The effects of novel variables on an iterated learning model of linguistic evolution by cultural transmission

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ABSTRACT Kirby, Cornish, and Smith (2008) introduced an experimental paradigm for studying the cumulative effect of cultural transmission on linguistic evolution. Their iterated learning model represented the first experiment on human participants to suggest that the cultural transmission of language leads cumulatively to the appearance of linguistic design without any explicit designer. This paper presents the results from a repeat of this experiment, which was conducted with a number of novel variables. In this sense, not only is the experimental paradigm verified, but the resilience of the approach is tested too. Notably, the experiment presented in this paper (a) adds an auditory modality to the participant's learning regime, which offers a closer analogue to natural language – a primarily spoken medium of communication, and (b) is initiated with languages concatenated from a wider selection of letters/phonemes. The results suggest that the addition of the auditory channel eases the task of learning the artificial languages holistically, that is, without recourse to compositional structure. Conversely, the broader 'signal-space' hinders both learning and the emergence of compositional structure. It is shown, however, that the languages circumvent this problem by finding another way to optimize their successful transmission.

Human language fills a small area within the larger space of logically possible communicative systems, and shows a proclivity for certain properties over all others. These properties are of great interest to linguistics, and as such have been widely documented; but the question remains: why should language exhibit *these* properties and not others? One fundamental property of human language is its compositionality – that the meaning of a signal is equal to the sum of the meanings of its parts. Another is recursion, which allows for the indefinite embedding of signals within signals. Explanations for such properties have been posited on innate constraints (e.g. Chomsky 1976), communicative function (e.g. Comrie 1981), or combinations thereof (e.g. Pinker and Bloom 1990).

More recently, alternative explanations for the origin of such properties have been proposed (e.g. Kirby 1999, Hurford 2000, Christiansen and Chater 2008), which broadly consider language to be 'a complex and interdependent "organism," which evolves under selectional pressures from human learning and processing mechanisms'[1] (Christiansen and Chater 2008: p489). Since a language will survive only if it can be learned/produced successfully *and* transmitted successfully, a combination of both the innate cognitive biases that predate language, *and* the impediments that obstruct its clean transmission may shape the fundamental properties we observe. In other words, languages are shaped by the constraints of their environments, which may be taken as human brains and the spatial and temporal distances that must be overcome in order to connect them; a language that does not conform to these constraints will simply not survive. This stance offers an alternative (though not incompatible) explanation for the fundamental universal schematic to which human languages resolutely adhere.

A variety of mathematical, computational and laboratory models of these phenomena have been conducted, which have shown that unsystematic artificial 'languages' can self-organize under pressure from a transmission bottleneck, becoming compositional epiphenomenally (see Hurford 2002, Brighton et al. 2005, Cornish et al. 2009, Scott-Phillips and Kirby 2010 for reviews). Kirby, et al. (2008) showed – in the first laboratory experiment to test this hypothesis – that random, unsystematic languages become compositional when they are passed down a line of language learners, or so-called *diffusion chain*. Crucially, they showed that compositionality evolves in response to pressure from a transmission bottleneck, which supports the claim that language may have evolved not despite the poverty of the stimulus but because of it (Zuidema 2003), and that, as a result, the languages become easier to learn, thereby securing their own existence. The design exhibited in the languages was cumulative, and could not have been due to the intentions of any one individual; the process is therefore akin to the *invisible hand* observed more generally in language change (Keller 1994).

These models of language evolution come broadly under the term *iterated learning*, in which some individual learns a behaviour from another individual who learned the behaviour in the same way (see Smith et al. 2003, Mesoudi and Whiten 2008). Iterated learning models (ILMs) have also been prevalent in studies of learned behaviour in other animals (e.g. Palameta and Lefebvre 1985, Laland and Williams 1997, Fehér et al. 2009). Since human language is an outcome of iterated learning, simplified models in the laboratory provide a useful method for isolating and testing interesting variables. Many of these models implicitly assume that human language emerged from an earlier holophrastic system, which has met with some debate (see Wray 2000, Arbib 2010 in support; Tallerman 2007 to the contrary). Nevertheless, one way of extending this line of inquiry is to perform similar experiments with novel variables, and see how these variables affect the results. By understanding how the environmental variables interact with linguistic evolution, it may be possible to determine what conditions needed to be present in the environment of our ancestors in order for the evolution of complex human language to get a foothold.

As such, this paper presents an ILM experiment (herein referred to as J), which makes use of a number of different variables from those used in Kirby et al. (2008) experiment 2 (herein referred to as K), while the methodology and statistical analyses remain broadly the same.

METHODOLOGY Thirty participants were recruited to take part in an 'alien language experiment'[2]. There were no prerequisites for participation other than a minimum age of 18 years. Participants were predominantly undergraduate students. The female:male sex ratio was 16:14. The mean age was 24.5. Participants were given written and verbal instructions, which portrayed the experiment as a

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[1] In which the contentious word 'organism' should strictly be understood as an analogy: a complex, adaptive system with interconnected constraints.

[2] Approved by the Glasgow University College of Arts Ethics Committee.

simple memory game (see appendix one). Specifically, participants were told that they would be learning words for alien fruit, and that their task was to memorize the mapping of words to images to the best of their abilities. Participants were not told about the cultural nature of the experiment, and were not primed to recognize or produce linguistic structure. Having received instructions, participants were left alone at a computer terminal to execute the experiment, which typically took around 20 minutes to complete.

Following Kirby et al. (2008), the experiment adopts a diffusion chain design, in which the output of a given participant becomes the input for the following participant. Three separate diffusion chains were run, labelled herein A—C. In each chain, an artificial 'language' was diffused down a line of ten participants, representing ten cultural generations. Each chain was initiated with a separate 27-word language, which was generated by randomly concatenating two-, three-, or four-syllable words from a syllabary of 28 syllables. Each participant was randomly assigned to one of the three chains, and acquired the language in one session.

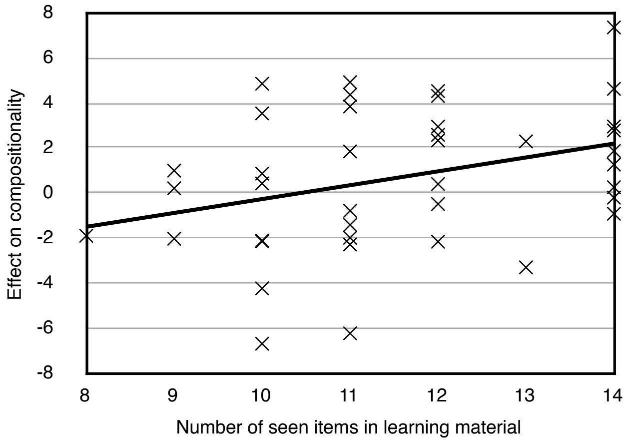
The visual stimuli were a set of 27 simple graphics (see appendix two), which conform to a strict 3 × 3 × 3 semantic-space, that is, the fruit came in three colours (red, yellow, blue), three shapes (square, circle, triangle), and three 'numbers' (one, two, or three segments[3]). During three training periods, the fruit were each presented for 5 seconds alongside their associated labels, both orthographically as a string of lower case letters, and acoustically by means of a computationally synthesized voice. Each period of training was followed by a test, which prompted the participant to input the names associated with particular fruit graphics. There is one important twist, however: during training, participants were only taught 14 of the 27 fruit, but were tested on all 27 in the final test. This enforces a transmission bottleneck: since participants cannot learn all 27 strings holistically, there exists a cumulative and invisible pressure to circumvent the bottleneck by exploiting the structure inherent in the semantic-space.

