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It's about Time:
Adding Processing to Neuroemergentism

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Hernandez, Claussenius-Kalman, Ronderos, Castilla-Earls, Sun, Weiss and Young (in press; henceforth HCRCSWY) offer a synthesis of a number of related theories seeking to understand the neural underpinnings of higher-level cognitive skills as they emerge across evolution and development. The resulting framework—dubbed Neurocomputational Emergentism (or Neuromergentism)—focuses on how human-specific cognitive abilities—such as reading and arithmetic—may capitalize on existing neurocognitive functions interacting with developmental processes. Thus, HCRCSWY see the emergence of such complex cognitive skills as corresponding to the suggestion by Bates, Benigni, Bretherton, Camaioni and Volterra (1979: p. 3) that "language is a new machine built out of old parts."

Given our own prior work (e.g., Christiansen & Chater, 2008) arguing that language has been shaped by the brain through processes of cultural evolution (as discussed by HCRCSWY), we are sympathetic toward the neuroemergentist framework. Indeed, we have previously discussed the relationship between our approach, cultural recycling, and the neural reuse accounts (Christiansen & Müller, 2014), stressing the importance of evolutionary and developmental perspectives (Chater & Christiansen, 2010; see Christiansen & Chater, 2016a, for an integrated framework for the evolution, acquisition and processing of language). Here, though, we highlight a key missing component of the neuroemergentist account: pressures from processing. Although HCRCSWY underscore the dynamic nature of development, they do not consider the importance of having to process and act on input in real-time. In this commentary, we therefore discuss how processing constraints may contribute explanatory value to neuroemergentism, focusing on language for the sake of brevity.

Linguistic exchanges occur in real time, on a moment-to-moment basis. The rapid rate of linguistic input (10-15 phonemes per second; Studdert-Kennedy, 1986), and its transience (50-100 milliseconds; Elliott, 1962; Remez et al., 2010) pose a fundamental challenge to processing, with information being delivered at a rate that strains the limit of the human auditory threshold (~10 non-speech sounds; Miller & Taylor, 1948). The additive effects of the linguistic signal's fast rate and fleeting nature are further exacerbated by the limitations of human working memory, which on average can retain no more than 4 ± 1 (Cowan, 2001) to 7 ± 2 items at a time (Miller, 1956). Together, these challenges form a *Now-or-Never Bottleneck* (Christiansen & Chater, 2016a,b): if input is not processed as soon as it is encountered, the signal is either overwritten or interfered with by new incoming material. In order to sustain linguistic functions, the cognitive system must overcome this bottleneck. Importantly, the Now-or-Never Bottleneck is not limited to linguistic processing. Rather, it extends to the perception of haptic (Gallace, Tan & Spence, 2006), visual (Haber, 1983), and non-linguistic auditory input (Pavani & Turatto, 2008). Understanding how the cognitive system deals with this bottleneck can therefore provide fundamental insights into the emergence not only of language, but also of the other complex cognitive abilities discussed by HCRCSWY.

The dynamics of how the linguistic signal unfolds in real-time underscores the importance of memory processes in considering how the cognitive system deals with the Now-or-Never bottleneck. Building on the basic memory process of chunking, Christiansen and Chater (2016b) suggest that the cognitive system engages in *Chunk-and-Pass Processing* to overcome the bottleneck. Using Chunk-and-Pass Processing, the cognitive system builds a multi-level representation of incoming input, by rapidly compressing and recoding the input into chunks of increasing levels of abstraction as soon as it is encountered. This process of compression and abstraction enables information to be held in memory for longer periods of time. To provide an example from language, the raw acoustic input may be chunked into syllables, syllables into words or multi-word phrases, and so on up to complex representations of the discourse. Throughout the multi-level process of chunking, top-down information driven by predictions from semantic, pragmatic and discourse expectations augmented by real-world knowledge will enrich the resulting representations. The reverse is hypothesized to happen during language production, with the intended message being broken down into chunks of increasing specificity.

Critically, chunking has been shown to be central to the perception of many different kinds of input, including visual (Brady, Konkle & Alvarez, 2009), spatial (Chase & Simon, 1973), and musical information (Vugt, Jabusch & Altenmüller, 2012). This suggests that basic chunking processes, which might have initially evolved to support a variety of cognitive functions, may have later been redeployed for language[1]. The tight connection between chunking and language is corroborated by work showing that chunking can capture key phenomena of linguistic development, including the statistical learning of individual words (McCauley & Christiansen, 2011; Isbilen, McCauley, Kidd & Christiansen, 2017), and of multi-word phrases (McCauley & Christiansen, 2014). Furthermore, individual differences in chunking abilities serve as a strong predictor of individual differences in language processing (McCauley, Isbilen & Christiansen, 2017).

