Progressive modularization: reframing our understanding of typical and atypical language development

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Abstract

The ability to acquire language is a critical part of human development. Yet there is no consensus on how the skill emerges in early development. Does it constitute an innately-specified, language-processing module or is it acquired progressively? One of Karmiloff-Smith's (1938-2016) key contributions to developmental science addresses this very question. Karmiloff-Smith persistently maintained that the process of development itself constitutes a crucial factor in phenotypic outcomes. She proposed that cognitive modules gradually emerge through a developmental process – 'progressive modularization'. This concept helped to advance the field beyond the stale nature-nurture controversy. It enabled language researchers to develop more nuanced transactional frameworks that take seriously the integration of genes and environment. In homage to Karmiloff-Smith, the current paper describes the importance of her work to the field of developmental psychology and language research. It examines how the concept of progressive modularization could be applied to language development as well as how it has greatly advanced our understanding of language difficulties in children with neurodevelopmental disorders. Finally, it discusses how Karmiloff-Smith's approach is inspiring current and future research.

Introduction

Language is a highly complex system. Yet infants acquire it rapidly and with relative ease. The speed and ease with which infants acquire their first language is so great that some theorists, nativists, take it as evidence that evolution endowed the human neonate with a built-in, genetically-specified language module (Chomsky, 1959, 1975, 1991). How else can a child learn something as complex as language so fast? Karmiloff-Smith's mentor, the great developmental psychologist Jean Piaget, rejected the nativist approach because, in his view, cognitive abilities (including those that subserve language) are too complex to be genetically specified; they must be constructed over developmental time through child-environment interactions (Piaget, 1970; see also Gottlieb, 1991; Oyama, 1985). Specifically, Piaget claimed that new developmental structures in childhood emerge through widespread cognitive reorganization as a result of interactions between cognitive processes (and/or sensory reflexes), the child's active exploration of the external world, and domain-general learning mechanisms (Piaget, 1970). But Piaget failed to explain how the child knows *what* must be learned and *when* (Fodor, 1980). For example, what aspects of the environment should the child pay attention to and when? What aspects of the speech stream should the child pay attention to and when? Are there any aspects of the speech stream that can be ignored?

One of Karmiloff-Smith's key contributions to developmental science was her advocacy for a 'middle ground' between nativism and Piagetian constructivism (Karmiloff-Smith, 1990). The middle ground was the theory that, over developmental time, neural circuits are progressively selected for different domain-specific computations. Some of these neural circuits gradually acquire the properties (e.g., encapsulated information) of a module (Karmiloff-Smith, 1992). In other words, whereas nativists claim that *genes* orchestrate the development of sophisticated cognitive modules (including language modules), Karmiloff-Smith (1992) argued that the modules are experience-dependent products of *development*.[1] Whereas Piaget (1970) advocated for general learning mechanisms that operate across cognitive/motor domains and modalities (e.g., the assimilation vs. accommodation of new information), Karmiloff-Smith (1992) proposed that innate *domain-relevant* mechanisms initially bias the infant's attention to important sources of information and constrain how the infant acts and processes information; these dynamic child-environment interactions help shape neural connectivity and the gradual emergence of domain-specific modules.

Karmiloff-Smith's 'middle ground' is one that, arguably, most developmental scientists now broadly adopt (e.g., Mareschal et al., 2007).[2] Although, like Piagetian constructivism, the general concept of progressive modularization (the middle ground) will not be completely mapped out until specific neurocognitive mechanisms of change have been identified and elucidated, Karmiloff-Smith's (1992) theory is consistent with developmental

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[1] Neurobiological evidence supports this view. For example, when small portions of cortex are transplanted into different regions, they develop features specific to the new region (e.g., Schlaggar & O'Leary, 1991). Also, when projections from one sensory modality are rerouted to cortices that typically receive projections from a different modality, then the recipient cortex develops functional properties appropriate for information from the rerouted projections (e.g., Frost & Metin, 1985; Sur et al., 1988, 1990). In other words, the brain is not initially modular and representational information is not embedded in cortical structure; the identity and functions of a brain region are experience-dependent.

