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Abstract words: 61
Text words: 1,280
References words: 812
Total words: 2,153

The Bottleneck May Be the Solution, Not the Problem

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Abstract.

As a highly consequential biological trait, a memory "bottleneck" cannot escape selection pressures. It must therefore co-evolve with other cognitive mechanisms rather than act as an independent constraint. Recent theory and an implemented model of language acquisition suggest that a limit on working memory may evolve to help learning. Furthermore, it need not hamper the use of language for communication.

The target paper by Christiansen and Chater (C&C) makes many useful and valid observations about language that we are happy to endorse. Indeed, several of C&C's major points appear in our own papers. These include: (i) an argument to the effect that non-chunked, "analog" approaches to language cannot compete with "digital" ones that use combinatorics over chunks (Edelman, 2008b); (ii) the use of chunking in a model of language acquisition and generation that learns incrementally, under constraints on memory (Goldstein et al., 2010; Kolodny et al., 2015b), and the possible evolutionary roots of these features of language (Lotem and Halpern, 2012; Kolodny et al., 2014, 2015a); (iii) the realization that language experience has the form of a graph (Solan et al., 2005; cf. Edelman, 2008a, p.274), which in the target article takes the form of a "forest tracks" analogy; (iv) a proposed set of general principles for language acquisition and processing (Goldstein et al., 2010), one of which is essentially identical to C&C's "Now-or-Never Bottleneck." However, our theory is critically different in its causality structure. Rather than assuming that the memory limit is a fixed constraint to which all other traits must adapt, we view it as an adaptation that evolved to cope with computational challenges. Not only does doing this bring it more in line with (extremely well motivated) standard practice in evolutionary biology, it is also more consistent with research findings and raises numerous important research issues. We expand on these points below.

No biological trait can be simply assumed as a "constraint"

Viewing the "Now-or-Never Bottleneck" as an evolutionary constraint to which language adapts — the idea on which C&C build their case — is unwarranted. In evolutionary theory, biological constraints — as opposed to constraints imposed by physics and chemistry, which are not subject to biological evolution — cannot simply be assumed: they must be understood in terms of trade-offs among selective pressures. Clearly, birds wings evolved under aerodynamic constraints rather than vise versa. However, biological traits such as memory are not exempt from evolving. In proposing a bottleneck to which everything else in the system must adapt while the bottleneck itself remains fixed and independent (Figure 1 in the target article), C&C implicitly assume that it cannot evolve.

To justify such an assumption, C&C should have offered evidence of stabilizing selection pressures that act against genetic variants coding for a broader or narrower bottleneck, and thereby affecting cognition and ultimately fitness. Alternatively, they might have assumed that the biological mechanisms underlying the memory bottleneck cannot be genetically variable — an odd assumption, which runs counter to substantial evidence in humans of (i) a range of values of verbal memory decay (Mueller and Krawitz, 2009), including in particular the increased extent of verbal working memory in individuals with Asperger's (Cui et al., 2010); (ii) heritable variation in language and in word memory (Stromswold, 2001; van Soelen et al., 2011) and in working memory (Blokland et al., 2011; Vogler et al., 2014); and (iii) variation in perceptual memory across animal species (Mery et al., 2007; Lind et al., 2015). Given that heritable variation in a trait means that the trait can respond to selection (e.g. Falconer, 1981), it is likely that the bottleneck *can* evolve, and that it is what it is because individuals with longer or shorter verbal working memory had lower rather than higher biological fitness.

If language is supported by domain-general mechanisms, verbal memory is even less immune to evolution

If the emergence of language constitutes a recent and radical departure from other cognitive phenomena, it is in principle possible that working memory evolved and stabilized prior to and separately from the "increasingly abstract levels of linguistic representation" posited by C&C. However, there are good arguments in support of a domain-general view of language (e.g., Chater and Christiansen, 2010). In particular, linguistic representations and processes are hardly as modular as the target paper assumes (Onnis and Spivey, 2012). Furthermore, theories of neural reuse (Anderson, 2010) point to the massive redeployment of the same mechanisms for new functions: despite specialization, the same brain regions are involved in numerous cognitive functions and diverse task categories. If circuits that support language continue contributing to non-linguistic functions (including working memory), it is difficult to see how a memory bottleneck could be a prior and independent constraint on language, rather than a trait that continues to evolve under multiple selective pressures that include language.

Cultural evolution leads to niche construction

If the verbal memory bottleneck can indeed evolve, language is the niche in which it does so. Surprisingly, however, in their discussion of the cultural evolution of language (section 5), C&C ignore the intimate connection between cultural evolution and niche construction (reviewed by Odling-Smee et al., 2003). Thus, C&C assume that "linguistic patterns, which can be processed through that bottleneck, will be strongly selected," yet ignore the possibility that, in addition to that, there is also selection for individuals with bottleneck types that can better process linguistic patterns. If language is important for human survival, and if memory parameters have some genetic variance, this must have happened.

The bottleneck may be the solution, not the problem

As we have suggested (Lotem and Halpern, 2008; Onnis et al., 2008; Goldstein et al., 2010; Lotem and Halpern, 2012), a limited working memory may be an adaptation for coping with the computational challenges involved in segmentation and network construction. (Importantly, regardless of whether or not this specific hypothesis is correct, entertaining such hypotheses is the only way of distinguishing a function from a constraint; cf. Stephens and Krebs, 1986, chapter 10.)

A recently implemented model that includes this hypothesis has been tested on tasks involving language acquisition and use, birdsong, and foraging (Kolodny et al., 2014, 2015a; Menyhart et al., 2015; Kolodny et al., 2015b) The model includes a time window during which natural and meaningful patterns are likely to recur and thus to pass a test for statistical significance (while spurious patterns gradually decay and are forgotten). Rather than viewing the duration of the window as a constraint, we emphasize the idea that it must co-evolve with the mechanisms influencing the distribution of data, so as to produce the most effective structure of memory representations (Lotem and Halpern, 2012).

We do agree with C&C regarding some of the consequences of the memory bottleneck, such as the need for online incremental construction of hierarchical representation. Indeed, our model effectively implements what C&C call "Chunk-and-Pass" (Kolodny et al., 2015b).[1] We believe, however, that the ultimate constraint on learning structure (such as that of language) in time and space is not the memory bottleneck in itself, but rather the computational challenges of chunking the data and of building hierarchies.

Biological communication is about affecting behavior, not pumping bits

Our final point focuses on the communicative function of language. Viewing a memory window as a communication "bottleneck" suggests that massive amounts of information must flow through the channel in question. Our view is that the key feature of external input is how it affects the rich network of connotations and interconnections already present in the listener's brain (cf. Edelman, 2015, sec. 2.3). Communication is about generating adaptive behavioral changes (Burghardt, 1970; Green and Marler, 1979) — it must provide the listener cues relevant to decision making. To do this, a signal must be informative and reliable in the given context (Leger, 1993); the amount of information is not the main issue, unless it is an indication of motivation or quality (as in a complex courtship song; Lachmann et al., 2001). This implies that evolutionary selection in language is for the content of the message and how it fits into the information already represented by the recipient; a bottleneck may not impose significant constraints here.

[1] As C&C note, correctly, with regard to the Chunk-and-Pass idea, "it is entirely possible that linguistic input can simultaneously, and perhaps redundantly, be chunked in more than one way." This suggests that chunking on its own, especially when carried out recursively/hierarchically, is likely to severely exacerbate the combinatorial problem faced by the learner, rather than cleanly resolve the bottleneck issue.

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