Thinking Developmentally from Constructivism to Neuroconstructivism

Introduction: Karmiloff-Smith from Piaget to neuroconstructivisim

A history of ideas

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Introduction

Annette Karmiloff-Smith was a seminal thinker in the field of child development in a career spanning more than 45 years. She was the recipient of many awards, including the European Science Foundation Latsis Prize for Cognitive Sciences (the first woman to be awarded this prize), Fellowships of the British Academy, the Cognitive Science Society, the Academy of Medical Sciences, and the Royal Society of Arts, as well as honorary doctorates from universities across the world. She was awarded a CBE for services to cognitive development in the 2004 Queen's Birthday Honours list. Annette passed away in December 2016, but she had already selected a set of papers that charted the evolution of her ideas, which are collected in this volume.

At the time of her death, Annette was engaged in an innovative research project studying development and ageing in Down syndrome (DS) as a model to study the causes of Alzheimer's disease. This multidisciplinary project, advanced by the LonDownS consortium, brought together experts in cognitive development, psychiatry, brain imaging, genetics, cellular biology, and mouse modelling. Annette's focus in this project was to explore early development in infants and toddlers with

Down syndrome. How could this inform Alzheimer's disease? The logic is a mark of Annette's brilliant theoretical insight. One of the genes implicated in Alzheimer's disease (the amyloid precursor protein or APP gene) is on chromosome 21. Down syndrome is caused by a genetic mutation where there is an extra copy of chromosome 21, and therefore of the APP gene. With extra APP production, the incidence of dementia in Down syndrome is much elevated. By age 40, nearly all adults with Down syndrome show evidence of protein build-up in their brains, the so-called plaques and tangles associated with Alzheimer's. Yet, notably, not all adults with Down syndrome go on to show the cognitive decline associated with dementia. This suggests that there are resilience factors in some individuals with Down syndrome which mean their cognitive functioning is resistant to the protein build-up. Annette speculated that these resilience factors should be visible in the early developmental profiles of infants and toddlers with Down syndrome, both in the emergence of their memory abilities and in functional brain activations. To understand dementia in Down syndrome, therefore, Annette argued for the importance of taking a developmental perspective.

This multidisciplinary project, rooted in developmental cognitive neuroscience, was far removed from Annette's early work in the laboratory of the renowned developmental psychologist, Jean Piaget. This volume charts Annette's physical journey, from Geneva, to Nijmegen, London, San Diego, and back to London. And it charts the journey of her ideas, from Piaget, to a reconciliation of nativist and constructivist theories of development in her ground-breaking book, *Beyond Modularity*; to her extension from typical to atypical development, her gradual move to a multidisciplinary investigation of the mind; and her continued focus on understanding the process of development, rather than treating it as a set of static snapshots.

Let us start in a bookshop in Geneva in 1969. At that time, Annette was working as a simultaneous interpreter for the United Nations. In her own words:

> I was bored, because I was always repeating other people's thoughts and not allowed, as an interpreter, to have any of my own. So I decided to go back to university. I originally thought of medicine, particularly child psychiatry. I was therefore often in the university bookshop looking at books under "P" for

> Psychiatry. Naturally, I also noticed those by Piaget on Psychology. Well, one day he walked into the bookshop (I recognized him from photos on his books), picked up a book he had ordered and then crossed to the University building. I followed him and audited his class. I was utterly amazed. *Un cou de foudre!* [A thunderbolt!] Psychology turned out to be much more than measuring reaction times. For Piaget, it included epistemology, logic, philosophy of mind, and philosophy of science. I was hooked, signed up that autumn and did my degree (Licence) in psychology at Geneva University. It was there I developed my absolute passion for research.

(Borovsky, 2005)

Jean Piaget was a founding figure of developmental psychology, and his theories dominated the field during most of the 20th century. Throughout her career, Annette's work was deeply influenced by Piagetian thinking in several ways. Like Piaget, she believed that the key to development was to understand the mechanisms that underlie the trajectory of changes across developmental time and which give rise to increasing complexity in behaviour. As we will see, she modernised this view by helping to establish the 'neuroconstructivist' approach to human development. Also, like Piaget, Annette believed that the study of development is inherently an interdisciplinary topic requiring input from many disciplines including philosophy, linguistics, genetics, and cognitive and developmental neuroscience – all fields to which she contributed. Finally, like Piaget she believed in the scientific value of observation (as a key supplement to experiments); one of her early contributions was to pioneer a radically different research strategy for understanding development, the so-called 'microgenetic' approach.