The transmission bottleneck was implemented as follows: at each generation, the 27 string-image pairs were randomly divided into a SEEN and UNSEEN set. The SEEN set consisted of 14 string-image pairs, and the UNSEEN set consisted of the remaining 13 string-image pairs. During each training period, participants were taught the SEEN set in its entirety twice in a random order. In the test that followed each training period, participants were asked to recall the name associated with fruit from both the SEEN and UNSEEN sets.

Kirby et al. (2008) showed in their first experiment that languages quickly degenerate to just a handful of words. For example, by the tenth generation in chain 1, the string *nepa* had been applied to every fruit apart from one. Kirby et al. (2008) refer to this as 'underspecification' (i.e. polysemy), which is a result of the model's shortcoming in enforcing expressivity. In other words, the languages naturally become polysemous because there exists no communicative pressure to maintain a 1:1 mapping between meaning and form. By contrast, K (i.e. their second experiment) ensured that underspecification was 'an evolutionary dead-end' by adding a filtering mechanism to the transmission bottleneck. This filter – an analogue of the pressure for expressivity in natural language – effectively removes duplicate strings from a participant's learning material to ensure that a 1:1 mapping is maintained between form and meaning, thereby encouraging the languages to remain unambiguous.

This experiment adopts a similar mechanism, which differs in the following way: in K, 14 fruit are randomly selected to constitute the SEEN set; then all except one token of fruit with duplicate strings are randomly removed; the result of this method is that participants are taught varying numbers of string-image pairs, which is arguably problematic (see figure 1). My alternative filtering mechanism is to randomly remove duplicates *first*; then randomly select 14 fruit to constitute the SEEN set. The advantage of this is that every participant is exposed to a learning material of equal magnitude, which promotes a more highly controlled experiment. However, Kirby notes (personal communication) that their bottleneck strategy could be considered more random and naturalistic than this alternative.

Fig. 1 Based on an independent analysis of K. Scatter plot showing the correlation ($r = 0.333$, $N = 40$, $p < .04$) between the number of seen items in a participant's learning material and his or her effect on compositionality. The linear regression line suggests that participants who were taught a greater number of words increased the compositionality of the language to a greater degree than those taught a smaller number of words.



Based on the results observed in K and the preceding research literature, the initially random languages should become increasingly easy to learn due to increasingly compositional linguistic structure. To measure learnability, this paper follows Kirby et al. (2008) and a measure of intergenerational transmission error is calculated based on the mean normalized Levenshtein edit distance between the strings in a given participant's output and the corresponding strings in the previous participant's output. To measure compositionality, this paper again follows Kirby et al. (2008) and a correlation between form and meaning is calculated for each participant's output; by applying Monte Carlo techniques, it is possible to measure the extent to which the alignment between form and meaning differs from that expected in a chance alignment. (The detailed methods section at the end of this paper provides more explicit information about the methodology used in this experiment.)

SUMMARY OF NOVEL VARIABLES In summary, J differs from K in four respects:

(i) A different filtering strategy is used, which exposes each participant to a SEEN set of equal magnitude (14 items). K has SEEN sets that vary in size from 8 to 14 items.
(ii) The semantic-space uses the colour yellow instead of black, and number instead of movement. This tests the human reaction to a slightly different set of visual stimuli.
(iii) The auditory modality is used alongside orthography. The motivation here is to more accurately represent human language, which is foremost a spoken medium of communication. K uses only written language.
(iv) The initial languages are concatenated from a larger syllabary of 28 syllables. K uses 9. This allows us to test the effect of initiating the experiment with a broader 'signal-space'.

The effects of these novel variables will be discussed below.

RESULTS The graphs in figure 2 show the experimental results for ten participants in each of three diffusion chains labelled A—C. Figure 2a shows a statistically significant decrease in transmission error between the initial and final generations (mean decrease =

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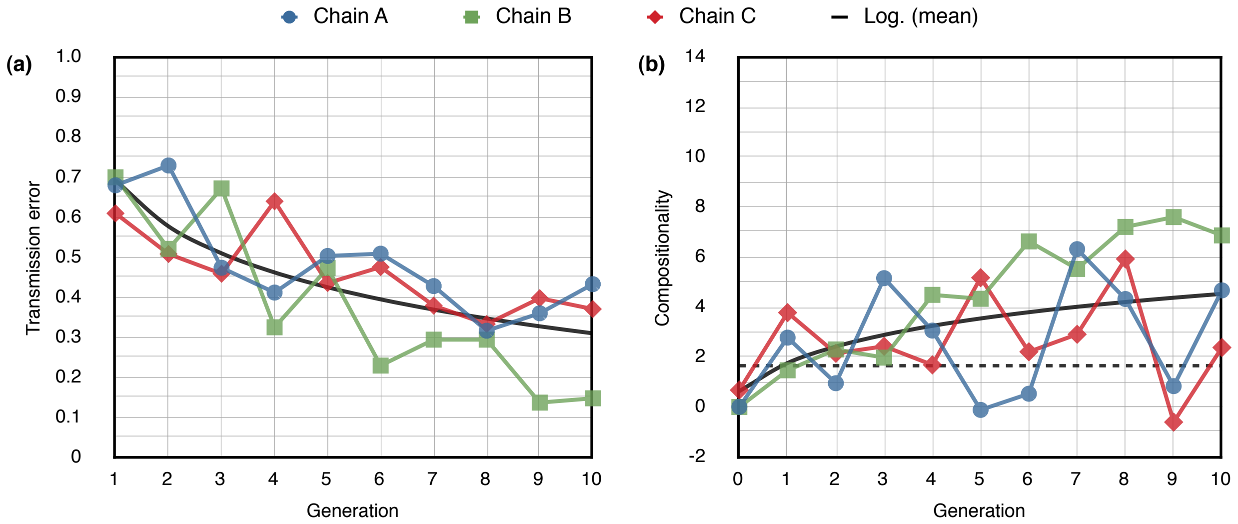
[3] N.b. the number system in this semantic-space spans just 1—3, which the human visual system can instinctively 'subitize' (Kaufman et al. 1949); i.e. higher brain functions are not required to explicitly count the number of segments in the images.

Fig. 2 Levels of transmission error (a) and compositionality (b) in three diffusion chains across ten generations. (a) gives the mean normalized Levenshtein edit distance between each participant's linguistic output and the output of the previous participant, and shows a downward trend as the languages become easier to learn. (b) gives a measure of compositionality for each participant's linguistic output, and shows an upward trend as the languages become increasingly more compositional. The dashed line in (b) shows the $p = .05$ significance level. Note that figures (a) and (b) are to approximately the same scale as their equivalents in Kirby et al. (2008) for easy comparison.

