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Chunk-Based Memory Constraints on the Cultural Evolution of Language

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Abstract

In the fields of linguistics and cognitive science, considerable attention has been devoted to the question of how linguistic structure emerged over evolutionary time. Here, we highlight the contribution of a fundamental constraint on processing, the Now-or-Never bottleneck. Language takes place in the here and now, with the transience of acoustic speech signals and our exceedingly limited memory for sound sequences requiring immediate processing. To overcome this bottleneck, the cognitive system employs basic chunking mechanisms to rapidly compress and recode incoming linguistic input into increasingly abstract levels of representation, thereby prolonging its retention in memory. Our suggestion is that these chunk-based memory processes influence linguistic structure across multiple time scales. Chunk-based memory constraints govern language acquisition and processing on the level of the individual. Through usage, linguistic structures that are more easily chunked will tend to proliferate, thus shaping the cultural evolution of language across generations of language users. This results in a selection of learnable structures, from individual words to multiword sequences that are optimally "*chunkable*," so as to better squeeze through the Now-or-Never bottleneck. From this perspective, language can be thought of as an adaptive system that culturally evolves to fit learners' cognitive capabilities, thereby resulting in the structure it bears today.

Keywords: Cultural evolution; Language evolution; Chunking; Serial recall; Statistical learning; Language acquisition; Memory

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1. Introduction

Understanding the evolution of linguistic structure, and the processes by which learners acquire and use these structures, is a major focus of the language sciences. During the renaissance of language evolution research in the 1990s, the theoretical emphasis was on the natural selection of language-specific brain mechanisms (Pinker & Bloom, 1990) as an explanation for the richness of human linguistic capacities. With the beginning of the new millennium, however, an alternative view has come to the forefront of the literature, which reevaluates the notion of language-specific adaptations and re-formulates the question of how humans evolved sophisticated linguistic abilities. Instead of the brain evolving to be optimally suited for language, language itself is argued to have adapted to the brain, through cultural—rather than biological—evolution. Cultural evolution through repeated cycles of language use within and between generations of speakers may instead favor the selection of linguistic structures that are easily acquired and processed by existing neural mechanisms, obviating the need to evolve brain regions devoted solely to language (see Christiansen & Chater, 2008, for a review). A key remaining challenge in the study of language evolution, however, is to identify the specific constraints that drive the cultural evolution of language and to elucidate how these constraints operate at the level of individual learners and their language use across generations.

The idea that language is an evolving system in its own right has a long historical pedigree. In his book *The Descent of Man*, Charles Darwin (1871) proposed that language, similar to the evolution of biological organisms, may be subject to the forces of natural selection, with linguistic structure gradually shifting and adapting over extended periods of time. Darwin thus suggested that learnability may act as a proxy for linguistic fitness, working as a selection pressure on the survival of linguistic units in a culture's language. Furthermore, the proposal that language, rather than the brain, may have undergone significant transformation is supported by findings suggesting that language has exapted pre-existing, low-level neural circuits, and redeployed them for language. More recent culturally evolved cognitive capacities, such as mathematics, display greater functional dispersion and diversity at the neural level; language both relies on a greater number of pre-existing circuits than many other cognitive functions and is among the most widely distributed functions observed (Anderson, 2008; Anderson & Penner-Wilger, 2013). The constraints on language learning that may inform language evolution, then, are likely to be those that pose a challenge to processing more broadly.

In the current paper, we focus on a central constraint on processing and acquisition: the *Now-or-Never bottleneck* (Christiansen & Chater, 2016b). Language happens in the here and now, on a moment-to-moment basis, and the temporal dynamics of our everyday linguistic interactions have profound consequences for how we process and acquire language. The brevity and rapid rate of the speech signal pose a fundamental challenge to the cognitive system, and create a profound pressure toward immediate processing in order to deal with incoming information before it is lost. Although by no means the only constraint on language acquisition and evolution, the fleeting nature of linguistic input underscores the vital role of memory processes when considering the nature of language.