Part I: From implicit to explicit knowledge: typical development

Annette completed her PhD at Geneva University in Piaget's laboratory, under the supervision of Bärbel Inhelder and Hermine Sinclair De Zwart. Her thesis was published in 1979 under the title "A functional approach to child language". After her thesis defence, Annette was recruited by Bärbel Inhelder to participate in a research program on the cognitive strategies used by children to move from one stage of cognitive development to the next.

At the end of the first paper in this volume, “If you want to get ahead, get a theory”, published with Inhelder, there is a list of projects in progress in Piaget’s laboratory. It gives an indication of the research emphasis and methods at that time. Among the studies are: building bridges with materials of varying physical properties; balancing blocks of varying physical properties; constructing instruments to move objects; controlling water levels by immersion of combinations of objects with varying properties; spontaneous exploratory activities in observed play with Russian Matriona dolls; and modifying the order of locomotives and carriages in a closed circuit. Development was being studied in terms of gaining an understanding of physical systems, operations, and transformations.

In this first paper, Annette reports research carried out on children of different ages as they work with a balance beam. In the balance beam task, children are given blocks of wood and asked to balance them on a thin metal bar. Some of the blocks are heavier at one end than the other, either because their shapes are asymmetric or because weights are hidden inside. The first intuition is to balance the beams in the middle. But of course, some of them need an offset because of the uneven weight distribution. Annette watched as children figured out the problem, testing children of three different ages: 4–5-year-olds, 6–7-year-olds, and 8–9-year-olds. The key methodological innovation of this paper was not just to focus on macro-development – change across age – but also micro-development, “children’s spontaneous organizing activity in goal-oriented tasks with relatively little intervention from the experimenter [where] the focus is not on success or failure per se but on the interplay between action sequences and children’s theories-in-action” as they explore and figure out how the balance beam task works (p. 196).

Four- and five-year-olds could solve the balance beam task using proprioceptive information, that is, by feel. The children move the block over the metal bar, releasing and catching it until eventually when they release it, the beam balances. In other words, 4–5-year-olds could eventually achieve mastery of the task. However, 6–7-year-olds in some respects performed more poorly. These children came to the task with a theory, a belief that objects should balance at their geometric centre. They would continually start by trying to balance beams in the middle, causing them to make more errors than the younger children. By contrast, 8–9-year-olds were more sophisticated, pausing first to weigh up the options (so to speak), and sometimes explicitly verbalising: "you have to be careful, sometimes it's just as heavy on each side, sometimes it's heavier on one side". While these children also had a theory, they could talk about the theory and extend it flexibly.

The key theoretical insight Annette gained from this study was that in development, behavioural mastery of a task is not enough. Children need to move beyond this to form a deeper understanding, and sometimes, in doing so, will get worse at the task. When a sophisticated theory is in place, accuracy will return, and with it, both an ability to extend knowledge to new situations and verbalise it. Annette made links between this pattern of 'U-shaped' learning and a similar pattern observed in children's learning of inflectional morphology in language. For example, when learning the past tense of English verbs, children first learn to produce a small number of past tenses correctly, including irregular verbs (e.g., *thought*); later, irregular verbs are then sometimes inflected erroneously (e.g., *thinked*); before finally all past tenses are produced accurately. Analogously, children implicitly seek a more general principle that moves beyond initial mastery of a small number of verbs. The principle is the regular past tense rule, which is then inappropriately applied to irregulars. The children finally adjust the scope of the rule to exclude irregular verbs. This parallel between physical systems and language acquisition gave the first hint that Annette was striving for a more general theory of developmental change, as the paper concludes: "leading us closer to general processes underlying cognitive and linguistic behaviour" (p. 210).