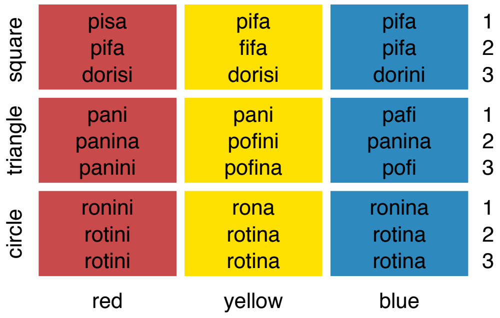


0.346, $SD = 0.179$, $t\,(2) = 3.358$, $p < .04$). This is in line with the predictions and results of K: the languages clearly adapt to increase their own transmissibility by becoming easier to learn over the course of the experiment. Furthermore, the effect is cumulative: the correlation between generation number and transmission error is statistically significant ($r = -0.762, N = 30, p < .001$).

As with K, this increase in learnability cannot be explained fully by underspecification (i.e. a mapping from one string to many meanings). Although some underspecification is present, the number of distinct words in participants' outputs remains high (mean = 17.4). Note also that where there *is* underspecification, it is often systematic: for example, participant A7 used *sepredoku* to refer to three fruit, all of which are square in shape. An explanation for increased learnability also lies, therefore, in the languages evolving increasingly compositional linguistic structure. As an example, participant B10 was able to correctly identify fruit #18 as *rotina*, even though this fruit was not present in her learning material (see appendix three for the complete linguistic data). By reducing the language to a set of generalized rules, participants are able to determine the correct answer, or a close-to-correct answer, for a given fruit without being explicitly taught its name.

These generalized rules are a product of the languages' increasingly compositional structure, and figure 2b confirms that compositionality increased significantly between the initial and final generations (mean increase = 4.408, $SD = 2.589$, $t\,(2) = 2.949$, $p < .05$). Furthermore, the majority of participants' outputs (those above the dashed 95% significance line) are statistically nonrandom, and – as with transmission error – the increase in compositionality is cumulative: the correlation between generation number and compositionality score is statistically significant ($r = 0.461, N = 33, p < .004$).

Fig. 3 Paradigm of the most compositional language (B9), which demonstrates that morphemes are used consistently to represent particular semantic features. For example, words beginning *ro-* are circular. Such generalizations allow the learner to accurately reproduce the language of the previous participant despite having access to only half (14/27) of the data.



		red	yellow	blue
square	1	pisa	pifa	pifa
	2	pifa	fifa	pifa
	3	dorisi	dorisi	dorini
triangle	1	pani	pani	pafi
	2	panina	pofini	panina
	3	panini	pofina	pofi
circle	1	ronini	rona	ronina
	2	rotini	rotina	rotina
	3	rotini	rotina	rotina

We can demonstrate the compositional structure that emerged by looking more closely at the languages. Figure 3 illustrates how the linguistic signals map on to the semantic-space in the language of participant B9. Shape is expressed by the first morpheme: *pi-* or *do-* in most cases of square fruit; *pa-* or *po-* in the case of triangular fruit; and *ro-* in all cases of circular fruit. Colour is not clearly expressed by any component, although final *-ni* tends to occur more often among red fruit, while final *-na* tends to occur among blue and yellow fruit (especially noticeable among the circular fruit). Number is also not clearly expressed, although medial *-ni-* and *-ti-* may mark a singular/plural dichotomy (again this is especially noticeable among the circular fruit). Note also that square fruit with three segments have a noticeably different (but internally regular) form from other square fruit which may be considered a marker of number in its own right.

This is not to say, however, that morphemes for colour and number did not emerge. The output of participant C8, for example, seems to mark colour with *-puni*, *-puri*, *-spuri* for red, yellow, and blue respectively, and number with NULL, *kiki-*, *piki-* for 1, 2, and 3 respectively. It must be stressed, however, that the structures that have emerged in this experiment are very tentative; the languages are not particularly compositional in comparison with those that emerged in K (see figure 5b). However, compositionality does, at least in part, contribute to an increase in learnability: for example, there is a significant correlation between the degree of compositionality in a participant's learning material and his or her transmission error ($r = -0.62, N = 30, p < .001$).

Aside from the emergence of underspecification and linguistic structure, there is a third mechanism by which the languages become easier to learn. Figure 4 tabulates the number of distinct syllables in each participant's learning material, and shows a statistically significant decrease in the variety of syllables being employed between the first and final generations (mean decrease = 9, $SD = 2.646$, $t\,(2) = 5.892$, $p < .03$). Furthermore, there is a strong correlation between the number of distinct syllables in a participant's learning material and his or her transmission error ($r = 0.633$, $N = 30$, $p < .001$). This suggests that the decrease in transmission error might also be explained, at least in part, by the erosion of the signal-space. Since these languages can operate compositionally and expressively with as few as nine morphemes (or even fewer, if they employ a strict morphological order), and given that the languages are easier to learn if there are fewer syllables/syllable patterns to memorize, the languages gladly sacrifice signal-space to the benefit of learnability. In other words, it makes sense from a language's per-

Fig. 4 Table showing the number of distinct syllables in each participant's learning material across chains A—C. Over a period of ten cultural generations, the number of distinct syllables gradually decreases, since such large signal-spaces are not required by languages with such small semantic-spaces. This provides another example of how the languages adapt to their environment.

	1	2	3	4	5	6	7	8	9	10
A	21	21	22	26	17	18	16	16	16	15
B	23	16	16	15	14	14	14	12	14	13
C	24	22	19	19	19	17	14	13	12	13

spective, to relinquish extraneous syllables that only serve to confuse the learner. This kind of adaption does not occur to a significant extent in K, since the initial languages were concatenated from a relatively small syllabary. This outcome is, therefore, quite significant, since it provides another example of how languages can adapt.

DISCUSSION In this laboratory experiment, we have observed the cumulative cultural adaption of language, and, since each participant's goal was to replicate the language taught to them as accurately as possible, there can be no intentional design on the part of any one participant. The result by the tenth generation is a set of languages that are more successful (by virtue of their increased learnability) than the set of languages that initiated the experiment. The languages achieve this increased success by adapting to their environment: they must circumvent the artificially induced transmission bottleneck and respond to the cognitive biases of their learners in order to optimize their faithful transmission. The languages in this experiment adapted primarily by three means: firstly, each language attempted to become polysemous, although this was filtered to enforce expressivity and could not have been known by individual participants. Secondly, each language developed increasingly compositional linguistic structure by exploiting the structure implicit in the semantic-space. Thirdly, each language relinquished extraneous syllables, focusing instead on a small number of more easily memorable syllables better suited to the small semantic-space.