The current paper highlights how a key learning and memory process, *chunking*, provides a means by which the cognitive system can cope with the transience of language input, and how chunking may also act as a constraint on the evolution of linguistic structure. The hypothesis proposed here is that chunking influences acquisition and processing at the level of the individual, which in turn may guide patterns of language use between individuals. Through usage, certain chunks may be reinforced, while others are culled; linguistic structures that are more easily chunked will proliferate, whereas those that are not will fall out of use. This may ultimately shape the linguistic input that serves as the foundation for learning in subsequent generations, by promoting the selection of linguistic structures that can be effectively chunked.

In the following sections, we highlight the contribution of chunking to the cultural evolution of language by drawing on a wide body of research, including experimental and computational evidence. First, we introduce the Now-or-Never bottleneck and explain how chunking can ameliorate the transience of the speech signal. This is followed by a discussion of how such chunking processes might extend to the cultural evolution of linguistic structure more broadly, and their connection to language acquisition. We conclude by considering the role of chunking in cultural evolution beyond language and outline a proposal for future research in this area.

2. The Now-or-Never bottleneck

Despite the seeming ease with which we use language on a day-to-day basis, the processing challenges associated with everyday conversation are far from trivial. To start, auditory speech signals are exceedingly short-lived, on average lasting 50–100 milliseconds (Elliott, 1962; Remez et al., 2010), with comparable constraints on sign language from visual perception (Pashler, 1988). Additionally, the rate at which linguistic input is delivered is exceedingly rapid, with speakers producing approximately 10–15 phonemes per second (Studdert-Kennedy, 1986). Compared to the human auditory resolution, which is only about 10 sounds per second for non-speech acoustic input (Miller & Taylor, 1948), this rate stretches language perception to the very limit of discernibility. To make matters worse, there are strict limitations on our memory for sound sequences, with memory for auditory linguistic items ranging between 4 ± 1 (Cowan, 2001) to 7 ± 2 items (Miller, 1956) and with comparable limitations for signed languages (Wilson & Emmorey, 2006). And this challenge is even further exacerbated by the incredibly fast nature of turn-taking in interaction: Across cultures and languages, people on average take about 250 milliseconds between one person finishing his turn and the other starting hers (Levinson, 2016). In sum, linguistic input is inordinately brief, the rate at which it is encountered is very fast, and our ability to perceive and retain the input is severely restricted, yet we respond to one another very rapidly. The combination of these challenges constitutes the *Now-or-Never bottleneck* (Christiansen & Chater, 2016b), and it acts as a constraint on many aspects of perception, behavior, and memory, including the processing of visual and auditory linguistic input, as well as non-linguistic auditory, visual, and haptic input (Gallace, Tan, & Spence, 2006; Haber, 1983; Pavani & Turatto, 2008).

Because of the Now-or-Never bottleneck, the cognitive system faces a strong pressure to engage in immediate processing: The incoming sensory signal must be processed and encoded as soon as it is encountered, before it is lost or overwritten by new incoming material. One key process that is proposed to mitigate this bottleneck is *Chunk-and-Pass processing* (Christiansen & Chater, 2016b). Chunk-and-Pass processing rapidly compresses and recodes incoming sensory information into discrete units (or chunks) of varying levels of abstraction, enabling quick and efficient processing of the input. As the input is encountered, it is rapidly recoded into chunks, which are subsequently passed to the next, higher level of representation. As the bottleneck recurs at each subsequent representational level, new information is recoded into increasingly higher levels of abstraction, enabling the construction of a multilevel representation of the input that can be held in memory for longer periods of time. For example, Chunk-and-Pass processing may convert the acoustic signal into phonemes or syllables, which are chunked into morphemes, words, or multiword sequences, and subsequently into discourse representations. The same process also applies to signed languages, with slight differences because of modality-specific constraints (for further discussion, see Christiansen & Chater, 2016a). The compressed representations that result from this process are “lossy,” providing an abstract summary of the input (Pani, 2000). This suggests that an integral aspect of language acquisition involves learning how to do Chunk-and-Pass processing in the face of the Now-or-Never bottleneck—that is, learning how to build and integrate chunks quickly and efficiently, before the incoming signal is overwritten or lost.

