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Tracking qualitative changes in cognition and brain development through bilingualism

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Neuroemergentism (Hernandez et al., 2018) aims to provide a framework for the study of cognition and the brain, with special emphasis on how early life experiences shape the mind. The theory is built on Emergentism, in which a natural phenomenon derived from traceable components (e.g., hydrogen and oxygen), may develop into a non-algebraic, *qualitatively new entity* (e.g., water). This line of reasoning, as originally posed by John Stuart Mill in the mid 19th century, helps to frame scientific questions surrounding the development of specialized cognitive processes, such as word reading.

Mill acknowledged that his reasoning around the philosophy of science was greatly influenced by Hegel, who, several decades earlier, also worked to reason logically through the scientific and social phenomena of his day. Many now know the famous Marxist extension of Hegel's work: *evolution through revolution*. Hegel's theory was revolutionary in its own right. In contrast to his predecessors like Kant and Aristotle, who argued that mechanisms of logical reasoning were fixed and could only change in quantity, Hegel argued that a critical mass of quantity can yield a qualitative shift – a revolution – and the emergence of new forms of reasoning.

At present, a critical mass of theories working to explain the development of highly specialized cognitive functions has emerged (e.g., Anderson, 2010; Dehaene, 2004; Johnson, 2011; Karmiloff-Smith, 2009). Hernandez et al. (2018) pose that the time has come for a new way of thinking about human brain development. Neuroemergentism conceptualizes development in terms of incremental growth across perceptual and cognitive domains that may combine to yield neural specialization for a higher cognitive function. Such reasoning makes it of paramount importance to study children's gradual or *quantitative* developmental change, so that we can better understand how cumulative changes may give rise to *qualitatively* new and specialized mental operations (a revolution!).

In particular, Hernandez et al. (2018) pose that our understanding of bilingual brain development can be refined through a Neuroemergentist framework. We argue that Neuroemergentism may also shed light on bilingual reading acquisition. Does accommodating an additional language in the brain facilitate quantitative changes in language processing capacity, or does it necessitate the development of a qualitatively different cognitive system?

Learning to read in one language. Learning to read builds upon a multitude of incremental fine-tunings of the visual systems and their interconnection with the language systems to yield rapid recognition of meaning on a printed page. The outcome of this gradual improvement is a remarkably cohesive concert of these multiple abilities, exceeding the simple sum of its parts. Beginning readers place effort on recognizing letters, linking letters to sounds, linking orthographic forms to meanings, and then connecting individual words to sentence meaning and context (Ehri, 2014). By accruing a critical mass of these component skills for reading, and moving through multiple phases of reading competence, there is a qualitative shift from effortful decoding to fluent reading. There is evidence of this shift at the neurological level as well; Dehaene and colleagues have demonstrated that visual information and spoken word processes are different in a literate versus an illiterate brain (Dehaene, Cohen, Morais, & Kolinsky, 2015).

Furthermore, in line with a neuroconstructivist or emergentist framework, the breakdown of smaller components in reading may have system-wide effects (Karmiloff-Smith, 2009). For example, English readers with dyslexia, a life-long impairment in learning to read, often show phonological deficits. At a neurological level, children with high familial risk for dyslexia show a reduced mismatch negativity response to phonological contrasts (Leppänen et al., 2011), and reduced superior temporal activation during phonological

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tasks in kindergarten, prior to formal reading instruction (Raschle, Zuk, Gaab, Merzenich, & Keck, 2012). This phonological deficit is thought to impede developing automaticity in rapid word recognition, or the formation of an efficient reading pathway. Note that while we can view phonetic processing as a molecular subcomponent of language and cognitive competence, phonological processing deficits in dyslexia have also been conceptualized as stemming from even more basic neural-level disruptions, such as enhanced glutamatergic signaling and increased neural noise (Hancock, Pugh, & Hoeft, 2017).

Importantly, monolingual reading development unfolds differently across languages and orthographies. This variation can be understood through the systematic differences in language structure, and how writing systems encode salient linguistic units. While some alphabetic languages such as Finnish, Spanish, or Malay have a high degree of sound-to-print predictability, others, like Chinese, encode meaning-to-print associations better than sound-to-print associations. Young Chinese readers logically show relatively greater reliance on morphological awareness (McBride-Chang et al., 2005). These language-specific differences are also apparent at the neural level. Cross-linguistic comparisons reveal that during phonological word reading tasks (e.g., visual word rhyming) English readers demonstrate greater activity in the superior temporal gyrus (STG), a region associated with phonological processing, than Chinese readers (Cao, Brennan, & Booth, 2015).