[2] Although Karmiloff-Smith's approach occupies ground between nativism and Piagetian constructivism, it is important to also note that both Karmiloff-Smith's neuroconstructivism and Piaget's constructivism occupy ground between nativism and empiricism. For the nativist, genes orchestrate the construction of domain-specific cognitive modules – the child is born innately expecting nouns, verbs, and grammatical rules. For the empiricist, nouns, verbs, and grammatical rules are extracted from the social and physical environment – the child discovers language. Although domain-general mechanisms such as 'statistical learning' undoubtedly help the child to acquire language by extracting important information from the environment (see D'Souza, D'Souza, & Karmiloff-Smith, 2017, for discussion), Karmiloff-Smith (1998) and Piaget (1970) rejected both nativism and empiricism; development involves deep interactions between genes and environment.

systems theory which states that the structure of the adult brain is not predetermined but is gradually constructed from complex cascades of gene-environment interactions (‘probabilistic epigenesis’; Gottleib, 1991). It is also consistent with evidence in the developmental cognitive neuroscience literature, which suggests that the infant brain is characterized by diffuse, barely-discriminate functional brain activity that only gradually becomes more focal and selective over developmental time (Johnson, 2001, 2011; Karmiloff-Smith, 2009).

The importance of progressive modularization

By applying a developmental perspective to a major debate in cognitive science (nativism vs. empiricism, domain-specific vs. domain-general mechanisms), not only did Karmiloff-Smith help progress the field beyond the nature-nurture controversy, but she also demonstrated the importance of taking development seriously. The child development literature often focuses on what cognitive science can offer developmental science. But Karmiloff-Smith (1992) demonstrated that developmental science has a lot to offer cognitive science. To gain a more nuanced understanding of the internal structure of the adult brain, cognitive scientists must elucidate: (1) early neurocognitive biases, (2) developmental processes such as progressive modularization, functional specialization, and ‘restriction of fate’, and (3) how internal representations change over developmental time (Karmiloff-Smith, 1986, 1992).

Take, for example, language learning. Adult Japanese speakers who are learning English have difficulty in accurately discriminating /r/ from /l/ (Hernandez & Li, 2007). Studying the adult brain (the “end-state”) is unlikely to reveal why the adult Japanese brain struggles to discriminate /r/ from /l/. But developmental studies reveal how infants' perceptual abilities start out broadly tuned to the environment and gradually narrow as they adapt to their specific environments. This developmental process of perceptual narrowing is a case of *functional specialization* (see Johnson, 2011), which has been identified in several domains, including face perception (Pascalis et al., 2005), motor ability (D'Souza, Cowie, Karmiloff-Smith, & Bremner, 2017), and language. In the language domain, it is manifested in an increase in the infant's ability to discriminate familiar (native) speech sounds, coupled with a decrease in the ability to discriminate unfamiliar (non-native) speech sounds during the first year of life (Kuhl, 2006; Werker & Tees, 1984). In other words, the adult brain—and its ability to discriminate /r/ from /l/—is emergent from *developmental processes*, which reflect complex interactions between various internal (e.g., attention) and external (e.g., social) factors over developmental time (see D'Souza, D'Souza, & Karmiloff-Smith, 2017, for details). Even an ostensibly small variation in early development may change the infant's long-term developmental trajectory. For example, the condition of preterm birth may constrain language development at preschool and school age. Six- and eight-year-old preterms performed worse on a battery of language tasks than age-matched fullterms, even with an absence of general cognitive delay and brain damage (Guarini et al., 2009, 2010). To understand the internal structure of the adult brain, it is therefore imperative that developmental processes are identified and investigated (D'Souza & Karmiloff-Smith, 2011, 2016).