The properties of linguistic exchanges between individuals have significant ramifications for how we use and acquire language, with chunking as a potential solution to the Now-or-Never bottleneck. Given the importance of chunking on a momentary basis, it is worth considering how the characteristics of memory in the here and now may impact language on the broader timescale of evolution. Our ability to chunk input in parallel across multiple levels of representation may be a key factor (among many) that contributes to human language’s high degree of sophistication compared to other animal communication systems (Christiansen & Chater, 2016a). Importantly, this does not mean that chunking serves as a “magic bullet” that can account for the entirety of why we have language while other species do not (see Smith; this issue). What we do suggest is that a significant constraint on the evolution of linguistic structure stems from online chunking processes that enable the construction of multilevel representations of incoming input in real time.

3. Chunking and cultural evolution

In considering the moment-to-moment dynamics of language, it is also important to situate linguistic interactions within its broader social context. Language learning and use do not take place in a vacuum. Rather, it is governed by communicative exchanges between individuals within and across generations. Chunk-and-Pass processing operates by compressing linguistic input (on the timescale of the utterance, in seconds) into chunks of varying levels of representation, which are subsequently used to update individuals' expectations during comprehension and production throughout their lifetime (decades). This process, in turn, affects the structure of language over historical time (millennia). The suggestion here is that the process of cultural evolution tailors linguistic input to fit existing cognitive capacities and their associated constraints, to maximize the learnability of the input. Linguistic patterns that are more easily processed through the Now-or-Never bottleneck are passed on to subsequent generations, whereas patterns that are difficult to process become disfavored in usage and die out. Importantly, however, this does not mean that languages become optimally learnable, as other pressures may work against the selection for learnability. For instance, usability constraints such as production efficiency have been shown to take precedence over learnability in certain cases (Fay & Ellison, 2013). Moreover, the history of a given language family can also influence the specific patterns emerging within a particular language (Dunn, Greenhill, Levinson, & Gray, 2011), which may not be governed by learnability alone. Thus, while there are a multitude of factors that may produce differences across the world's languages, the argument put forth here simply states that short-term memory limitations—and the chunking processes used to overcome them—are an important component of cultural evolution (D'Andrade, 2001).

Sequential learning mechanisms have previously been hypothesized to play a pivotal role in language acquisition and, in turn, shape the cultural evolution of language by promoting the endurance of easy-to-process structures (Christiansen, Dale, Ellefson, & Conway, 2002). Here, we refine this perspective by highlighting the contribution of chunking, which has long been suggested to be key to learning and memory (e.g., Christiansen, in press; Miller, 1956). But can repeated processes of chunking across generations of language learners actually shape aspects of linguistic structure? A recent study by Cornish, Dale, Kirby, and Christiansen (2016) attempted to answer this question using an experimental version of cultural evolution known as "iterated learning" (see Scott-Phillips & Kirby, 2010, for a review). Iterated learning experiments can be thought of as a lab-based version of the childhood game of telephone: Participants are organized in "generational" chains, in which what one person learns is passed on to the next one in a chain to simulate the cultural transmission of linguistic structure.

In the Cornish et al. study, participants were trained on sequences of consonants, which they were subsequently asked to recall. The first participant in a chain would receive a set of letter strings that contained a flat distributional structure, very much unlike natural language. Critically, the experiment was designed to be non-communicative and unlike language—participants were told they were in a memory experiment, and the session made no reference to language. The responses supplied during recall from one participant were then used as the input for the next participant across 10 generations of learners (and across eight separate evolutionary chains), thereby emulating cultural transmission.

The results showed that over generations, participants' responses exhibited a cumulative increase in chunk-based structural reuse, leading to more accurate recall of the sequences. Specifically, the results revealed a notable increase in distributional structure such that over subsequent generations, participants implicitly came to favor the *reuse of chunks* across strings, which significantly improved learning. This demonstrates that through the transmission process, chunk-based memory constraints implicitly gave rise to reusable chunks that facilitated learning and memory for novel structures.