Annette left Geneva to take up the position of Visiting Scientist at the Max Planck Institute for Psycholinguistics in Nijmegen (1981–1982). Before we consider the next step her research took, we might reflect for a moment on Annette's relationship with Jean Piaget. Piagetian theory was a launching point, and in *Beyond Modularity*, Annette would later seek to identify which parts of the theory should be taken forward and which let go. In Annette's own words:

> I spent some 13 years immersed in Piagetian theory at Geneva University, first as a student and then as a research collaborator. During that time, the home-grown Piagetians always considered me a heretic, both personally and theoretically. I refused to address Piaget as *Patron*, meaning "Boss", as he

> expected everyone in his department to do; I dared to put in writing that Piaget had underestimated the role of language in cognitive development; and, worse, I argued that sensorimotor development alone could never explain how language acquisition initially got off the ground – that there had to be some innate component, even if more general processes might operate.

(Preface to *Beyond Modularity*)

It is perhaps unfortunate that at the time Annette was in Geneva the Piagetian School was under attack from a number of prominent ‘anti-Piagetians’, who demonstrated apparently precocious infant and toddler abilities before Piagetian stage theory had predicted. These attacks led to a closing of ranks within Geneva around defending a precise and literal interpretation of Piaget’s statements. As a student of Piaget who questioned aspects of the theory, it was inevitable that conflict with her mentors would arise. Her filed correspondence reveals angry exchanges over a mysteriously withdrawn conference abstract on the limits of the Piagetian account of language acquisition, a position that she later articulated in the book based on her PhD thesis – “A functional approach to child language” (Cambridge University Press, 1979). The quote above alludes to these troubled years, and her uncomfortable position straddling between the Piagetian school and its critics. Happily, over more recent years as Piaget’s contribution to the field is seen more as foundational, rather than literal gospel, Karmiloff-Smith was welcomed back to Geneva and her visits increased. It is unfortunate that her terminal illness prevented her delivering a lecture at a major tribute conference to Piaget in the summer of 2016. Her correspondence and working notes from the Geneva period are now lodged with the Piaget Archives.

When Annette left Geneva, there was perhaps an opportunity missed. As Jean-Paul Bronckart from the University of Geneva recently wrote:

> During her Geneva period, Annette was distinguished by her intelligence and by a theoretical requirement that sometimes led her to take positions different from those of her thesis director, and even from “le patron” (Piaget) she nevertheless venerated. Appreciated by a few, Annette’s liberty was only moderately pleasing to the Piagetian “guardians of the temple” … Annette gradually took her distance from Geneva and, with her departure for Nijmegen, began the long and rich scientific journey that was to make her famous. Had she succeeded

Inhelder, she would no doubt have been able to ensure a genuine critical continuity to the Piagetian project, now almost abandoned.

(Bronckart, 2017)

At the Max Planck Institute for Psycholinguistics in Nijmegen, Annette focused on language acquisition, collecting data that were subsequently published in a 1986 paper entitled “From meta-process to conscious access: Evidence from children’s metalinguistic and repair data” (Karmiloff-Smith, 1986). This paper gave a much fuller exposition of Annette’s theoretical ideas. The research considered French-speaking children’s gradual construction of a system of nominal markers, including definite and indefinite articles and possessive adjectives (in English: *the*, *a*, *my*, *her*). In French, these markers must agree with the grammatical gender and number of the noun to which they refer. While focused on language acquisition, the theoretical goals of her work were much wider, and the beginning of the paper lays out a more fully formed model of what happens when children proceed beyond behavioural mastery, including introduction of the key theoretical idea of *representational redescription* (RR).

The empirical data driving these ideas revolved around a developmental asynchrony in three types of behaviour – that is, behaviours that emerged at different ages. Children were presented with situations to elicit language using articles and possessives. Annette would then ask the children why they chose the words they did. The first emerging pattern of behaviour was increasingly levels of accuracy: between 4 and 5 years, children were starting to produce the correct linguistic form. However, later emerging was the phenomenon of self-repair: children would sometimes start to output a certain linguistic form and then stop and correct themselves, as if they were monitoring their own output and had spotted an error. Still later emerging was the demonstration of meta-linguistic awareness, where the child was able to verbalise why they chose the linguistic form they did (e.g., a child of 8 years 4 months says: “I said *the* book because all the other things aren’t books, there’s just one”; p. 123).