The utility of Karmiloff-Smith's (1992) theory of progressive modularization also extends to the field of individual differences. Most experimental tasks in psychology and cognitive neuroscience treat individual differences as background noise, and experimenters focus on identifying the desired signal amidst the noise. For example, if a scientist hypothesizes that there is a direct causal relationship between brain size and vocabulary size, then he or she may test their hypothesis by ascertaining whether children with a larger brain have a larger lexicon than children with a smaller brain. If the result of their analysis is significant, then they may conclude that their data hint at a causal relationship and that any "noise" in their data is the result of measurement error. But if brain development involves progressive modularization—a probabilistic, rather than a predetermined, process—then the scientist ought to care about individual differences ("noise") as well as any overall or group effect (the "signal"). This is because variation necessarily plays a role in shaping developmental processes (e.g., modularization) and outcomes (e.g., modules).

In other words, if language development is innately predetermined, then researchers need to average out individual differences in task performance to unmask the genetically prespecified language module that evolution has purportedly endowed infants with. However, if language abilities are gradually constructed from complex interactions between multiple interdependent (internal and external) factors over developmental time, then researchers should investigate variations in these factors if they want to understand how language arises; they should not expect a direct causal relationship between any two factors. Take, for example, the role of attention. A nativist may want to average out individual differences in attention during a language task to unmask what he or she believes is an independent, minimally interactive language module. But a neuroconstructivist would argue that language abilities arise in part from how the infant focuses and shifts attention in naturalistic environments. Therefore, studying variations in these attentional processes, and how they relate to infant-environment interactions, is critical to understanding language development (D'Souza, D'Souza, & Karmiloff-Smith, 2017).

Karmiloff-Smith's theory of progressive modularization therefore has far-reaching implications for domains within developmental psychology (e.g., the field of individual differences) as well as for domains external to developmental psychology (e.g., cognitive science). But perhaps Karmiloff-Smith's greatest contribution was to the field of *atypical development*. Why do some children struggle to develop language? Karmiloff-Smith's theory sheds light on atypical language development.

When progressive modularization goes awry

According to nativists, at least some aspects of language (e.g., grammar) develop independently from other cognitive functions, and atypical language development results from genetic defects that impact the formation of the language module. Evidence that initially seemed to support this claim was brought to the attention of cognitive scientists in the late 1980s in the form of a rare "experiment of nature": Williams syndrome (Bellugi et al., 1988, 1994). This rare genetic disorder is caused by microdeletion of about 26 genes from chromosome 7. Individuals with Williams syndrome present with an uneven cognitive profile including mild to moderate intellectual disability, severe cognitive impairments in the visuospatial domain, and relative strengths in language and face processing. The case of Williams syndrome had important implications for fundamental questions that were being debated in the cognitive sciences, such as the extent to which the mind is modular, the role of innate knowledge in language development, and the relationship between language and cognition. This was especially true when some researchers contrasted Williams syndrome with a group of children diagnosed with 'specific language impairment' (SLI). Children with SLI appeared to have spared intellectual—but impaired language—ability. To quote Pinker (1999): "The genes of one group of children [with SLI] impair their grammar while sparing general intelligence; the genes of another group of children [with Williams syndrome] impair their intelligence while sparing their grammar" (p. 262). From this nativist perspective, developmental processes play only a minor role and the job of the research scientist is to identify selective (domain-specific) neurocognitive impairments (e.g., language) and attribute them to missing or malfunctioning genes.

According to Karmiloff-Smith (1998), however, a small genetic deficit is likely to have cascading effects on the developing brain, such as perturbing the process of gradual modularization. This would affect how the infant selects and processes environmental input, and impact child-parent interactions, both of which would further constrain brain and cognitive development (D'Souza, D'Souza, & Karmiloff-Smith, 2017; Karmiloff-Smith et al., 2012). Hence, impairments are likely to be widespread (though some might be subtle), and the research strategy of the neuroconstructivist is not to identify genetic defects and domain-specific impairments but rather to understand the complex interplay of internal and external constraining factors over developmental time, with a focus on studying the developmental effects that the lowest level of impairment has on later-emerging higher-level cognitive processes (Karmiloff-Smith, 1998).