[1] The chunking processes described here may seem to resemble the notion of Merge proposed within the Minimalist Program (e.g., Berwick & Chomsky, 2015). There are, however, several important differences, including 1) Merge is strictly binary creating an unordered set of exactly two elements, whereas chunking can combine more than two elements and preserves order; 2) Merge is suggested to be specific to language, capturing recursion (Chomsky, 2010), whereas chunking is a general memory process applying not only to language but throughout cognition (Christiansen & Chater, 2016b); and 3) Merge has been argued to arise from a singular mutational event during human evolution (Chomsky, 2010), whereas chunking processes are not unique to humans (Isbilen & Christiansen, submitted).

From the viewpoint of the Chunk-and-Pass framework, language acquisition involves learning how to process input – that is, learning how to effectively chunk linguistic input using top-down information in the face of the Now-or-Never bottleneck. Importantly, the real-time pressures from language processing not only shapes language acquisition, but also the cultural evolution of language itself. Linguistic patterns that more easily squeeze through the Now-or-Never bottleneck by way of Chunk-and-Pass processing are more likely to proliferate in the language. Through repeated cycles of learning and use, cultural evolution will have driven languages towards linguistic patterns that better fit through the bottleneck. This powerful selectional pressure (alongside others, e.g., for semantic and pragmatic richness) gave rise to the structures observed in the world's languages today.

The hypothesis that repeated chunking amplified by cultural evolution can give rise to language-like structure has recently been tested using a lab-based cultural transmission experiment. The experiment uses the framework of iterated learning (e.g., Smith, Kirby & Brighton, 2003), which resembles the childhood game of "telephone." Learners are exposed to stimuli and attempt to recall those stimuli; the result becomes the input to the next learner, and so on for several "generations" of learners. In the study, participants were exposed to a small set of consonant strings that participants were subsequently asked to recall (Cornish, Dale, Kirby & Christiansen, 2017). The answers provided at recall were given as the training input for the next participant, thereby simulating cultural transmission. Importantly, at no point during the experiment were participants told that their responses would be supplied to the following participant, nor was any reference made to language – participants were simply informed that they were partaking in a memory experiment. The first training set was designed to have a flat distributional structure, which as the experiment progressed spontaneously became increasingly structured in a way that facilitated learning. Notably, implicit memory biases gave rise to *chunk reuse*, whereby chunks of consonants were reused across multiple different strings in the training corpus. This increase in distributional structure in turn led to a significant increase in string recall, with considerably higher recall accuracy of strings in the final generation (49%), compared to the fairly low recall in the first generation (23%). Furthermore, a comparison of the distributional patterns in the final generation to a corpus of child-directed speech (CHILDES; MacWhinney, 2000) revealed similar patterns of chunk reuse, suggesting that chunk-based memory constraints may play a central role in shaping structural reuse not only in the lab, but also in natural language.

Relatedly, insights from the nonhuman primate literature reveal similar patterns. An iterated learning task with baboons demonstrates that, as for humans, cultural transmission can give rise to particular shape configurations that are more easily learned (Claidière, Smith, Kirby & Fagot, 2014). Similar to the human data, a pattern of structural reuse was found, which in turn facilitated the baboon's memory for the shape configurations by the final generation of learners. Additionally, as the structure of the input became more learnable, so did the fidelity of transmission between generations. This suggests that cultural transmission selects for learnability by both removing structures that are not as easy to chunk, and by preserving those that are more easily processed in the face of the Now-or-Never bottleneck.

Although the findings by Cornish et al. (2017) and Claidière et al. (2014) were derived from tasks that were non-communicative and non-language like in nature, similar patterns have also been found in contexts that more closely simulate natural language interactions. Under such conditions, the progression of chunk reuse proceeds in a similar manner (Kirby, Tamariz, Cornish & Smith, 2015), with smaller sub-units encoding specific semantic dimensions that are incorporated into larger words. The incorporation of these smaller chunks into larger lexical items results in increased expressivity of a language, and in increased communicative success between its users.

Similarly, the incorporation of multiple cues in natural language can also facilitate both the usefulness and learnability of linguistic structures. Because the Now-or-Never Bottleneck makes back-tracking very hard, the language system needs to rely on all available information to be right-the-first-time when chunking the input. Fortunately, linguistic input is replete with probabilistic cues to linguistic structure (see Monaghan & Christiansen, 2008, for a review). For example, the systematic relationship between the sound of a word and its grammatical category is a prevalent feature of many languages, including English, French, Dutch, and Japanese (Monaghan, Christiansen & Chater, 2007), and similar systematicity has also been found in British Sign Language (Vinson, Thompson, Skinner & Vigliocco, 2015). This systematic relationship between lexical category and phonological cues, wherein nouns and verbs tend to sound differently, is found to facilitate the learning of word categories in both children and adults (Fitneva, Christiansen & Monaghan, 2009; Brooks, Braine, Catalano, Brody & Sudhalter, 1993). It is the availability of cues like these that allows language to be as expressible as it is while still being able to squeeze through the bottleneck. Through cultural evolution, the language system has recruited a multitude of probabilistic cues, which have become incorporated into the structure of language to make it easily learned and processed (Christiansen, 2013; Christiansen & Dale, 2004). In sum, the interplay of chunk-based memory constraints and cultural evolution work together to ensure both the learnability and communicative efficacy of language.