These three evolutionary outcomes contributed to the increased learnability of the artificial languages, but perhaps more importantly are reflected in the natural properties of human language. Compositionality is a well-documented universal property of language, and it is well understood that polysemy is rife across languages. Consider also that the phonologies of natural languages are both optimally distinctive acoustically and optimally economical articulatorily (de Boer 2001); similarly, the languages in this experiment are able to self-optimize by increasing the economy of the signal-space to the detriment of the distinctiveness of the signal-space.

This experiment lends further support, therefore, to the results of Kirby et al. (2008) and the preceding research literature. It supports the idea that the cultural transmission of language ought to be viewed as an autonomous evolutionary system in its own right, since language adapts by numerous means in response to the pressures involved in its faithful self-replication. The natural question, however, is: how do the two experiments compare?

Figure 5a shows mean transmission error across chains A—C in J, and chains 1—4 in K. The results from the two experiments are *not* statistically different (mean difference = 0.025, t (68) = 0.621, p = .536), although the languages in K are, in general, marginally easier to learn than in J. Conversely, figure 5b shows that mean levels of compositionality in the two experiments *are* significantly different (mean difference = 3.174, t (68) = 4.57, p < .001): K produces, on average, more highly structured languages at almost every generation. The similarity observed in terms of transmission error, alongside the dissimilarity observed in terms of compositionality might, at first, seem puzzling, but, since the experimental methodologies in J and K are essentially the same, an explanation must lie in the novel experimental variables introduced here in J, which were:

(i) A slightly different filtering strategy
(ii) A slightly different semantic-space
(iii) An auditory modality
(iv) A larger initial signal-space.

These variables will be considered in turn.

Variable (i) introduces a different selective dynamic to the experiment. Consider that if a string-image pair is particularly memorable, then a participant is less likely to apply that string to multiple images. This, in turn, means that that particular string-image pair is more likely to pass through the filter, since it is less likely to be ambiguous. And vice versa. A similar dynamic exists in K, although it is difficult to ascertain precisely how each would impact on the final results. It seems likely, however, that the overall effect would be insignificant. More importantly, this new filtering mechanism means that every participant in J was exposed to a learning material of equal magnitude (i.e. 14 items). In K the magnitude of participants' learning materials varied (mean = 11.55). Therefore, participants in J were, in general, learning from a larger dataset. We saw in figure 1 that larger datasets in K correlated with greater increases in compositionality, but in fact, intergenerational increases in compositionality are lower in J than for participants exposed to 14 items in K (mean difference = 1.819, t (37) = 1.78, p < .09). Although there are other variables involved, this might suggest that variable (i) did not have a *strongly* significant effect on compositionality in J; if the predicted effect was present, it has been entirely counteracted by

Fig. 5 Mean levels of transmission error (a) and compositionality (b) in J and K over the course of ten generations. (a) shows that the results for transmission error in the two experiments have a very similar mean and range. Conversely, (b) shows that the levels of compositionality in the two experiments are markedly different. In J, compositionality begins to plateau earlier and at a lower level, while K develops much stronger structures.

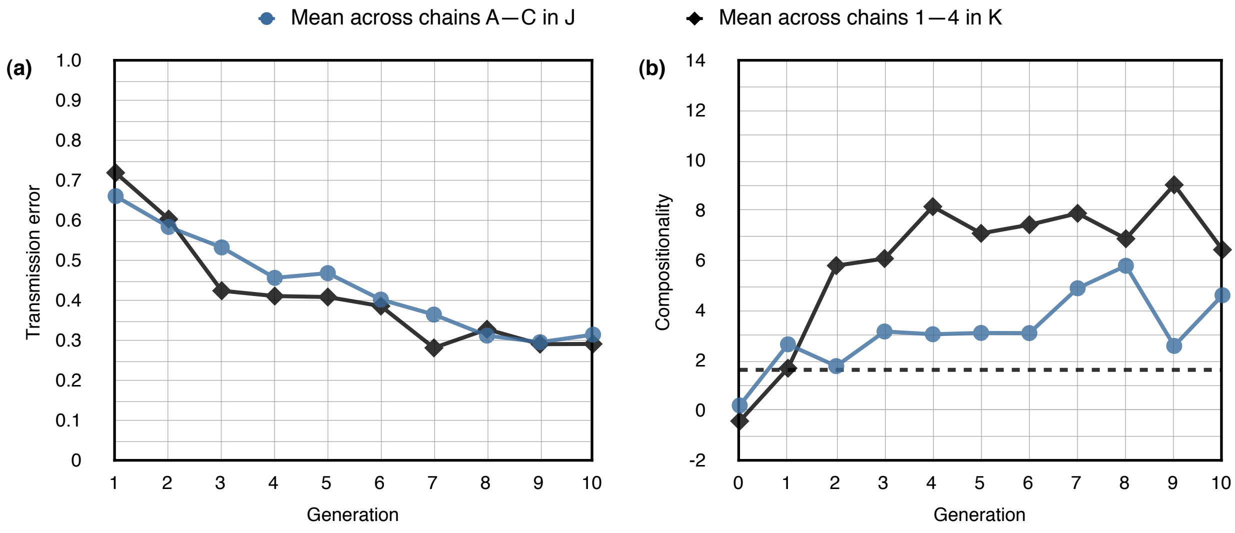
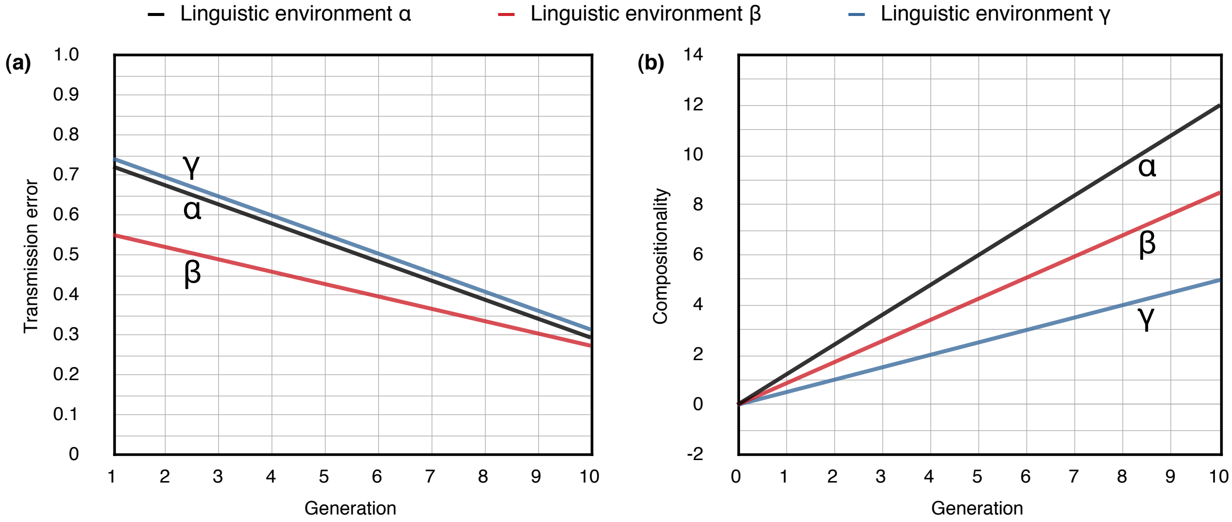


Fig. 6 The results for transmission error (a) and compositionality (b) from three hypothetical linguistic environments (i.e. sets of experimental parameters) labelled α—γ. Environment α is much like the environment in K. Environment β is identical to α, but includes an auditory modality. Environment γ is identical to β, but is initiated with words concatenated from a larger syllabary, and is, therefore, much like the environment in J. Environment β is easier to learn than α, which in turn exerts less pressure on the emergence of compositionality. Environment γ is harder to learn than β, and is less likely to induce compositionality by chance in the process of cultural transmission. This theoretical analysis explains, therefore, the similarity observed in terms of transmission error and dissimilarity observed in terms of compositionality between J (represented by γ) and K (represented by α). Compare with figure 5.



other variables.