Do empirical data lend support to Karmiloff-Smith's probabilistic progressive modularization perspective or to Pinker's predetermined genetic approach? Although adults with Williams syndrome are often described as having ‘perfect’ grammar (e.g., Piatelli-Palmarini, 2001), this is not surprising when one considers the fact that the typically developing child has mastered most syntactic structures by 3 to 4 years of age (Brock, 2007; Karmiloff-Smith, 1998). Yet contrary to claims of spared language abilities in the early literature (Bellugi et al., 1988, 1994), there is no compelling evidence to suggest that individuals with Williams syndrome outperform typically developing (TD) controls of comparable mental age on tests of syntax or morphology (see Brock, 2007, for review). In other words, grammatical abilities are delayed, not ‘spared’, in Williams syndrome. For example, grammatical gender assignment is worse in French-speaking individuals with Williams syndrome than in TD controls (Karmiloff-Smith et al., 1997). Furthermore, some aspects of complex grammar—such as passives of psychological verbs and raising constructions—are possibly never acquired in Williams syndrome (Perovic & Wexler, 2007, 2010). Moreover, evidence that the visuospatial deficit in Williams syndrome is mirrored by specific difficulties with grammatical constructs involving spatial or relational terms suggest that language and cognition do not develop independently in these children (Landau & Zukowski, 2003; Lukacs et al., 2004; Phillips et al., 2004).

What about the claim that language is a specific impairment in SLI? Fonteneau and van der Lely (2008) presented sentences containing syntactic or semantic violations to individuals with grammatical-SLI (G-SLI). Whereas the semantic violations elicited a normal N400 electrophysiological response, the syntactic violations failed to elicit an early left-anterior negative (ELAN) response and yet elicited a P600 (which indexes reanalysis). This led the authors to claim “that grammatical neural circuitry underlying language is a developmentally unique system in the functional architecture of the brain, and this complex higher cognitive system can be selectively impaired" (p. 1). However, as D'Souza and Karmiloff-Smith (2011) pointed out, the participants were adolescents with a receptive vocabulary of children half their chronological age, so the deficit was not confined to grammar. Furthermore, the P600 was maximally distributed on anterior sites in the right hemisphere rather than being equally lateralized, suggesting that the P600 may not have been 'typical'. Many researchers (e.g., Krishnan, Watkins, & Bishop, 2016) no longer consider language to be the only impairment in SLI.

The debate between the two approaches is not over. Nativists such as Spelke (2000) and Carey (2009) still argue that core aspects of human knowledge, including language, originate from an architecture that is, itself, highly constrained. But if language development is controlled by a predetermined language module, then damage to it should result in irrevocable language impairment. Yet perinatal lesions to 'language areas' of the brain do not prevent a child from learning language. Most children with left hemispherectomy early in life subsequently fall within the normal range on language tests and attend age-appropriate schools (Stiles, Bates, Thal, Trauner, & Reilly, 2002). This suggests that the developing brain is flexibly adapting to its environment. Adults with left hemispherectomy, however, often present with irrevocable language impairment. Furthermore, whereas left anterior damage particularly impairs grammatical abilities in adults, it causes only a temporary general language delay in children under 5 years of age (see Bates & Roe, 2001, for review). This suggests that the adult brain has specialized to such an extent that it has lost some of its early unconstrained plasticity. In other words, highly constrained, minimally-interactive modules are gradually constructed over developmental time, so an injury at an early timepoint may have very different neurocognitive effects than an injury at a later timepoint.

