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journal homepage: www.elsevier.com/locate/jneurolingEmergent *and* constrained: Understanding brain and cognitive developmentDean D'Souza^{a,*}, Hana D'Souza^b^a Department of Psychology, Anglia Ruskin University, Cambridge, UK^b Centre for Brain & Cognitive Development, Birkbeck, University of London, London, UK

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ABSTRACT

The process by which neural structures and cognitive functions arise through manifold local interactions (*emergence*) is at the core of many neurocognitive frameworks (as reviewed by Hernandez et al., 2018). However, the emergence of neural structures and cognitive processes is not unconstrained; it is *context dependent*. Therefore, to truly understand brain and behaviour, it is necessary to identify the contexts or factors that interact to constrain the emergence of higher-level neurocognitive processes and behaviour (Mareschal et al., 2007; Thelen & Smith, 1994; Waddington, 1957). It is also important to understand how these factors interact over different timescales (Gottlieb, 1992). We illustrate these points using examples from language development, and conclude by arguing that specifying the processes that *constrain* emergence is the key to understanding brain and cognition.

As Hernandez and colleagues (2018) point out, the process by which neural structures and cognitive functions arise through manifold local interactions (*emergence*) is at the core of many neurocognitive frameworks (e.g., neural reuse [Anderson, 2016]; neuroconstructivism [Mareschal et al., 2007]). For this reason, Hernandez et al. (2018) argue that an overarching neurocognitive framework should be built around the concept of emergence, a concept already incorporated into existing neurocognitive approaches to understanding brain and behaviour. However, the emergence of neural structures and cognitive processes is not unconstrained. Emergence is *context dependent*. Therefore, to truly understand brain and behaviour, it is necessary to identify the contexts or factors that interact to *constrain* the emergence of higher-level neurocognitive processes and behaviour (Mareschal et al., 2007; Thelen & Smith, 1994; Waddington, 1957). It is also important to understand how these factors interact over different timescales. For instance, the development of neural structures and cognitive processes constrain the emergence of future structures and processes (Gottlieb, 1984, 1992; Karmiloff-Smith, 1998; Kuo, 1967; McClelland & Vallabha, 2009). Moreover, a focus on *constraints* not only sheds light on typical development, it also elucidates individual differences and atypical development (Mareschal et al., 2007). To demonstrate the importance of understanding how emergence is shaped by multiple constraints operating on different levels and timescales, we will discuss the development of language. We will begin by discussing some traditional neurocognitive processes involved in language development. This will be followed by sections on two sources of constraints which have received less attention than more traditional ones: the body and language itself. Finally, we will conclude by arguing that specifying the processes that *constrain* emergence—rather than emergence per se—is the key to understanding brain and cognition, and that this perspective is already

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encapsulated in current developmental systems¹ approaches.

1. Commonly-described constraints on language development

As a complex adaptive system adjusting to a complex, dynamic environment, from the very beginning the human infant is driven to minimise uncertainty by matching its sensory information with its models of the external world (Friston, 2010). It does this by sampling, selecting, and acting on various aspects of its environment (i.e., by changing its sensory input), and altering its models and predictions (which in turn change how it perceives the world) (see D'Souza, D'Souza, & Karmiloff-Smith, 2017; for discussion). Processes that influence how infants sample, select, and act on aspects of their environment constrain infants' language (and cognitive) development. These constraints can be internal (e.g., gene-gene interactions) or a fusion of both internal and external processes (e.g., involving parent-child interaction). Take phoneme perception, for example. Infants are initially sensitive to a wide range of native and non-native phonological contrasts (Eimas, Siqueland, Jusczyk, & Vigorito, 1971). However, during the first year of life, the infant brain becomes progressively specialised to its native language; sensitivity to native phonological contrasts increases while sensitivity to non-native contrasts decreases (Kuhl et al., 2006; Werker & Tees, 1984; Werker, Yeung, & Yoshida, 2012). This process of progressive *specialization* involves neural commitment to processing a specific set of stimuli (native contrasts) and is thus accompanied by a reduction in neural plasticity (Johnson, 2011; Kuhl et al., 2008). In other words, neural networks are refined and honed in an adaptive process that involves a process of self-organization (at the neural level) in response to external stimulation (language input). If an infant is raised in a multilingual environment, they are likely to be provided with fewer samples from each language (an exogenous constraint) than a monolingual child would receive from its one language (Byers-Heinlein & Fennell, 2014). They may also receive more variable and less consistent language input. For example, Bosch and Ramon-Casas (2011) found that Catalan-Spanish bilingual mothers who had been raised in Catalan-Spanish or Spanish speaking homes made significantly more errors when producing words that contain the Catalan/e/-/e/contrast than Catalan-Spanish bilingual mothers who had been raised in Catalan-speaking homes. How might these constraints (fewer samples, more variability, less consistency) affect the process of progressive specialization in infants raised in bilingual homes? Pi Casaus (2015) found that bilingual infants can discriminate between non-native contrasts for up to six months after the ability has been lost in their monolingual peers. This suggests that progressive specialization (an internal process) is prolonged in infants who face relatively challenging language environments (D'Souza et al., 2017).