Variable (ii) introduces a new semantic-space to the experiment, but given the general lack of compositionality observed in J, it is difficult to ascertain precisely how participants responded to these meanings. However, since participants readily learned to distinguish between all types of meaning, it is possible that this novel semantic-space also had little overall impact on the results.

Conversely, novel variables (iii) and (iv) appear to have had a strong influence on the outcome of the experiment, and it is proposed here that it is primarily these two variables – acting in tandem – that contribute to the different experimental results observed between J and K. For simplicity, the more subtle effects of novel variables (i) and (ii) will be disregarded hereinafter, but could be subjected to more specific empirical research in the future.

The similarity observed in terms of transmission error between J and K (as illustrated in figure 5a) may actually be a coincidence caused by the combined effects of variables (iii) and (iv): variable (iii) makes the languages easier to learn in J than in K, while (iv) simultaneously makes them harder to learn in J than in K. These hypotheses are abstracted by figure 6a, which shows the outcomes of three hypothetical linguistic environments (i.e. sets of experimental parameters), which are labelled α—γ. Linguistic environment α represents K. By adding an auditory modality to α, we derive linguistic environment β, which is easier to learn (illustrated by a downward shift), since participants are (a) provided with two streams of sensory information, and (b) provided with a consistent phonological framework, both of which aid memory. By increasing the initial syllabary size of β, we derive linguistic environment γ (which represents J). γ is harder to learn than β (illustrated by the upward shift), since participants must learn a greater number of syllables, and greater number of possible permutations of syllables. The net outcome is that transmission error between α (i.e. K) and γ (i.e. J) is notably similar, while the dynamic that produced these results is quite different.

The significantly lower levels of compositionality observed in J in comparison with K (as illustrated in figure 5b) may also be explained by the combined force of variables (iii) and (iv), both of which discourage the emergence of compositionality. This is abstracted by figure 6b, which shows the results for compositionality from the same three hypothetical linguistic environments labelled α—γ. Again, linguistic environment α represents K. By adding an auditory modality, we derive linguistic environment β, which is less likely to induce compositionality (illustrated by a downward shift), since the auditory modality makes the languages easier to learn holistically. By increasing the initial syllabary size of β, we derive linguistic environment γ (which represents J). γ further hampers the emergence of compositionality compared to β (illustrated by another downward shift), since linguistic patterns that map on to the structure of the semantic-space are less likely to emerge by chance in the process of cultural transmission and become analysed as grammatically significant by learners. The net result is that compositionality between α (i.e. K) and γ (i.e. J) is considerably different.

It must be stressed, however, that these hypotheses should be subject to further empirical research. By isolating individual variables, it should be possible to form a much clearer understanding of the way in which linguistic environments shape the languages that emerge from them. What this paper has shown, however, is that, under a different permutation of variables, compositional structure can still emerge from an ILM. This supports the experimental paradigm introduced by Kirby et al. (2008), and the more general theory that human language may have evolved traits such as compositionality by means of cultural evolution.

An interesting extension to J would allow the languages to continue evolving for perhaps five or ten more generations. It may be that, once the signal-space becomes significantly eroded, compositional structure will be able to get a proper foothold. It may also be useful to test hypothetical linguistic environment β above, and observe whether the results are as predicted.

CONCLUSIONS The present experiment supports the findings of Kirby et al. (2008), and validates their experimental paradigm. It shows that compositional structure can emerge from an initially unsystematic language over repeated cycles of expression and induction. Notably, it shows that the degree of structure that emerges in a language is determined by its linguistic environment, and that there is at least one other way in which languages can adapt.

From a practical angle, this paper shows that it is possible to add an auditory modality to the learning regimen of this ILM, which could be particularly useful to research grounded more firmly in the study of phonetics. It also shows that there exists an alternative methodology for filtering ambiguous strings, which promotes, in general, a more controlled experiment.

The next major step in developing a fully fleshed-out theory of language evolution by cultural transmission will be to show empirically that compositionality, as well as other universal properties of language, can emerge under environments that more closely resemble the real world. In particular, grounding similar models in child language acquisition could reveal interesting results.

DETAILED METHODS

LINGUISTIC STIMULI The initial arbitrary holistic languages of 27 strings were generated randomly under the following constraints: each string was two to four syllables in length; each syllable consisted of 2 letters – a consonant followed by a vowel; consonants were selected from the set (d, f, k, n, p, r, s); vowels were selected from the set (a, i, o, u)[4]. These orthographical forms were accompanied by vocalizations that were synthesized computationally. Specifically, the strings were translated into machine-readable phonemes to a consistent phonology[5] with primary stress placed on the penultimate syllable, and a 1:1 mapping maintained between grapheme and phoneme. These were passed through Apple's MacinTalk speech synthesizer using the 'Alex' voice, which rendered a sound file of the articulation.

EXPERIMENTAL REGIMEN Each initial language, which consisted of 27 string-image pairs, was randomly divided into two sets: a SEEN set of 14 string-image pairs, which would be taught to the participant during training, and an UNSEEN set of 13 string-image pairs, which would not be taught. The experiment was conducted in three rounds; each round consisted of a training session, followed by a test. In round one training, each of the 14 SEEN fruit were presented twice in a random order for five seconds each. Each was accompanied by its corresponding orthographical string and vocalization, which was played over a set of headphones. In the round one test, the participant was presented with the image for each of 13 fruit (7 randomly selected from the SEEN set, and 6 randomly selected from the UNSEEN set), and prompted to type its name[6].

Round two was conducted in much the same way as round one, with the exception that the test consisted of 14 fruit (the remaining 7 fruit from the SEEN set, and the remaining 7 fruit from the UNSEEN set). In this way, the participant was exposed to every one of the 27 fruit images at least once during the first two rounds, but only taught the strings of the 14 SEEN fruit. In round three, the training was conducted as before, but the test comprised all 27 fruit presented in a random order.

The answers provided in this final test constituted the language to be taught to the following participant, which was redivided into a SEEN and UNSEEN set. This redivision underwent a filtering process in order to form a SEEN set that contained only unique strings. Specifically, all uniquely named images were placed into a POTENTIAL set; where a single string mapped on to many images, only one string-image pair (selected randomly) was added to the POTENTIAL set. From this set, which now consisted only of unique strings, 14 were randomly selected to constitute the SEEN set.