Developmental theories may also help to explain the mixed effects of aphasia (the impaired ability to comprehend and/or produce language as a result of brain damage) on children's language processing abilities. Karmiloff-Smith (1986) proposed four different levels of linguistic representation in the human brain: (1) 'implicit' representations, which are procedural and cannot be manipulated, (2) 'primary explication' representations, which can be accessed tacitly (e.g., in real-time lexical decision tasks), (3) 'secondary explication' representations, which can be accessed consciously (e.g., in word-picture matching), and (4) 'tertiary explication' where links across domains and subdomains can be drawn (e.g., semantic similarity judgements). Karmiloff-Smith (1986) argued that different aspects of language can be represented at different levels in different children at different timepoints in development. This would explain why the nature of aphasia varies more in children than in adults – i.e., because not all linguistic knowledge is represented at the highest level in young children, so similar injuries can have very different effects depending on when in development they occur.

Taking development seriously is also critical because new structures in the brain emerge as adaptions to the infant's environment, compensating for weaknesses. Indeed, Johnson (2017) argues that some phenotypic outcomes and conditions (e.g., autism) are not static genetic disorders but rather neurocognitive adaptations in response to genetic deficits and a complex environment. For example, he proposes that repetitive behaviours observed in children with autism are not the direct result of faulty genes but are adaptations in response to neural imbalance; the child cannot process normal environmental input and thus needs to simplify it (Johnson, 2017). Thus, Karmiloff-Smith's (1998) developmental approach is the foundation upon which we base our current theories; to understand how a disorder emerges, researchers must study how variation (genetic, environmental) in the initial start state constrains downstream gene-environment interactions, leading to an uneven cognitive profile where some domains develop relatively better than others.

In sum, the debate between nativists and neuroconstructivists continues. Few (if any) scientists would now argue that the ability to learn language is directly controlled by genes or directly controlled by influences external to the child, but detailed transactional frameworks that take seriously the integration of genes and environment are still being hotly contested: How domain-specific or domain-general are language-learning processes? How much information about the external world is contained at the level of the gene? To what extent can gene expression be manipulated by environmental factors such as parenting? Karmiloff-Smith's key contribution to language research was to convince researchers that their fundamental questions can only be understood by adopting a developmental approach.

Why only humans possess language

Moreover, Karmiloff-Smith (1992) was convinced that understanding developmental processes informs science of what separates humans from other mammals. If the human brain does not start out with prespecified modules (e.g., for language), and yet we still cannot train chimpanzees, our closest relatives, to learn language, then developmental processes involving innate biases, as well as environmental input, may play an important role in differentiating the adult human from the adult chimpanzee. What might that developmental process be? Karmiloff-Smith (1992) hypothesized that it was a process of progressive explication, whereby knowledge (representations) stored *in* the mind is progressively turned into explicit knowledge *to* the mind ('representational redescription'). This developmental process would allow the human child to reuse information for other purposes. It would also allow the human child to integrate representational information across different domains and thus construct new knowledge from distinct parts.

Take language, for example. Early in development, the human infant builds up a database of linguistic representations which help it to communicate with others. Karmiloff-Smith (1992) argued that these representations are initially stored and run as independent, sequentially-specified procedures. Many animals can respond appropriately to learned words – for example, dogs can be taught to obey verbal commands. However, Karmiloff-Smith speculated that only the human child has the potential to take its own representations as objects of cognitive attention. Her favourite example was a conversation she had with her 4-year-old daughter, Yara. "What's that?" inquired Yara. Karmiloff-Smith responded by saying that it was a typewriter. "No," rebuffed Yara: "You're the typewriter, that's a typewrite". Karmiloff-Smith (1992) argued that this was evidence of metalinguistic reflection. Not only could Yara use words, she had also worked out that the suffix "-er" is agentive and thus rejected the label provided by her mother. In other words, she exploited her knowledge in a way that *prima facie* non-human animals do not. Karmiloff-Smith (1992) argued that some of the knowledge embedded implicitly in linguistic procedures had been transformed ('redescribed') into a format that could be analysed and manipulated and, later in development, serve other cognitive domains. While it is true that humans spontaneously play with and exploit knowledge, it is not clear whether other animals do. Non-human animals can learn and produce independent action patterns, such as making requests for food, but there are no examples in the literature of a non-human animal analysing its own linguistic knowledge and using the component parts as Yara did upon hearing the label *typewriter*. Irrespective of whether the theory of representational redescription will be borne out by the evidence, Karmiloff-Smith once again demonstrated the importance of thinking developmentally and applying a developmental perspective to understanding fundamental questions in language-related sciences.

