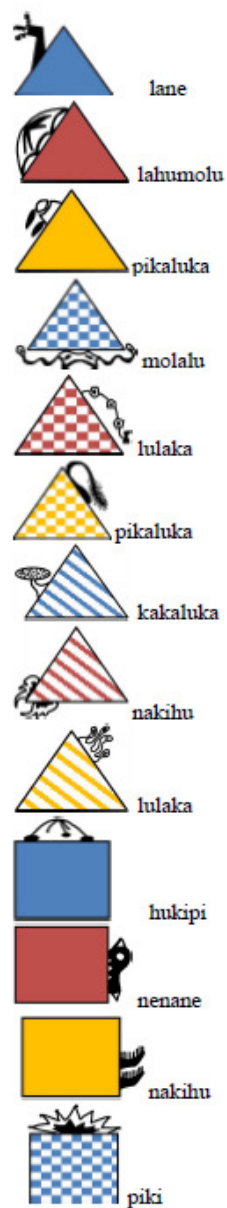
If you wish to make changes to the dictionary, we just ask you to update your dictionary using the pencil provided.

Good luck and have fun!

APPENDIX C

Dictionary for UseOnly condition

Centaurean Dictionary



APPENDIX D: The Language Families

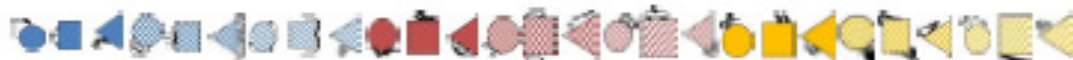
LearnPlusUse languages

Start	LPU1	LPU2	LPU3	LPU4	LPU5	LPU6	LPU7	LPU8	LPU9	LPU10	LPU11
kakaluka	kakaluna	kakaluna	lane	lane	lane	lane	lane	lane	lane	lane	lane
hukipi	hukipi	hukipi	kakaluna	kakalu	kakaluna	lakimo	nepiki	nepiki	nehule	nehule	nehule
lane	lane	lane	lane	lane	lane	lakilo	nekilo	nekilo	nekilo	nekilo	nekilo
pinaki	pinaki	pinaluka	lapiki	lakimulo	lakimulo	lakilumo	lemule	lemule	lemule	lemule	lemule
piki	kina	lupila	piki	piki	piki	lakimulo	lumaki	lumaki	lumaki	lumaki	nepikaki
molalu	nakihi	nakihi	lakihu	lakipu	kakanipiki	lakipi	lakipi	lumumaki	lumakiki	lumakiki	nekiki
lupila	lupila	lupila	kakaluna	kakaluna	kakaluna	lakhulo	lakhulo	lahula	lahula	lamaki	lamaki
piki	piki	piki	lakipu	lakimula	lakimulo	lakhulo	lakhule	nepakiki	lumumaki	lumakiki	lumaki
kakaluka	nakihi	nakihi	nakihi	lakihu	lakihu	lakimulo	lumule	lumule	lemule	lumule	lemule
piki	piki	piki	piki	lapiki	lapiki	lapiki	lupaki	lumule	lumule	lumule	lumule
nenane	nenane	nenane	nanene	nenane	nenane	lapiki	lepaki	lepaki	lepaki	lepaki	lepaki
lahumolu	pikiluna	pikiluna	pikiluna	lakipiki	kakaniko	ne	ne	ne	ne	ne	ne
nehupilu	nehuluka	nehuluka	kapila	kapila	kapila	pikilomo	lumapiki	nepiki	nepakilo	nepaki	nepaki
hukipi	lulaka	lulaka	nanene	ne	ne	lipaki	lepaki	lepaki	nepaki	nepaki	nepikaki
lulaka	kakaluha	kakaluha	nanepilu	lakihu	lakihu	pikilo	pikilo	nepakilo	lumakiki	lumapaki	lumapak
nenane	nenane	nenane	kakaluna	lumuholu	lumumulo	lumumulo	lumumu	lumumule	nepakiki	nepakiki	lamaki
nakihi	ne	ne	ne	lumoholu	lumumula	pikilomo	lumumule	lumumule	nepakiki	nepakiki	lumaki
nakihi	nakila	nakila	kakanene	napiki	napiki	napiki	nepaki	nepaki	nepaki	nepaki	nepaki
lupila	kina	kina	lupiki	lapiki	lapiki	lumumu	lakimule	lumupiki	lumaki	lumaki	lumaki
nakihi	luhumolu	luhumolu	luhumolu	lumumola	lumumola	lumunepaki	lumupakiki	lumapakiki	nepakiki	nepakiki	nepakiki
pikaluka	pikahu	pikahu	pikahu	pikahu	pikahu	lumumu	lumumu	lumumu	lumakilo	lumakilo	lumakilo
lahumolu	luhamolu	luhamolu	piluha	lapiki	lapiki	lakimulo	lakimulo	nepaki	nepaki	nepaki	nepaki
lupila	lupila	lupila	lahumolu	pikimulo	pikihulo	nepake	nepaki	nepaki	nepaki	nepaki	nepakiki
pikaluka	lupila	lupila	lapilu	lumuhulu	lumuholu	lumumu	lumumu	lakhule	nehule	nehume	nehume
lulaka	hukipi	hukipi	lupiki	pikiluna	lumumulo	lumumulo	lumumule	luhule	lahule	lumaki	nepaki
kina	lohumolu	lohumolu	luhumolu	lumumolu	lumumulo	lumumulo	pikilo	lekilo	nekilo	nekilo	nepakiki
lulaka	lulaka	lupila	kapilu	lakimolu	lumumulo	lumumupiki	nepakiki	nehule	lepakilo	lumakilo	lumule