MEASURE OF TRANSMISSION ERROR The mean edit distance between the strings in a participant's output and the corresponding strings in the previous participant's output provides a measure of intergenerational transmission error, and is given by

$$E(i) = \frac{1}{|M|} \sum_{m \in M} \frac{\mathrm{LD}(s_i^m, s_{i-1}^m)}{\max(|s_i^m|, |s_{i-1}^m|)}$$

where mean transmission error E at generation i is 1 over the magnitude of meaning set M, multiplied by the sum of the normalized Levenshtein edit distances for each meaning m in meaning set M. The Levenshtein edit distance[7] is computed between string s (for meaning m at generation i) and string s (for meaning m at generation i–1), and normalized by dividing by the length of the longer string[8]. This measure is expressed over the interval [0,1], where 0 is no error and 1 is maximal error.

MEASURE OF COMPOSITIONALITY A correlation between the difference in form and the difference in meaning for each possible pairing of strings in a given participant's output provides a measure of the degree to which similar meanings are expressed by similar forms, and is calculated as follows: firstly the normalized Levenshtein edit distance is computed for each of the 351 possible pairings of strings in a participant's 27-string output; a hamming distance[9] is then computed for each of the corresponding pairs of meanings; finally a Pearson's product-moment correlation coefficient is calculated between these edit distances and their corresponding hamming distances, giving an indication of their statistical alignment.

To measure significance and standardize the coefficients across languages, a Monte Carlo sample of 10,000 randomized permutations of each participant's output is produced, against which the participant's veridical coefficient is compared. This is performed by calculating the mean and standard deviation of the coefficients in the Monte Carlo sample, and then deriving the standard score, which constitutes our final measure of compositionality. To put this measure in context, a randomly generated language scores ~0, while English (which is fully compositional) scores ~17.7[10].

NOTES

I The output of two participants contained an insufficient number of distinct strings (10 and 11 strings respectively) to create the following participant's SEEN set of 14 items. Their results in terms of transmission error and compositionality were otherwise normal. In these two cases, the participants were replaced by two new ones. Thus, this paper reports the results from only 30 of the 32 total participants recruited.

II All analyses of K are based on the raw data made available in the supporting information published online (http://www.pnas.org/content/early/2008/07/29/0707835105/suppl/DCSupplemental). Since the results for compositionality are based on randomized Monte Carlo techniques, the numbers calculated for K in this paper may vary slightly, although not to any significant degree.

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[4] Thus, letters that have an ambiguous pronunciation according to English orthography – c, e, j, x, etc – were avoided in the initial languages, but could naturally develop over the course of the experiment. Where they did develop, they were assigned a consistent phonological value.

[5] a = /ɑ/ c = /k/ d = /d/ e = /ɛ/ f = /f/ h = /h/ i = /i/ k = /k/ l = /l/ m = /m/ n = /n/ o = /oʊ/ p = /p/ r = /r/ s = /s/ t = /t/ u = /u/

[6] This prompt accepted lower-case alphabetical characters only.

[7] Defined as the minimum number of additions, deletions, or substitutions required to transform one string into another (Levenshtein 1966). E.g. the Levenshtein distance between *pisa* and *posaf* is 2, since it requires 1 substitution and 1 addition.

[8] Thus the *normalized* Levenshtein distance between *pisa* and *posaf* is 2 ÷ 5 = 0.4.

[9] The hamming distance is the number of different fruit attributes shared by any two fruit. E.g. if a pair of fruit differ in just one attribute, say colour, the hamming distance is 1; if a pair of fruit differ in three attributes – colour, number, and shape – the hamming distance is 3, etc.

[10] Measured by giving each fruit an English name – *singleredsquare*, *doublebluecircle*, *tripleyellowtriangle*, etc.

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APPENDICES

APPENDIX 1 The following brief – adapted from Kirby et al. (2008: supporting information, p1) – was provided to each participant. This was reinforced with verbal instructions to the same effect.

Welcome to Stella Fructa in a galaxy far, far away. This planet is inhabited by an intelligent alien life form with its own language, and we need you to learn some words from this language as best you can.

The words you are going to learn are for alien fruit. It's a difficult task: the language is quite unlike ours, and their fruit are quite different too. But don't feel alarmed: these aliens know how challenging the task is, and they will try their best to understand what you say.

You will be shown pictures of alien fruit, and below these you will see their names. The computer will also say the name out loud. As well as teaching you the words, the aliens will also test your knowledge by showing you pictures and asking you to type in the correct names.

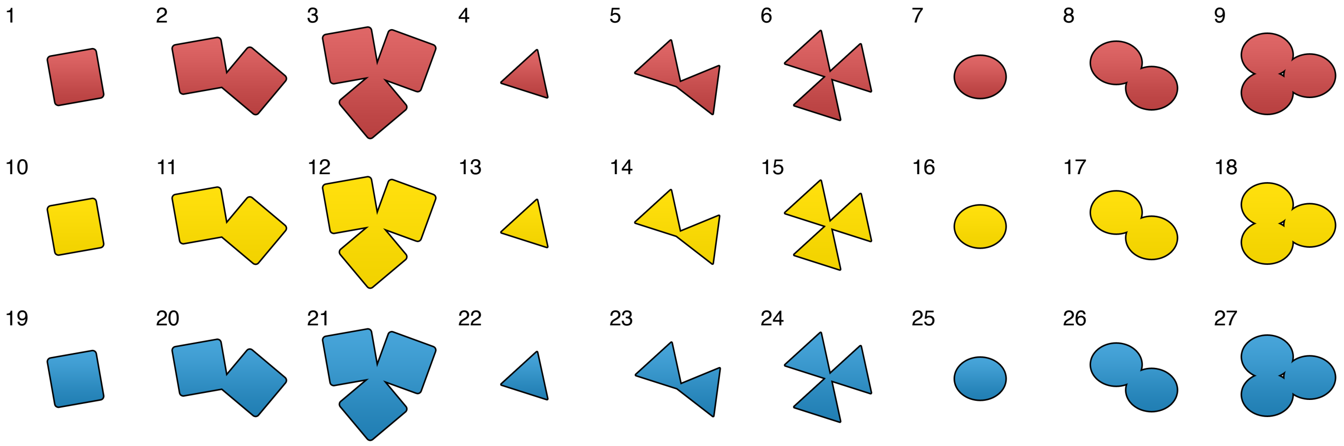
Don't worry if you feel you have not yet mastered the language. The aliens are very patient, and the most important thing is to maintain good relations with them by giving it your best shot. Always give an answer, even if you know it's wrong; that way the aliens will know you are trying.

There are three rounds, and in each round there will be a period of training followed by a period of testing. During the training periods you will see each fruit twice, and they will be presented in a random order. During the testing periods you will only be presented with pictures of the fruit, and you must enter their names as best as you can remember.

You will be given the opportunity to take a break between each round.

Good luck!

APPENDIX 2 The following visual stimuli constituted the semantic-space in the experiment. The numbers correspond to those referred to in the raw data in appendix 3.