A developmental approach to research on multilanguage acquisition

Annette Karmiloff-Smith was a proficient bilingual and had worked as a simultaneous interpreter for the United Nations. Therefore, it is not surprising that one of her interests was about the acquisition of multiple languages and, specifically, how this can affect cognitive development (and decline) throughout the lifespan.

Research in the field of bilingualism/multilingualism has soared in the last two decades for three main reasons: (1) it is estimated that more than half of the world's population regularly speaks more than one language (Grosjean, 2010); (2) there is growing evidence that the acquisition of multiple languages may enrich cognitive development, especially executive functions (e.g., Bialystok, 2009); and (3) there is some evidence that the use of multiple languages may serve as a neurological protector in later stages of life, and may also delay the onset of dementia (e.g., Bak, Nissan, Allerhand & Deary, 2014).

On this line, Karmiloff-Smith inspired and co-authored a seminal study of control of interference in language comprehension carried out in a primary school in the UK (Filippi, Karmiloff-Smith et al., 2015). English monolingual and bilingual children from different linguistic backgrounds aged 7-10 years were compared when performing a sentence comprehension task in the presence of verbal interference. Bilingual children outperformed monolingual peers; they were more accurate in comprehending speech (i.e., in identifying the subject of a sentence) than monolingual children. Remarkably, bilingual children had better responses than monolinguals when comprehending particularly difficult and more cognitively demanding sentences, such as passives.

This study is the basis for two current larger scale projects that aim to build a developmental trajectory from infancy to older age, of the effects of multi-language acquisition on cognitive abilities, including memory, visual and auditory attention, core and higher-level executive functions, and metacognitive processing. These projects are heavily characterized by Karmiloff-Smith's theoretical and experimental approach. For example, the prevailing theory for the bilingual advantage suggests that bilinguals have to draw upon a domain-general resource—inhibitory control—to inhibit the automatic activation of non-target languages in order to produce only the target language (Green, 1998). However, neither this theory nor others explain why a bilingual advantage has been found in preverbal infants exposed to bilingual environments. Taking inspiration from Annette Karmiloff-Smith, we strongly advocate that a developmental perspective is needed to generate new hypotheses and advance the research in this area (Filippi, D'Souza & Bright, in preparation).

In addition, the main challenge for research of multi-language acquisition is to pinpoint the exact mechanisms that determine differences between monolinguals and bilinguals using a convergence of methods, including neuroimaging, genetic and qualitative techniques. The current literature provides evidence from individual studies involving infants, children, young adults, adults and the elderly in a non-developmental way, focusing on a single age group, in a single domain, and with different tasks. The current theoretical frameworks do not fully provide an account of all the subtle differences that occur between the monolingual and the multilingual brain through development. Karmiloff-Smith stressed the need to approach this line of investigation with the aim to explore change over developmental time and to focus on the interaction of different domains across the lifespan (Filippi & Karmiloff-Smith, 2013).

Karmiloff-Smith's legacy

This, then, is Karmiloff-Smith's legacy: development ought to be taken seriously. To some researchers (e.g., in the field of developmental systems), this is a truism. But to others, this is not so obvious. For some researchers, the environment merely triggers a prespecified programme, and development is the unfolding of that programme. But to Karmiloff-Smith, development itself is key to understanding the human mind.

As she put it: "I had thought that psychology was just about psychoanalysis or reaction time and questionnaires, but … [it embraces] logic, physics, biology, mathematics, evolution, genetics, anthropology and, above all, *development*, in the deepest sense of the term." (Karmiloff-Smith, 2008, p. 280).

Her work and guidance will live on in generations of researchers.

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