Differences in sampling may also result from differences between individuals. For example, upon hearing that their child has a neurodevelopmental disorder, the parents' behaviour towards their child may change (Karmiloff-Smith et al., 2012a). They may become over protective and constrain their child's exploratory behaviours or provide the child with less variation in linguistic input. Indeed, Zampini, Fasolo, and D'Odorico (2012) found that mothers use more simple language to address their child with Down syndrome (DS) than mothers of typically developing children matched on lexical skills. Although it is possible that children with DS benefit more from simple linguistic input, it shows how an interaction between external and internal environments alters language input. Furthermore, because children with neurodevelopmental disorders present with uneven cognitive profiles (e.g., Karmiloff-Smith et al., 2012b; D'Souza, 2014), parents may find it difficult to assess their child's developmental level and adjust their behaviour accordingly (D'Souza et al., 2017).

Finally, differences in sampling may also result from variation *within* organisms. For example, the development of neural circuitry is also constrained by internal constraints, such as variation in FMR1-protein production. The FMR1 protein is essential for synaptic plasticity; therefore, variation in production of the protein may constrain the ability of the neural circuitry to accurately sample from, and optimally adjust its connectivity to, events in the external world. If this is the case, then we expect that infants with an FMR1 premutation² would compensate for the sampling errors by taking more samples than infants without a premutation (D'Souza et al., 2017). A recent study found that infants with an FMR1 premutation did indeed show more sensory-seeking behaviours than age-matched controls (Wheeler et al., 2016).

2. Body as a constraint

Factors that are *prima facie* unconnected to the language domain also constrain the emergence of language functions. Take, for example, the infant's body. By constraining access to moment-by-moment sensory information, the body guides learning and development. The infant's short sightedness may guide visual exploration to the most salient features of an object; their short arms could limit exploration to one object at a time; their short legs, exploration to only part of a scene. How do these constrain word learning? For years, researchers have been trying to understand how infants can learn the label of an object when its visual field is often

¹ Like Ulrich (2010), we (e.g., D'Souza et al., 2017) use the phrase 'developmental systems' to refer to a group of (non-nativist) perspectives that share (or complement) the core tenets of 'developmental systems theory' (Ford & Lerner, 1992; Oyama, 1985; Oyama, Griffiths, & Gray, 2001) and which view neurocognitive and motor development as the emergent functions of a complex adaptive system. These perspectives include the four approaches mentioned by Hernandez et al. (2018) as well as many others – e.g., dynamic systems theory (Thelen & Smith, 1994; Thelen, 1992) and connectionism (Rosenblatt, 1958). For example, both dynamic systems theory and connectionism share the central tenet of developmental systems theory that development emerges from, and is constrained by, a complex web of interactions between diverse, interconnected factors (Blumberg, 2016).