APPENDIX 3 The following three tables give each participant's linguistic output. Black arrows indicate fruit that passed through the transmission bottleneck and ambiguity filter to form the learning material for the next participant. Fruit numbers correspond to those given next to the visual stimuli in appendix 2.

CHAIN A	Generation number										
Fruit	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	sudunasu	nanidapo ➤	kosoriki ➤	keprosa ➤	sepriona ➤	sepriko ➤	sperini ➤	spereni ➤	sepredi	sepradino	speredi
2	rinuni ➤	nanidapo	perikori ➤	rokirika	perioka	teridoki	speridoka ➤	speredoka ➤	sepradino ➤	sepradoku	heredoku
3	sukuruna ➤	suposa	kosorika ➤	ricorica	sperioni ➤	terioka ➤	speriono ➤	sepredoku ➤	sepradoku ➤	feredoka ➤	heredoku
4	nunidado ➤	sudopa ➤	keprosa ➤	keprosa	keprosa	fifi	sepridoku	ferini	speredi	seperino ➤	seperdoka
5	dupi	suposa	feminaco ➤	feminaco ➤	feminaco ➤	feminaco	feriano ➤	feriono	ferino ➤	sperino ➤	ferdino
6	dopufa	fifi ➤	fifi ➤	fifi ➤	fifi ➤	fifi	sepridoki ➤	ferinoka ➤	feredoku	speradoku	heredoka
7	nopa	sapano ➤	seprosa	seprioni ➤	seprioni ➤	sperioka	sepriano	speredi ➤	speredi	sperinu	sperino
8	fufi ➤	risori	seproi	sepriconi	perioni	sporiko ➤	sepridoku ➤	speredo ➤	speredoka ➤	sepredoku ➤	feredoku
9	panidako ➤	suposa	nanipano	rakirika ➤	rakirika	teriako	speriano	sperinoka	speredoku	heredino ➤	sperdoka
10	fasuru	delipano ➤	nemsa ➤	kesa	perioki	teradoka	feriano	sepredo ➤	feredoku ➤	speredino	seperino
11	foripiki	piridoki ➤	peridoca	perisoka ➤	peridoki ➤	sperioki ➤	ferioko	sepreano	speridoku ➤	separinu ➤	speredi
12	risoru ➤	fuko ➤	keprosa	sperika ➤	sperika ➤	speriona ➤	sepridoki	sepredoka ➤	speredoku ➤	speredoku ➤	heredoka
13	saduposu ➤	napu ➤	keprosa	nemsa	keprosa	seperano	feriano	ferino	sepredi ➤	separino ➤	sperino
14	sufosa ➤	risori	peridoki	perisoki ➤	perioki ➤	piriako ➤	ferioko ➤	ferino ➤	ferino	speredoka ➤	seperino
15	napu ➤	fuko	namipano ➤	nemospan ➤	keprosan	sepridoki ➤	speriano ➤	speredono	feredoka ➤	speredoka	heredoku
16	surokipa	nanidapo	seprosa	seprikoni ➤	seprioki	seprini ➤	feriano	spereko ➤	sperdini	speredino ➤	sperino
17	rususiri	risori ➤	seprosa ➤	sakiria ➤	speridoki ➤	perioka ➤	sepriano ➤	speredono	sperino ➤	sepradino	serpino
18	fuko ➤	fuko	perisoki ➤	speriako ➤	sperioka ➤	teriano	seprioni ➤	seperona ➤	speridoku	sperdinu	heredoka
19	fifasu	nanidapo	nanipano	kesa	speroka ➤	spiriado	feriano	sperino ➤	sperdini ➤	sepadoka ➤	speredi
20	dosa ➤	dosa ➤	nanipano	peridoki ➤	sepridoki ➤	speriano	feriano	sepredoku	sepradoku	sepradino	speredi
21	nofiku	fuko	keprani ➤	parioki ➤	keprosan	speriko ➤	sepriano	sepredoku	sepradoku	heredino	feredoka
22	kosiriku ➤	kosoriki ➤	kesa ➤	kesa	seproka ➤	feriako ➤	feriana ➤	ferina	ferinu ➤	ferinu ➤	seperinu
23	fiforufu ➤	risoru ➤	nanipano	prodiki	peridoka	speriano ➤	feridoka ➤	feridoku	feredoku	ferinu	heredino
24	fokirina	kosoriku ➤	peridoki	perodoki	keprosan	sperioni ➤	sperioko	feredoku ➤	heredoku ➤	heredoku ➤	feredoku
25	rasuno	suposa	seprosi ➤	seprioni	peridoka	speridoka ➤	spidoko ➤	spereko	speredi	sepredi	feredino
26	fokunoko	nanidapo	peridoki ➤	parioki	sepridoka ➤	teriako	feridoka	speredoka	speredi ➤	speredi ➤	ferino
27	sopano ➤	suposa ➤	seprosa	perikoi	speriako	seperano	sperioko ➤	speredoku ➤	speredoku	speradoku	feredoku