APPENDIX D: The Language Families
LearnOnly languages

Start	L01	L02	L03	L04	L05	L06	L07	L08	L09	L010
kakaluka	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane
hukipi	lupila	nenane	nenane	nenane	nenane	nenane	hikipilu	hikipilu	nenane	nenane
lane	lane	lane	lane	lane	lane	lane	lane	lane	lane	lane
pinaki	nenane	nenane	nenane	nenane	nenane	kipilu	nenane	nenane	nenane	hikipilu
piki	piki	piku	nenane	nenane	kipi	kipilu	nenane	nenane	nenane	nenane
molalu	hukipi	hikipu	hikipu	hikipu	kipi	kipi	nenane	nenane	nenane	nenane
lupila	lupila	lupilu	lupilu	hikupilu	hikipilu	kipilu	piki	piki	piki	lane
piki	piki	piki	piki	piki	kipi	kipilu	lane	lane	lane	lane
kakaluka	kakahilu	kikipilu	kikipilu	kikipu	kipilu	kipi	hikipilu	hikipilu	hikipilu	hikipilu
piki	piki	piku	piku	piku	piki	piki	piki	piki	piki	piki
nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane	lane
lahumolu	nehupilu	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane	hikipilu
nehupilu	kipi	kipi	kipi	kipi	hikipilu	hikipilu	hikipilu	hikipilu	hikipilu	nenane
hukipi	hukipi	kipi	kipi	kipi	hikipilu	hikipilu	lane	lane	lane	hikipiul
lulaka	nehupilu	nenane	nenane	nenane	nenane	hikipilu	piki	piki	piki	hikipilu
nenane	nenane	kipi	nenane	nenane	nenane	hikipilu	hikipilu	hikipilu	hikipilu	nenane
nakiu	nehupilu	hikupilu	hikupilu	hikupilu	hikipilu	hikipilu	hikipilu	hikipilu	hikipilu	hikipilu
nakiu	nehupilu	hikupilu	kipi	kipi	kipilu	hikipilu	hikipilu	hikipilu	hikipilu	hikipilu
lupila	hukipi	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane
nakiu	piki	piki	piki	piki	kipi	kipi	lane	lane	lane	lane
pikaluka	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane	nenane
lahumolu	nenane	nenane	nenane	nenane	hikipilu	hikipilu	hikipilu	hikipilu	hikipilu	hikipilu
lupila	nehupilu	nenane	nenane	nenane	nenane	nenane	hikipilu	hikipilu	hikipilu	hikipilu
pikaluka	hukipi	hikipu	hikipu	hikupilu	hikipilu	hikipilu	nenane	nenane	nenane	hikipilu
lulaka	kipi	kipi	kipi	kipi	hikipilu	hikipilu	piki	piki	nenane	hikipilu
kina	kina	kinu	kinu	kinu	nenane	nenane	hikipiul	hikipiul	hikipiul	hikipiul
lulaka	nenane	hikipilu	hikupilu	kipilu	hikipilu	hikipiul	hikipilu	hikipilu	hikipilu	hikipilu