In summary, we have argued that language processing in the here-and-now has important implications for acquisition and evolution. How language unfolds on the timescale of milliseconds has a deep impact across millennia. The manner in which language is processed by individuals shapes linguistic structure over many generations, by promoting the preservation and proliferation of sequences that are effectively chunked-and-passed through the Now-or-Never bottleneck (Christiansen & Chater, 2016a,b; Isbilen & Christiansen, submitted). Thus, language evolution and linguistic change are seen as synonymous, with the item-based tinkering over many generations of learners resulting in the structures that are observed in languages today. In contrast to accounts that argue for the biological adaptation of language-specific brain areas (e.g., Pinker & Bloom, 1990), the cultural evolution account suggests that language may be seen as the redeployment of existing computations and circuits for novel purposes (Anderson 2008; Anderson & Wilger, 2013), with memory-based constraints being catered to through cultural rather than biological change. In line with the neuroemergentism framework, language evolution may be seen as the successful exaptation of pre-existing chunk-based learning and memory skills, repurposed for use with a new form of input.

References

Anderson, M. L. (2008). Circuit sharing and the implementation of intelligent systems. *Connection Science*, *20*, 239-251.

Anderson, M. L., & Penner-Wilger, M. (2013). Neural reuse in the evolution and development of the brain: Evidence for developmental homology? *Developmental Psychobiology*, *55*, 42-51.

Berwick, R. C., & Chomsky, N. (2015). *Why only us: Language and evolution*. Cambridge, MA: MIT press.

Brady, T. F., Konkle, T., & Alvarez, G. A. (2009). Compression in visual working memory: Using statistical regularities to form more efficient memory representations. *Journal of Experimental Psychology: General*, *138*(4), 487.

Brooks, P. J., Braine, M. D., Catalano, L., Brody, R. E., & Sudhalter, V. (1993). Acquisition of gender-like noun subclasses in an artificial language: The contribution of phonological markers to learning. *Journal of Memory and Language*, *32*(1), 76.

Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology*, *4*(1), 55-81.

Chater, N. & Christiansen, M.H. (2010). Language acquisition meets language evolution. *Cognitive Science, 34,* 1131-1157.

Chomsky, N. (2010). Some simple evo devo theses: How true might they be for language? In R.K. Larson, V. Déprez & H. Yamakido (Eds.), *The evolution of human language* (pp. 45-62). Cambridge: Cambridge University Press.

Christiansen, M. H. (2013). Language has evolved to depend on multiple-cue integration. In R. Botha & M. Everaert (Eds.), *The evolutionary emergence of language: Evidence and Inference* (pp. 253-255). Thousand Oaks, CA: Sage Publications.

Christiansen, M. H., & Chater, N. (2008). Language as shaped by the brain. *Behavioral and Brain Sciences*, *31*, 489-509.

Christiansen, M.H. & Chater, N. (2016a). *Creating language: Integrating evolution, acquisition, and processing*. Cambridge, MA: MIT Press.

Christiansen, M. H., & Chater, N. (2016b). The Now-or-Never bottleneck: A fundamental constraint on language. *Behavioral and Brain Sciences*, *39*, e62.

Christiansen, M. H., & Dale, R. (2004). The role of learning and development in the evolution of language. A connectionist perspective. In D. Kimbrough Oller & U. Griebel (Eds.), *Evolution of communication systems: A comparative approach. The Vienna Series in Theoretical Biology* (pp. 90-109). Cambridge, MA: MIT Press.

Christiansen, M.H. & Mueller, R.-A. (2014). Cultural recycling of neural substrates during language evolution and development. In M.S. Gazzaniga & G.R. Mangun (Eds.), *The Cognitive Neurosciences V* (pp. 675-682). Cambridge, MA: MIT Press.

Claidière, N., Smith, K., Kirby, S., & Fagot, J. (2014). Cultural evolution of systematically structured behaviour in a non-human primate. *Proceedings of the Royal Society of London B: Biological Sciences*, *281*(1797), 20141541.

Cornish, H., Dale, R., Kirby, K. & Christiansen, M. H. (2017). Sequence memory constraints give rise to language-like structure through iterated learning. *PLoS ONE, 12(1): e0168532.*

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 87-185.

Elliott, L.L. (1962). Backward and forward masking of probe tones of different frequencies. *Journal of the Acoustical Society of America, 34*, 1116-1117.