CHAIN B

	Generation number										
Fruit	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	kosonu	pipina	fifa ➤	fifa ➤	fifa ➤	fifa	fifa ➤	fifa ➤	fifa	pisa ➤	pisa
2	kukafapo	konanono ➤	kokonono	fifa	rinifi	rotuna	fipa	pifa ➤	pifa	pifa	pisapisa
3	rifuko	pufa	pufi	rinosa ➤	rinosa	dorisa ➤	dorisa ➤	dorisa ➤	dorisi ➤	dorisi	dorina
4	pofapaka	konanono	fifi ➤	pani ➤	pafi	pani ➤	pani ➤	pani ➤	pani ➤	pani	pani
5	pisoka	fidoku ➤	pafi	pafi ➤	pafi ➤	ronisa ➤	panisi ➤	panisa ➤	panina ➤	panina	pafina
6	rinuku ➤	radosu ➤	radisu	riniti ➤	rinifi	rotini ➤	rotini	parisi	pafi	panini ➤	panini
7	pifi ➤	pufa	rona ➤	rona ➤	rona ➤	rona	rona	ronisi	rotina	ronini ➤	ronini
8	fasu	pufa	rinisi ➤	fifi	rotuna	rotuna ➤	rotuna ➤	rotuna	rotina	rotini ➤	rotini
9	pipina ➤	pipina	fapo ➤	rosuna ➤	rosuna	rotuna	rotisa ➤	rotina ➤	rotini ➤	rotini	rotina
10	pafu	fupa ➤	fipa ➤	rotino ➤	fotuna	fifa ➤	fifa	fipa	fifa	pifa	pisa
11	kinora	rinoku ➤	rinoko ➤	fotuna ➤	fotuna ➤	fipa ➤	fipa ➤	pafi	fifa ➤	fifa	pisapisa
12	radosu ➤	radosu	pufi	rotina	fotuni ➤	rotini	dorisa	dorisi ➤	dorisi	dorisi ➤	dorisi
13	sofasa	fufu ➤	fupa	pani	riniti	pani	pani	pafi ➤	pafi ➤	pani ➤	pani
14	fina	pafu ➤	pafi ➤	fifa	ritini ➤	pafi	pifa ➤	pifa	pani	pofini ➤	pofini
15	nakasa ➤	radosu	ritino ➤	ritini	ritina ➤	parisa ➤	parisa ➤	parisa	panisa ➤	pofina ➤	pofina
16	nisipapa ➤	fipa ➤	fupa	rona	rona	rona	rona ➤	rona ➤	rona ➤	rona	ronini
17	dapo ➤	konanono	pani ➤	rotuna ➤	rotuna ➤	tunisi ➤	rotuna	ronisi	rotina	rotina	rotini
18	konanono ➤	pipina ➤	pipiku	ritini	rosuna ➤	dorisa	ronisa ➤	ronisa ➤	rotina	rotina	rotina
19	pufa ➤	fifa ➤	fifa	fifi	panisu	fifa	fifa	fipa	pifa ➤	pifa ➤	pifa
20	furipa ➤	radosu	kokonono	panisu ➤	panisu	fotini ➤	fipa	fipa	pifa	pifa	pifapifa
21	dofoki ➤	pufa ➤	pufi	finasu	panisa ➤	panisa ➤	panisa	dorini ➤	dorini ➤	dorini ➤	dorini
22	fufu ➤	dorisu ➤	doriso ➤	doriso	pani ➤	pani	pani	panisi ➤	pafi	pafi ➤	pafi
23	puku	nisipapa ➤	dorisu	ritini ➤	rinifi ➤	pafi ➤	pafi ➤	pafina	pifa	panina ➤	panina
24	ponu ➤	radosu	radiso	ritina ➤	ritina	panisa	rotini	parisi	pofi ➤	pofi	ponina
25	kokiripo ➤	nisipapa	pafa ➤	rona	rona	rona ➤	rona	ronisi ➤	ronina ➤	ronina ➤	ronina
26	finokani	kokuna ➤	kokuna ➤	fifu	panisu ➤	rosuna ➤	rosuna ➤	rotuna	rotina ➤	rotina	rotina
27	sasiro	pipina	fupa ➤	doriso ➤	doriso ➤	dorisa	rosini ➤	rotisa ➤	rotino ➤	rotina ➤	rotina

CHAIN C

	Generation number										
Fruit	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	pasu	kaku ➤	kaku	skipnuri ➤	kip	skip	kikspuri ➤	puni ➤	puni ➤	spruni	spruni
2	dipurafa	kikduna ➤	kiknura ➤	kikispuni ➤	difopa ➤	difopa ➤	skipuni	kikispuni ➤	kikipuni ➤	skikipuni	spikispruni
3	kura	sakipuna	dipnuri ➤	dipspuni	skif ➤	skif	kikispuni	skifado	pikipuni	kikipruri	spikispruni
4	kifaropa ➤	fidinora	dipsona ➤	skiksona ➤	difado	kip	skipuni ➤	skipuni ➤	skipuni ➤	spuni	pikpuni
5	fidinoru ➤	fidinora	kikifopa ➤	kikispuni	kip	kipspuni ➤	difopa	skikipuri ➤	skifado	skikifado	pikipuni
6	sikiduni ➤	sikinuri ➤	skiknura ➤	skipnura ➤	radofo ➤	radofo	skikipuri ➤	skifado ➤	skikifado ➤	skikifado ➤	kikipruni
7	kisada ➤	kisada ➤	kaku	rapspuni ➤	difopa	kikspuri ➤	kipuri ➤	puni	puni	spuni	puni
8	sarupuku ➤	fidinora	sikifopa ➤	kikifopa	kikispuri ➤	kikspuri	skipuri	spuni ➤	spuni	skikipuri ➤	spruni
9	nidafo ➤	fidinora	dipinuri	dipspuni	kikispuni ➤	kikispuri ➤	skikispuri	kikispuri	pikispuni	spruni ➤	spruni
10	dunopi	radofo ➤	dipfopa ➤	dipspuna	kikispuri	skip	pikspuri ➤	puri ➤	puri	spruni	spikispruni
11	dipifopa ➤	dipifopa ➤	dipinuri	skipscuni ➤	skip	spikspuni ➤	kipuni ➤	kikispuri	kikipuri	skikipuni	kikiprudi
12	disa	kisiduni ➤	skikspuni ➤	skikspuni ➤	kipsnuri ➤	pikspuri	kikispuri	skikipuri	kikipuri ➤	skipuni	spikifado
13	dukofu ➤	fidinora	dipsuna	kiknuri	difopa	kip ➤	kip ➤	kip ➤	kip ➤	kip ➤	kip
14	duforu	fidinora ➤	skiknuri	kikisona ➤	kip	pikispuni ➤	kikispuni	kikispuri ➤	skifado	pikipruni ➤	pikipuni
15	radofo ➤	skiknuri ➤	sikinora	skipnuri	piksnuri ➤	pikspuri	skipuri	skifado	skikipuri ➤	pikipuni ➤	kikipruni
16	sisakaru ➤	kisada	radofo ➤	radofo ➤	rofado	pikspuni ➤	skipuri	kip	puri ➤	skikfado ➤	spikfado
17	runokupo	dokusa ➤	dipifopa	skipscuni	rofado	spikspuri	pikspuri	kikispuni	spuri	spuni	spikipruni
18	siradi ➤	dipifopa	dipispuna ➤	dipispuna	spiksnura ➤	pikspuri ➤	skikispuri ➤	skikipuni ➤	pikipuri ➤	kikipuni	spikispruni
19	kaku ➤	kaku	kaku	kikispuni	skip	skip	puni ➤	puni	spruri	skikipuni ➤	spikipruni
20	nokado	kikiduna ➤	kikinuri	skip ➤	skip ➤	skiksnuri ➤	skikspuni	kikfado ➤	kikspuri ➤	skikipruni ➤	spikfado
21	dini	saspuna ➤	saspuna ➤	dipspuni ➤	skiksnuri ➤	skif	kipuni	pikispruri ➤	pikispruri	spruri	spikfado
22	fikidi	fidinora	skiknori	kip ➤	kip ➤	kip	spuni ➤	spuri ➤	spuri	kikispuri ➤	kikpuni
23	kapinu	fidinora	kikinora ➤	kikifopa	kikispuna ➤	kikispuni	difopa ➤	pikuni ➤	kikispuri ➤	kikipruni ➤	pikipruni
24	sona ➤	sikiduni	skiknuri ➤	kiknuri ➤	skifado ➤	skifado ➤	skifado ➤	skifado	spruri	skikifado	pikifado
25	sinakupa ➤	kisada	dipifopa ➤	dipifopa	rofado	spuri ➤	puri ➤	puni	spruri ➤	pikipuri ➤	spikfado
26	dako	sikifopa ➤	kikinuri	difopa ➤	rofado	kikispuni ➤	kikspuri	spuri	spuri ➤	puni ➤	spikispuni
27	ruripi	sikinora ➤	kikinuri	dipispuna	kikspuri ➤	skikspuri ➤	kikispuri ➤	skikipuri	pikispruri ➤	kikispuni ➤	spikispruni