The developmental asynchrony between these three types of behaviour, where behavioural mastery is only the first, led Annette to think in much more detail about what might be happening at a representational level. The paper argues for a ‘recurrent 3-phase model, which stresses the distinction between implicitly defined representations and progressive representational explicitation at several levels of processing, culminating in the possibility of conscious access' (p. 95). Behavioural mastery could be achieved by implicit representations, but some intrinsic process would continue to recode this knowledge, making it more general and more flexible, taking knowledge that was *in* the system and making it available *to* the system. This was the proposed process of representational redescription. The two types of behaviour Annette observed beyond mastery, self-repair followed by explicit, verbalisable meta-linguistic knowledge, suggested to her that the process was iterative and involved several levels, listing in the paper at least four: Implicit (I), Primary explicitation (E-i), Secondary explicitation (E-ii), and Tertiary explicitation (E-iii), with knowledge in each case more general and more flexible.

As Tomasello and Rochat (1994) comment, this proposal marks a divergence from Piagetian theory:

> cognitive changes in terms of redescription occur when a stable state is achieved, this stability being viewed as necessary for the RR process to occur. This position is in sharp contrast to views that emphasize conflicts and contradictions as major sources of progress in development (i.e., Piaget's model of equilibration).

Two points are notable in the 1986 paper. First, Annette appears to endorse Fodor's idea that there might be at least some innate 'modules': specialised, self-contained cognitive processing devices dedicated to specific cognitive domains (Fodor, 1983). But she proposes for the first time that such innate modules might also be complemented by another sort of module, those that arise as product of development.

Second, the terminology of this paper makes it evident that Annette is striving for a notion of mechanism. Here she appeals to the information processing terminology of the time, in terms of symbolic computer programs. There are terms like scanning, recoding, control, closed feedback loops; information is stored, indexed, accessed, restructured; there are procedures and routines. Sometimes this leads to rather painful exposition:

> It thus follows from the model that *unconscious* metaprocedural processes could operate on the representations of *conscious* inter-domain metacognition, thereby

defining in E-i form new connections which remained implicitly defined for as long as the representation were in different codes.

(p. 143)

Annette would ultimately give up on the specific model of representational redescription articulated in this paper, with its particular set of phases and levels, and become more interested in computational approaches constrained by the properties of the neural substrate (e.g., connectionism). As we shall see, there was little further discussion of RR in the middle part of her career, until it re-emerges in the final paper included in this volume.

The second paper in the volume is also addressed to RR, but now in the domain of children's drawing: "Constraints on representational change: Evidence from children's drawing". The goal of the study was to hone in further on how representations change during the iterative process of RR. Imagine a child has mastered a motor program for drawing a human, or a house, or an animal (however rudimentary). Under the RR scheme, the initial representation is inflexible and only allows for the sequential execution of the program. Annette asked children in two age groups, 4–6 and 8–10 years, to produce such drawings. But crucially, she then asked them also to draw a human, house, or animal 'that does not exist'. By definition, the pictures should now be novel. She then examined what the children altered to make their pictures novel.

In the 4–6-year-olds, the novel picture was always drawn in the same sequence; merely the size or shape of the elements was altered (e.g., a human might have a larger head, or a square head). In the 8–10-year-olds, however, both the position and orientation of elements could be altered, and children could add elements from other conceptual categories (e.g., they might draw a human with two heads, or a half human half four-legged animal). Construed as RR, 4–6-year-olds had carried out a redescription of 'drawing a human' that gave some flexibility, but the program was still constrained by the list of elements and their order. The further redescription of the older children released those constraints and additionally allowed links across categories, or as the paper describes it, 'inter-representational flexibility'.

Perhaps the young children were simply less inventive? In a fascinating second experiment, Annette recruited another group of 4–6-year-old children, and specifically asked them to draw a human with two heads. If, at this age, their motor program had not been re-represented sufficiently to allow flexibility over the elements of drawing a human, this challenge should have been beyond them. Annette continues:

> As the first young subject began to draw a second head, I was reminded of T. E. Huxley's lament: "the great tragedy of science; the slaying of a beautiful hypothesis by an ugly fact"! However the first subject, and all but one of the seven others tested, then went on laboriously and very slowly to draw two bodies, two arms and legs on each body, etc.; that is, they used a complete man-drawing procedure for each head, and they kept starting again because dissatisfied with the result.
>
> (p. 68)