Fitneva, S. A., Christiansen, M. H., & Monaghan, P. (2009). From sound to syntax: Phonological constraints on children's lexical categorization of new words. *Journal of Child Language*, *36*(05), 967-997.

Gallace, A., Tan, H. Z., & Spence, C. (2006). The failure to detect tactile change: A tactile analogue of visual change blindness. *Psychonomic Bulletin & Review*, *13*, 300-303.

Haber, R. N. (1983). Stimulus information and processing mechanisms in visual space perception. In *J. Beck, B. Hope & A. Rosenfeld* (Eds.), *Human and machine vision* (pp. 157-235). New York: Academic Press.

Hernandez, A.E., Claussenius-Kalman, H. L. Ronderos, J. Castilla-Earls, A. P., Sun, L., Weiss, S. D. & Young, D. R. (in press). Neuroemergentism: A framework for studying cognition and the brain. *Journal of Neurolinguistics*.

Isbilen, E.S. & Christiansen, M.H. (submitted). *Chunk-based memory constraints on the cultural evolution of language*.

Isbilen, E.S., McCauley, S.M., Kidd, E & Christiansen, M.H. (2017). Testing statistical learning implicitly: A novel chunk-based measure of statistical learning. In G. Gunzelmann, A. Howes, T. Tenbrink, & E.J. Davelaar (Eds.), *Proceedings of the 39th Annual Conference of the Cognitive Science Society* (pp. 564-569). Austin, TX: Cognitive Science Society.

Kirby, S., Tamariz, M., Cornish, H., & Smith, K. (2015). Compression and communication in the cultural evolution of linguistic structure. *Cognition*, *141*, 87-102.

MacWhinney, B. (2000). *The CHILDES project: The database* (Vol. 2). Mahwah, NJ: Lawrence Erlbaum.

McCauley, S. M., & Christiansen, M. H. (2011). Learning simple statistics for language comprehension and production: The CAPPUCCINO model. In L. Carlson, C. Hölscher,

& T. Shipley (Eds.), *Proceedings of the 33rd annual conference of the Cognitive Science Society* (pp. 1619-1624). Austin, TX: Cognitive Science Society.

McCauley, S. M., & Christiansen, M. H. (2014). Acquiring formulaic language: A computational model. *The Mental Lexicon*, *9*, 419-436.

McCauley, S.M., Isbilen, E.S. & Christiansen, M.H. (2017). Chunking ability shapes sentence processing at multiple levels of abstraction. In G. Gunzelmann, A. Howes, T. Tenbrink, & E.J. Davelaar (Eds.), *Proceedings of the 39th Annual Conference of the Cognitive Science Society* (pp. 2681-2686). Austin, TX: Cognitive Science Society.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81-97.

Miller, G. A., & Taylor, W. G. (1948). The perception of repeated bursts of noise. *The Journal of the Acoustical Society of America*, *20*, 171-182.

Monaghan, P. & Christiansen, M.H. (2008). Integration of multiple probabilistic cues in syntax acquisition. In H. Behrens (Ed.), *Trends in corpus research: Finding structure in data* (TILAR Series) (pp. 139-163). Amsterdam: John Benjamins.

Monaghan, P., Christiansen, M.H. & Chater, N. (2007). The Phonological-Distributional Coherence Hypothesis: Cross-linguistic evidence in language acquisition. *Cognitive Psychology, 55*, 259-305.

Pavani, F., & Turatto, M. (2008). Change perception in complex auditory scenes. *Perception & Psychophysics*, *70*, 619-629.

Pinker, S., & Bloom, P. (1990). Natural language and natural selection. *Behavioral and Brain Sciences*, *13*, 707-727.

Remez, R. E., Ferro, D. F., Dubowski, K. R., Meer, J., Broder, R. S., & Davids, M. L. (2010). Is desynchrony tolerance adaptable in the perceptual organization of speech? *Attention, Perception, & Psychophysics*, *72*, 2054-2058.

Smith, K., Kirby, S., & Brighton, H. (2003). Iterated learning: A framework for the emergence of language. *Artificial Life*, *9*, 371-386.

Studdert-Kennedy, M. (1987). The phoneme as a perceptuomotor structure. *Haskins Laboratories: Status Report on Speech Research, SR*, *91*, 45-57.

Van Vugt, F. T., Jabusch, H. C., & Altenmüller, E. (2012). Fingers phrase music differently: trial-to-trial variability in piano scale playing and auditory perception reveal motor chunking. *Frontiers in Psychology*, *3*, 495. doi:10.3389/fpsyg.2012.00495.

Vinson, D., Thompson, R. L., Skinner, R., & Vigliocco, G. (2015). A faster path between meaning and form? Iconicity facilitates sign recognition and production in British Sign Language. *Journal of Memory and Language*, *82*, 56-85.