APPENDIX D: The Language Families

UseOnly languages

Start	U01	U02	U03	U04
kakaluka	kakaluka	bkakaluka	bkakaluka	bkakaluka
hukipi	hukipi	ahukipi	ahukipi	ahukipi
lane	lane	lane	lane	lane
pinaki	pinaki	pinaki	pinaki	pinaki
piki	piki	*pikiblueth	piki	piki
molalu	molalu	molalu	molalu	molalu
lupila	lupila	clupila	clupila	clupila
piki	piki	bpiki	bpiki	bpiki
kakaluka	kakaluka	akakaluka	akakaluka	akakaluka
piki	piki	*pikiround	piki	piki
nenane	nenane	*rednenane	nenane	nenane
lahumolu	lahumolu	alahumolu	alahumolu	alahumolu
nehupilu	nehupilu	nehupilu	nehupilu	nehupilu
hukipi	hukipi	bhukipi	bhukipi	bhukipi
lulaka	lulaka	alulaka	alulaka	alulaka
nenane	nenane	bnenane	bnenane	bnenane
nakihu	nakihu	cnakihu	nakihu	nakihu
nakihu	nakihu	*nakihured	nakihu	nakihu
lupila	lupila	blupila	blupila	blupila
nakihu	nakihu	bnakihu	bnakihu	bnakihu
pikaluka	pikaluka	pikaluka	pikaluka	pikaluka
lahumolu	lahumolu	lahumolu	lahumolu	lahumolu
lupila	lupila	alupila	alupila	alupila
pikaluka	pikaluka	bpikaluka	bpikaluka	bpikaluka
lulaka	lulaka	blulaka	blulaka	blulaka
kina	kina	kina	kina	kina
lulaka	lulaka	blulaka	blulaka	blulaka

Start	U05	U06	U08	U09
kakaluka	kakaluka	kakaluka	kakaluka	kakaluka
hukipi	hukipi	hukipi	hukipi	hukipi
lane	lane	lane	lane	lane
pinaki	pinaki	pinaki	pinaki	pinaki
piki	piki	piki	piki	piki
molalu	molalu	molalu	molalu	molalu
lupila	lupila	lupila	lupila	lupila
piki	piki	piki	piki	piki
kakaluka	kakaluka	kakaluka	kakaluka	kakaluka
piki	piki	nakihu	nakihu	nakihu
nenane	nenane	nenane	nenane	nenane
lahumolu	lahumolu	lahumolu	lahumolu	lahumolu
nehupilu	nehupilu	nehupilu	nehupilu	nehupilu
hukipi	hukipi	hukipi	hukipi	hukipu
lulaka	lulaka	lulaka	lulaka	lulaka
nenane	nenanee	nenanee	nenanee	nenanee
nakihu	nakihu	nakihu	nakihu	nakihula
nakihu	nakihu	nakihu	nakihu	nakihu
lupila	lupila	lupila	lupila	lupila
nakihu	nakihu	nakihu	nakihu	nakihu
pikaluka	pikaluka	pikaluka	pikaluka	pikalukaa
lahumolu	lahumolu	lahumolu	lahumolu	lahumolu
lupila	lupila	lupila	hukipi	hukipi
pikaluka	pikaluka	pikaluka	pikaluka	pikaluka
lulaka	lulaka	lulaka	lulaka	lulaki
kina	kina	kina	kina	kina
lulaka	lulakaa	lulakaa	lulakaa	lulakaa

Start	U07
kakaluka	kakalukaqwe
hukipi	hukipioop
lane	lane
pinaki	pinaki
piki	piki
molalu	molalu
lupila	lupiloioop
piki	pikivbn
kakaluka	kakaluka
piki	pikiqwe
nenane	nenane
lahumolu	lahumoluasd
nehupilu	nehupilu
hukipi	hukipi
lulaka	lulaka
nenane	nenaneqwe
nakihu	nakihuvbn
nakihu	nakihu
lupila	lupila
nakihu	nakihughj
pikaluka	pikaluka
lahumolu	lahumolu
lupila	lupilazxc
pikaluka	pikalukajkl
lulaka	lulakaqwe
kina	kina
lulaka	lulakaasd

APPENDIX E

Exit questionnaires

The participants in the LearnOnly and LearnPlusUse conditions were given the following questionnaire.

Follow-up Questionnaire

Participant number:

1. Male / Female (please circle)

2. Age:

3. Languages spoken:

4. On a scale of 1 (very easy) to 5 (very difficult), how did you find the alien language?

5. How did you memorise the words or word/picture pairs?

6. Did you find that the language changed over the experiment? How?

7. Any other comments?

9. Can you remember the alien word to describe these images? Please write the word below the image.

 _____	 _____	 _____	 _____
 _____	 _____	 _____	 _____
 _____	 _____	 _____	 _____
 _____	 _____	 _____	 _____
 _____	 _____	 _____	 _____
 _____	 _____	 _____	 _____
 _____	 _____	 _____	

The participants in the UseOnly condition were given the following questionnaire:

Follow-up Questionnaire

Participant number:

1. Male / Female (please circle)

2. Age:

3. Languages spoken:

4. On a scale of 1 (very easy) to 5 (very difficult), how easy was it to communicate successfully using the alien language (i.e. did it allow you to get the right answers)?

5. How did you manage to communicate successfully?

6. Did you find that the language changed over the experiment? How?

7. Any other comments?

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