The distributional structure of the experimental data was compared to a corpus of child-directed speech (CHILDES; MacWhinney, 2000), to determine whether common structural properties could be found in both sets of data. Comparisons between the two data sets revealed striking parallels in the structural reuse of chunks in the final generation of the experiment and the child-language data. Cornish et al. (2016) interpreted their analyses as suggesting that cultural evolution, both in the lab and in the real world, may favor the selection of structures that attenuate the challenges posed by the Now-or-Never bottleneck. To ensure that these patterns were in fact reflective of chunk-based memory processes, and not simply a consequence of the strings being generated from a limited set of elements, network analyses were repeated on three additional types of human-generated sequences: word frequencies, passwords, and random numbers. The analysis of these sequences failed to reveal similar patterns of chunk reuse as those displayed in the experimental data, suggesting that chunk-based memory processes may be dependent on the learned material possessing structural relationships between one another—such as those found in language—to promote chunk reuse. Overall, the findings by Cornish et al. suggest that through the process of cultural evolution, constraints on chunk-based processing may have shaped linguistic structure.

Another iterated learning study provides parallel findings from non-human primates, further corroborating the role of chunking processes in shaping culturally evolved structure (Claidière, Smith, Kirby, & Fagot, 2014). To test whether individual memory constraints in non-human primates could lead to the emergence of systematic structure, 15 Guinea baboons were trained to memorize and recall the positions of four red squares in random configurations on a computer screen. After training, an iterated learning procedure was implemented, where the output of one baboon's memory performance on a set of 50 configurations subsequently served as the input for the next baboon. Similar to the findings reported for human subjects above, the configurations of squares took on a recurring structure across generations, wherein they became organized into grids with all four squares connected in an arrangement referred to as a "tetromino." The development of this pattern is striking, given that tetrominos comprise only 6.2% of the possible grid configurations.

Mirroring the reuse of chunks reported by Cornish et al. (2016), baboon performance on the memory task also significantly increased over generations (reaching approximately 72% by the final generation), which suggests that tetrominos may be easier for the baboons to spatially chunk and recall relative to other configurations. This idea parallels evidence from the human literature, which demonstrates that the presence of recurring visual statistical regularities can allow learners to compress information into chunks, which in turn strengthens visual working memory representations of that information (Brady, Konkle, & Alvarez, 2009). Scores on tetrominos during transmission trials were significantly higher than non-tetrominos, suggesting that the advantage yielded by the presence of tetrominos may be dependent on the accumulation of this structure within the training set. Thus, the reuse of certain structures—or chunks—increases their stability, which in turn results in the progressive accumulation of easy-to-learn chunks that foster better learning outcomes for subsequent generations. Together, the human and non-human primate results from iterated chunking point to a potential role for general primate sequence learning skills in the cultural evolution of language (a suggestion also supported by similar neural substrates for such learning across primates; see Milne, Wilson, & Christiansen, 2018, for review).

The results above suggest that structural reuse through generational transmission appears to emerge under chunk-based cognitive constraints, in tasks that are explicitly non-communicative and non-semantic in nature. However, sociopragmatic constraints on communication are also likely to play a role; in addition to being learnable, human language also faces a strong pressure to be expressive, to ensure effective communication (Christiansen & Chater, 2008). A series of recent computational simulations and iterated learning experiments by Kirby, Tamariz, Cornish, and Smith (2015) highlight how linguistic compression—which may be construed as the formation of chunks (e.g., Brady et al., 2009; Christiansen & Chater, 2016b)—arises from natural biases toward simple, learnable linguistic structures that permit the use of compressed mental representations under communicative conditions. In this experiment, dyads of participants were tasked with learning an artificial language paired with abstract figures. After training, the dyads were required to communicate with one another, taking turns as both speaker and listener. The speaker saw a figure from the training set on the screen and was asked to label the figure for the listener. The listener was tasked with selecting the correct figure from six possible figures after reading the speaker's label. The responses from one of the participants were then randomly selected to serve as the input for the next pair of participants. The structure of the input language shifted over generations of learners such that individual words began to encode the shape, fill, and texture of the figures by implicitly generating smaller chunks that encoded this meaning, and incorporating them into larger chunks, in a similar manner to the results of Cornish et al. (2016). The results further showed that at the final generation, error rate and communicative success had significantly improved relative to the first generation, supporting the idea that better mastery of the language as a result of this culturally evolved structure also aided communicative efficacy between pairs of individuals. Taken together with the findings by Cornish et al., biases that arise from online learning and memory capacities appear to influence the transmission of easy-to-process structures in both communicative and non-communicative contexts.

