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Turing redux: Enculturation and computation

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Abstract

Many of our cognitive capacities are shaped by enculturation. Enculturation is the acquisition of cognitive practices such as symbol-based mathematical practices, reading, and writing during ontogeny. Enculturation is associated with significant changes to the organization and connectivity of the brain and to the functional profiles of embodied actions and motor programs. Furthermore, it relies on scaffolded cultural learning in the cognitive niche. The purpose of this paper is to explore the components of symbol-based mathematical practices. Phylogenetically, these practices are the result of concerted organism-niche interactions that have led from approximate number estimations to the emergence of discrete, symbol-based mathematical operations. Ontogenetically, symbol-based mathematical practices are associated with plastic changes to neural circuitry, action schemata, and motor programs. It will be suggested that these practices rely on previously acquired capacities such as subitizing and counting. With these considerations in place, I will argue that computations, understood in the sense of Turing (1936), are a specific kind of symbol-based mathematical practices that can be realized by human organisms, machines, or by hybrid organism-machine systems. In sum, this paper suggests a new way to think about mathematical cognition and computation.

Keywords: Enculturation; Mathematical cognition; Computation; Hybrid cognition; Neural plasticity; Embodied cognition

1. Introduction

Numerical symbols are ubiquitous in our cognitive lives. We deal with numerical symbols each time we go shopping or check our account balance. In the sciences, we seek to understand our world by performing computations over sets of empirical data. These cognitive activities are realized by symbol-based mathematical practices. Symbol-based mathematical practices belong to the class of cognitive practices. Cognitive practices are defined as embodied, socio-culturally shaped interactions with epistemic resources (e.g., numerical symbol systems, writing systems) in the cognitive niche (Menary, 2007, 2012).

The successful performance of symbol-based mathematical practices and other cognitive practices is the result of enculturation. Enculturation is a temporally extended developmental process that is characterized by plastic changes to neural circuitry and motor profiles (Fabry, 2018; Menary, 2013, 2015a). Furthermore, it relies heavily on structured novice-teacher collaboration and on the scaffolded interaction with epistemic resources. The purpose of this paper is to explore the conditions under which symbol-based mathematical practices can emerge and how

AbbreviationsLDP, learning driven plasticity; LDBA, learning driven bodily adaptability; ANS, approximate number system; DNS, discrete number system; IPS, intraparietal sulcus; vITG, ventral inferior temporal gyrus; vOT, ventral occipito-temporal area; VWFA, visual word form area; VNFA, visual number form area

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they are applied to genuinely new forms of thinking and reasoning.

To this end, I will introduce the most important concepts and ideas of the present account of enculturation in the next section. In particular, I will explore the phylogenetic and ontogenetic components of this temporally extended developmental process. With this theoretical background in place, I will trace the phylogenetic and ontogenetic trajectory of symbol-based mathematical practices in Section 3. I will argue that evolved organizational principles governing the development of neuronal circuitry and motor programs, cultural learning, and the history of numerical symbol systems jointly give rise to the development of symbol-based mathematical practices during ontogeny. Section 4 is dedicated to a re-assessment of the concept of computation. Based on an examination of the history of this concept, especially in Turing's (1936) work, I will suggest that computation is a specific type of symbol-based mathematical practices. Historically, human computation has paved the way towards machine-based digital computation in the course of the 20th century. An important consequence of this development is the possibility of hybrid computational processes that are realized by the structured interaction of enculturated human organisms and computational artefacts. The upshot will be that the present analysis of enculturation and computation provides us with a fresh look at symbol-based mathematical practices and at some of the ways in which these practices shape our interactions with the (empirically observable) world.

2. The phylogenetic and ontogenetic components of enculturation

Enculturation is defined as the ontogenetic acquisition of culturally shaped cognitive practices such as symbol-based mathematical practices, reading, and writing. Cognitive practices are evolutionarily recent and date back to the first emergence of symbol systems in Mesopotamia approximately 5000 years ago (Donald, 1991; Olson, 1994; Ong, 2012). Given the evolutionary recency of cognitive practices, there has not been sufficient time for the development of dedicated brain circuits, motor programs, and learning mechanisms that can be unequivocally, directly, and exclusively associated with symbol-based mathematical practices and other cognitive practices (Dehaene, 2010, 2011, Menary, 2014, 2015a). However, several evolved properties of human organisms and of their local environment jointly give rise to the possibility of enculturation. In this section, I will explore the most important neuronal, bodily, and socio-cultural components that have led to our capacity to skilfully engage in symbol-based mathematical practices.

2.1. The phylogenetic components of enculturation

Cognitive practices are situated in the *cognitive niche*. The cognitive niche is the result of the continuous *trans*-generational manipulation and modification of the local environment (Clark, 2006; Menary, 2014; Odling-Smee & Laland, 2011; Sterelny, 2003, 2012; Stotz, 2010). The active construction of the cognitive niche by human organisms has brought about the development and refinement of epistemic resources, e.g., numerical symbol systems and writing systems. Furthermore, large-scale socio-cultural structures such as kindergartens, schools, and universities are also the result of active cognitive niche construction. Like epistemic resources, they have been transmitted from one generation to the next. The theoretical import of work on niche construction in biology is the insight that only explanations of life forms that take the interaction of organisms (e.g., spiders, termites, beavers, apes, humans) with their local environment into consideration are able to fully account for the variety of phenotypes expressed in the animal kingdom – both in the here-and-now and across the evolutionary trajectory of a certain species. In the case of humans (and possibly other animals as well), the cognitive niche has been constructed across multiple generations so as to enable and facilitate the completion of cognitive tasks. This relationship of human organisms and their cognitive niche is of particular importance for our understanding of the phylogenetic trajectory of the biases, potentials, and limitations of the human brain (Downey & Lende, 2012). On the one hand, the innovation of new epistemic resources is constrained by the structural and functional potentials of the human brain. On the other hand, cognitive practices heavily rely on the interaction with culturally evolved epistemic resources that need to be attuned to the "neuronal niche" (Anderson, 2010). This structurally and functionally constrained allocation of specific neuronal resources is known as *neural reuse* (Anderson, 2010, 2015) or *neuronal recycling* (Dehaene, 2005, 2010).

Neuronal recycling can be understood as a specific type of the more general principle of neural reuse. According to the neuronal recycling hypothesis, the acquisition of cognitive practices is associated with the re-exploitation of already existing neuro-functional units in order to develop "cognitive abilities for which there has been insufficient time for specialized neural circuits to have evolved" (Anderson, 2010, p. 262). The neuronal recycling of specific brain areas depends on their functional and structural biases and on the functional proximity of uses to which these areas can be put (Anderson, 2015). The upshot is that neuronal recycling can be depicted as an evolutionary, adaptive response to the cognitive processing needs afforded by the cognitive niche (Menary, 2014). At the same time, the subsequent modification and refinement of the cognitive niche has been dependent upon the possibility space of brain development as it is expressed by the principle of neuronal recycling.

The phylogenetic potentials for enculturation are characterized by the overall properties and abilities of human organisms and their on-going interaction with the cognitive niche. This also applies to the capacity to develop new motor repertoires that significantly contribute to the performance of cognitive practices. For example, the embod-