² The FMR1 gene typically contains between 5 and 44 CGG trinucleotide repeats (Santoro, Bray, & Warren, 2012). For most loci, trinucleotide expansion is harmless. However, if the FMR1 gene contains more than about 200 repeats (called a "full mutation"), FMR1 messenger RNA becomes entangled in the mutated segment (Colak et al., 2014). This leads to the silencing of the gene and the development of fragile X syndrome. Individuals with around 55–200 repeats are described as having a "premutation". Although their genes have not been silenced, premutation is associated with atypical neurocognitive functioning (Hagerman & Hagerman, 2004).

cluttered with different objects (the *referential ambiguity problem*). How does the child know which object is being named? Pereira, Smith, and Yu (2014) found the answer after taking into account the perspective of the infant. They placed head-mounted cameras on the infant and mother, and recorded gaze data as the infant played with novel objects while the mother spontaneously named them. They found that when the infants grasped an object with their relatively short arms, the object filled their entire field of view. Furthermore, the infants were significantly more likely to learn the label of an object if the mother provided the label while the object was being handled by the child and was thus visually dominant. In other words, they found that the infant's body constrained the learning space to such an extent that it eliminated the referential ambiguity problem. Again, the discovery was not a result of trying to understand how new neural structures emerge from older neural structures (though this too is an important, complementary research programme); it was the result of exploring the *sensorimotor constraints* that underpin dynamic, free-flowing social interactions.

What about changes over developmental time? Gradual mastery over the body may also affect parent-child interactions and shape early language development. For example, sitting upright without assistance may help the infant to breathe more efficiently, maintain subglottal pressure, and generate longer utterances in one breath (Iverson, 2010). Learning to walk provides the child with opportunities to increase social interaction and bring objects for their parent to label (Karasik, Tamis-LeMonda, & Adolph, 2011). Indeed, Walle and Campos (2014) have identified a number of factors in the physical and social environment (e.g., distance from parent) that predict vocabulary size in walking *but not crawling* infants.

3. Brain as a constraint on language

We have, hitherto, discussed evidence of factors that constrain the emergence of language in infant development. Clearly, the infant brain is highly adaptive to language learning. But could the reverse be also true? Might language be a complex adaptive system that is highly adaptive to the infant brain? The idea that language alters its form and structure to fit the human brain is controversial (pace Deacon, 1997; Christiansen & Chater, 2008). Nevertheless, there is some evidence in support of it. Kirby, Cornish, and Smith (2008) trained adult participants on a simple artificial language containing various string-picture pairs. They subsequently tested the participants' knowledge of the artificial language using test items with familiar and novel meanings. Specifically, the participants were presented with a series of pictures (some familiar, some novel) and instructed to produce a string that would form a correct string-picture pair. A "new generation" of participants was then trained on the artificial language – but using the data from the previous generation rather than the original items. In other words, the artificial language now included the errors and alterations of the previous generation. Kirby et al. (2008) discovered that the artificial language that they had created became progressively easier to learn over successive generations; the language morphed in ways that better fit with the biases and expectations of the human learners. This is because human biases and expectations affect how language is recalled and constrain how learners behave when presented with novel information. In other words, humans are adaptive systems, but so too is language. As infants are adapting to the social world, *language is adapting to infants*. Neonates with little linguistic experience, for example, already prefer syllables like blif to syllables like bdif or lbif (Gómez et al., 2014), which may constrain the evolution of language itself. To some extent, the cumulative cultural transmission (or evolution) of language may itself constrain language development. Rather than focus only on how neural structures emerge from various parts in the brain, it may therefore be more profitable to view neural structures and cognitive processes as emerging properties of a complex adapting system *developing within* larger adapting systems (i.e., context dependent).

4. Conclusion

Although the process through which neural structures emerge from local interactions in the brain is at the core of many neurocognitive frameworks (as pointed out by Hernandez et al., 2018), any overarching framework for understanding brain and cognition must also focus on the factors and contexts that constrain (shape) emerging neurocognitive functions. For instance, we may know that language emerges from interactions within the infant and between the infant and their caregivers, but seemingly intractable problems such as referential ambiguity are solved only when the physical, biological, and social *constraints* that underpin infant-caregiver interactions are investigated. Furthermore, a focus on constraints/contexts (rather than emergence per se) elucidates how language itself may be adapting to the infant brain. In other words, for an overarching neurocognitive framework to be useful, it must include not only the concept of emergence (Hernandez et al., 2018), but also a specific focus on the contexts and factors that *constrain* emergent processes.

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