The work on cultural evolution points to an intimate connection between the evolution of language and how language is acquired and used (e.g., Brighton, Kirby, & Smith, 2005; Chater & Christiansen, 2010; Kirby & Christiansen, 2003). Language acquisition by novice learners appears to create a strong pressure for simplicity or compressibility, and the use of language between individuals may cater to this need in both communicative and non-communicative contexts. The linguistic patterns that emerge in the world's languages may, therefore, be in part, attributable to the interactions of language use on these different timescales. For example, cultural transmission can increase the predictability of lexical patterns (Smith & Wonnacott, 2010), wherein nouns can become chunked with specific marker words in a way that resembles grammaticalization. Similarly, over generations, consistent head-orderings can emerge due to linguistic adaptation to sequence memory constraints (Christiansen & Dale, 2004; Reali & Christiansen, 2009). The result of cultural transmission may thus be seen as the creation and proliferation of learnable structures, from individual words to multiword sequences that are optimally "*chunkable*" to help cope with the Now-or-Never bottleneck. But does chunking actually play a role in language acquisition and use? To answer this question, we next discuss the importance of chunking skills for statistical learning and language processing, which provides more concrete examples of why chunking may hold the degree of precedence in cultural evolution argued for in the current paper.

4. Implications for language acquisition

Although historically, language acquisition and the concept of chunking have existed in separate literatures, statistically based chunking may also play a key role in the processes typically studied in the field of language acquisition, namely that of implicit statistical learning (Christiansen, in press). The exact computational basis of statistical learning has to date remained largely underspecified despite much debate (Romberg & Saffran, 2010). Following the proposal of Christiansen (in press), we suggest that statistical learning may be reconceptualized as statistically based chunking. Given the ubiquity of statistically driven computations in learning across domains, examining the role of chunking in language acquisition may provide further insights into how cultural evolution might be constrained by chunking abilities, as discussed in the previous section. Recent evidence by Isbilen, McCauley, Kidd, and Christiansen (2017) suggests that chunk-based recall can serve as an effective measure of learning in statistical learning-based tasks. Participants' ability to chunk and subsequently recall the words presented in the artificial language they were exposed to significantly increased memory retention compared to random control strings, in line with findings showing that short-term recall reflects long-term distributional learning (Jones & Macken, 2015). Similarly, chunk-based computational models have successfully captured classic findings of statistical learning, both at the level of individual words (PARSER; Perruchet & Vinter, 1998) and at the level of multiword units (CBL; McCauley & Christiansen, 2014, in press). In the case of CBL, online chunking can account for learning, comprehension, and production, suggesting, in line with the Now-or-Never bottleneck framework, that a substantial component of language acquisition simply amounts to learning how to process linguistic input (Chater, McCauley, & Christiansen, 2016).

The vital role of chunking in language processing is further supported by several individual differences studies that highlight the close relationship between chunking skills and language processing. To start, chunking aptitude in children predicts their ability to acquire new words (Jones, 2012), in accordance with a long line of work indicating that chunking-based memory measures such as non-word repetition reliably predict language skills in both impaired and normal populations (Gathercole, 2006). Similar results have been reported in adults, with chunking serving as a robust predictor of individual differences on a variety of language processing abilities. Sensitivity to sequential structure as measured through recall performance significantly correlates with people's ability to use word predictability to facilitate speech processing in degraded listening conditions, when controlling for short-term and working memory, as well as intelligence, attention, and vocabulary knowledge (Conway, Bauernschmidt, Huang, & Pisoni, 2010). Furthermore, individuals who demonstrate more advanced chunking abilities of statistically derived letter sequences are also found to be better at online sentence processing (McCauley & Christiansen, 2014). These findings appear to operate at different levels of linguistic abstraction, with phonological chunking positively correlating with the ease of processing complex sentences that feature phonological overlap, and with multiword chunking ability being associated with the processing of sentences involving long-distance number agreement with local interference (McCauley, Isbilen, & Christiansen, 2017). Taken together, the evidence suggests that many aspects of language learning and processing appear to be mediated by chunking abilities, even if the literatures have remained largely separate to date. Given the importance of Chunk-and-Pass processing to individual learning and as a predictor of linguistic proficiency, this reinforces the notion that it may also be key to language change more broadly.