Learning to read in two languages. Does learning to read in two languages influence a qualitatively different developmental trajectory, or result in qualitatively different cognitive processes than in monolinguals? In bilinguals, the brain must develop highly complex and specialized reading processes for two distinct linguistic systems. Theories of bilingualism pose that readers may transfer literacy skills across their two languages (Cummins, 1979). For instance, in Singapore, bilingual Malay-English children make phonological errors, spelling "tabel" instead of "table," while bilingual Chinese-English children make lexical errors, spelling "grass" instead of "green" (Dixon, Zhao, Joshi, & Quentin, 2010). Similarly, bilingual Chinese adults show patterns of brain activation for reading in English that are more consistent with their first language, Chinese, than English (Tan et al., 2003).

Yet, there is also evidence to suggest that in young bilinguals, with systematic preschool exposure to their two languages, these transfer effects emerge with minimal literacy instruction in either of their languages. For instance, Spanish-English kindergarteners were found to outperform English monolinguals and Chinese-English bilinguals on spoken phonological awareness tasks in English (Bialystok, Luk, & Kwan, 2005). One underlying mechanism for this might be the transfer of salient language features that jointly characterize spoken and written processing in a given language. In the inflectionally-rich Spanish, fine-grained phonemic changes can yield significant sentence-level changes, which is effectively transmitted by Latin alphabet. Experience with Spanish spoken language may thus necessitate greater attention to fine-grained phonological variation. This may translate into relatively more advanced phonological awareness abilities in Spanish-English bilinguals in both of their languages, even with minimal Spanish literacy experience (Bialystok et al., 2005). It is therefore possible that bilinguals' reading mechanisms are jointly shaped by their spoken and written language experiences across their two languages.

In our own research, we find that Spanish-English bilinguals who have experienced English-only or English-dominant literacy instruction show greater reliance on phonological awareness (Kremin, Arredondo, Hsu, Satterfield, & Kovelman, 2016), and greater activation in left STG regions when reading in English (Jasińska, Berens, Kovelman, & Petitto, 2017), relative to reading-proficiency matched monolingual English peers. In contrast, Chinese-English bilinguals with similar English-only or English-dominant instruction showed greater reliance on semantic processes (Hsu, Ip, Arredondo, Tardif, & Kovelman, 2016), and greater activation in left middle temporal (MTG) regions relative to their monolingual peers (Ip, Hsu, Arredondo, Tardif, & Kovelman, 2016). We have interpreted these findings to suggest that bilinguals' linguistic system is qualitatively changed, biasing the speakers to attend to salient characteristics of Language B, even if the speakers are perfectly proficient in Language A. In support of this hypothesis, Hernandez et at. (1994) have shown that balanced bilingual speakers of Spanish and English were more likely to pay attention to word order in Spanish (relative to Spanish-dominant bilinguals) and more likely to pay attention to morphological variation in English (relative to English-dominant bilinguals). This finding suggests that systematic use of two languages does not simply *quantitatively* boost proficiency in each language, but rather it creates a *qualitatively* different system for language processing in bilingual speakers.

Bilingualism as a model for testing theoretical perspectives. Moving forward, if the newly proposed neuroemergentist framework is to be effective for hypothesis testing, we must work as a field to carefully define what constitutes a quantitative versus a qualitative shift. While no process is absolute in terms of quality or quantity, we can gain better understanding of developmental processes by trying to delineate the two. For example, in early bilingual acquisition, it has been suggested that bilinguals may take longer to develop phonological representations and neural markers of phonological representations for each of their languages (Ferjan Ramírez, Ramírez, Clarke, Taulu, & Kuhl, 2017). One way of conceptualizing this difference in bilingual development is through the amount of exposure. In contrast to monolinguals whose entire linguistic experience is in one language, a bilingual child's exposure is split between the two languages. Logically, researchers find a relationship between bilingual children's exposure to each of their languages and the extent of proficiency (Place & Hoff, 2011) and neural commitment (Garcia-Sierra, Ramírez-Esparza, & Kuhl, 2016) to each of their languages. Note, however, that there might also be some critical mass of exposure at which the bilingual acquisition may proceed in an age-appropriate manner for each of the children's languages (Petitto & Kovelman, 2003; Peña, Bedore, & Kester, 2016).

Another way of conceptualizing early bilingual acquisition is through a qualitative shift in the mechanisms of acquisition and their neural underpinnings. In particular, the dual language experience may extend young bilinguals' period of sensitivity to the regularities of language, such as the contrasting non-native phonemic features (Petitto et al., 2012; Werker & Hensch, 2015). This, in turn, may yield life-long enhancements in bilinguals' ability to compute linguistic information such that they may have an easier time learning another new language later in life (Kuo & Anderson, 2012). In this manner, consistent with the Neuroemergentist perspective, bilingual evidence inspires our reasoning about linear gains in cognition and brain development as well as qualitative shifts in processing.

Hernandez et al. (2018) provide a promising lens for studying the neurobiology of bilingual language and literacy development. Neuroemergentism paves an exciting opportunity for exploring the dynamic between children's experiences, cognitive processes, and the formation of neural networks for higher cognitive functions.

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