5. Chunking in cultural evolution of language and beyond

From a cultural evolution perspective, language faces a vital drive to fit our cognitive capabilities; although humans can survive without language, language likely would not exist in the absence of human learners (Christiansen, 1994; Christiansen et al., 2002). The ability to effectively perform Chunk-and-Pass processing appears to play a pivotal role not only in moment-by-moment language comprehension and production but also has fundamental implications for language outcomes over the course of development, and processing abilities into adulthood. Although it is far from being the only contributor to linguistic change, our argument is compatible with other proposals of learnability-driven linguistic structure. For example, multiple-cue integration is an important feature of language acquisition and evolution (Christiansen, 2013), and it may be reconceptualized as the encoding of multiple redundant sources of information either within chunks, or that point to chunk boundaries. By recruiting these cues, language can become more expressive and complex, while still being learnable. Similarly, although cultural evolution incontrovertibly involves social learning, there is ample room for further elaboration on how the dynamics of social interactions may influence chunking behavior, such as its interaction with parental contingency (Goldstein, King, & West, 2003), and turn-taking dynamics in conversations between individuals (Levinson, 2016).

One potential counterargument to the current hypothesis is the role of hierarchical structure in language (such as those found in syntactic tree structures; Chomsky, 1975), given that Chunk-and-Pass processing encodes incoming information into chunks that are local in nature. However, during language acquisition and use, sequential processing appears to be preferred to hierarchical processing when performing online comprehension, with individual words chunked into multiword units that share a linear order, but no overarching structure (Frank, Bod, & Christiansen, 2012). Moreover, the chunked representations gleaned from learning are specific to the properties of the input, which suggests that learners are not extracting abstract grammatical rules about language, but instead utilize distributional information to form words and multiword units (e.g., Arnon & Christiansen, 2017; McCauley & Christiansen, in press). These results are in line with findings from usage-based accounts of language acquisition, wherein learners are thought to acquire language based on concrete expressions (or chunks) present in the input they have received (e.g., Tomasello, 2003).

Importantly, the perspective outlined here is not necessarily limited to language. Indeed, the common suggestion that language may have "piggy-backed" on pre-existing neural substrates meshes with the finding that chunking extends to other domains. Similar to language, the structure of music makes use of repeated units that are often organized into phrases, displays complex temporal dynamics, and has also been described as relying on chunking processes for its perception (Godøy, Jensenius, & Nymoen, 2010), and its production (Van Vugt, Jabusch, & Altenmüller, 2012). Accordingly, recent experimental evidence suggests that similar to language, rhythmic structures can become more systematic and easier to learn through cultural evolution (Ravignani, Delgado, & Kirby, 2017), which may explain the presence of comparable musical structures across divergent cultures. Similarly, chunking processes also appear to govern the segmentation of events. Language has been proposed as a form of action perception (Maier & Baldwin, 2016), which is also subject to the Now-or-Never bottleneck. Although chunking is understudied in other animal species, patterns of phrasal-level change in humpback whale song are found to be driven by cultural transmission in a similar manner as human language (Garland, Rendell, Lamoni, Poole, & Noad, 2017). This indicates that the role of chunking in cultural evolution is not human specific, but extends to other social learning species.

The ubiquity of the Now-or-Never bottleneck provides ample opportunity for further investigation of the role of chunking in numerous areas. We envision the future of cultural evolution research to include forays into the areas outlined above, with potential intersections with second language learning and bilingualism. Languages that are spoken by a large number of non-native speakers tend to be less morphologically complex than languages spoken by fewer individuals (Lupyan & Dale, 2016), suggesting that cultural evolutionary processes work to ease acquisition for second language learners. How chunking strategies may be constrained by previous linguistic experience—and how such diverse strategies influence the evolution of linguistic structure—may be a fruitful area for future enquiry. Additionally, recent years have seen a surge of interest in the cultural evolution of signed languages, particularly with the emergence of Al-Sayyid Bedouin and Nicaraguan sign languages. The application of lab-based iterated learning procedures to sign language may help elucidate the contribution of memory constraints to the cultural evolution of structure in visual linguistic systems. Lastly, whether cultural transmission may have shaped the evolution of chunking processes themselves requires further investigation (Heyes, 2012) and provides fertile ground for cross-species and cross-disciplinary research on the cultural evolution of cognition.

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