Once more, this paper strived for the more general picture, drawing parallels with similar phenomena in other domains where flexibility in sequencing only seems to emerge with developmental time. Examples include seriation, number, phonological knowledge, and learning to play tunes on the piano. Once more, mechanism is discussed in terms of symbolic computation (data structures, data formats, procedural sequences and sub-routines, compiled and automatised programs). Indeed, here Annette makes explicit links to artificial intelligence research, noting that in AI, there is a distinction between procedures that generate outcomes and those that operate on other procedures, thereby changing those procedures (p. 59). We find Annette once more willing to entertain the possibility of innate modularity alongside her theory of representational change, a possibility she would go on to reject in later years: "My view is that the basic syntactic component of language is innately specified and modular" (p. 77).

The culmination of this line of theorising came with the publication of Annette's 1992 book, *Beyond Modularity*, which integrated her multiple lines of research to date. This book was largely written during a sabbatical year at Carnegie Mellon University in Pittsburgh during which Annette was more frequently exposed to the emerging field of cognitive neuroscience, and the associated advances in brain-inspired connectionist computational modelling. These fields offered new ways of mechanistic thinking that Annette integrated into her book. The third paper in this volume is a précis of the main arguments, published in 1994. *Beyond Modularity* remains a highly influential book. As Ansari recently commented: "[it] represents, in my view, the most complete post-Piagetian theory of developmental change and is still a must read for anybody studying cognitive development, almost 25 years following its publication" (Ansari, 2017).

The majority of the book comprises a consideration of representational redescription in several domains, summarising empirical findings with the child viewed as a linguist, a physicist, a mathematician, a psychologist, and a notator. Each characterises the initial state of the infant, subsequent domain-specific learning, and then explores empirical data on older children's problem solving and theory building, with particular focus on evolving cognitive flexibility and metacognition. Annette describes it as her "best shot at giving an integrated account of data across a wide variety of domains which in isolation may be better accounted for by a series of different explanations" (Karmiloff-Smith, 1994, p. 740).

However, the book had two more far-reaching aims. The first was to situate development more firmly within cognitive science, encouraging researchers to go beyond characterising the on-line processing of steady state systems and to investigate mechanisms of developmental change at the cognitive/representational level, rather than simply the behavioural level, or as she puts it, to

> treat cognitive development as a serious theoretical science contributing to the discussion of how the human mind/brain develops and is organized internally, and not merely as a cute empirical database addressing the question of the age at which external behaviour can be observed.
>
> (p. 693)

The second was to attempt a reconciliation of the then dominant and opposing theoretical views of development, those of Fodor and Piaget. In Fodor's nativist theory, the mind/brain is made up of genetically specified, independently functioning, special-purpose modules, with their own dedicated processes and proprietary inputs. Each module then outputs data in a common format suitable for central, domain-general processing. In Piaget's constructivist theory, all data are processed by the same mechanisms, while development involves domain-general changes in representational structures. Annette's solution to the opposing positions was to accept some degree of Fodor's modularity as an endstate in adults, but now to argue that this was always the outcome of a domain-general developmental process of modularisation from a less specialised initial state. "I hypothesize that if the human mind/brain ends up with any modular structure, then this is the result of a process of modularization as development proceeds" (p. 695). Emergent specialisation would be complemented by representational redescription, with sharing of information proceeding beyond mastery to generate the (perhaps unique degree of) cognitive flexibility observed in humans. With some prescience, Annette argued that the degree of specialisation in the infant would only be established with the emergence technologies for measuring on-line brain activation with neonates and young infants.

> If Fodor's thesis of pre-specified modules is correct, such studies should show that, from the very outset (or the moment at which the infant shows sensitivity to particular forms of input), specific brain circuits are activated in response to domain-specific inputs.
>
> (p. 695)

By contrast, her emergentist view would predict less differentiated and specialised brain activation in infants. When these technologies arrived, the results would broadly prove her right (see, e.g., Dehaene-Lambertz, 2017).

The précis of *Beyond Modularity* was published in *Behavioral and Brain Sciences* as a target article, and was accompanied by a range of commentaries, along with Annette's response. It is instructive to consider some of those commentaries, for they ultimately picked up on the direction in which Annette's thinking was already headed. Johnston (1994) argued that a serious theory of development situated in cognitive science could not incorporate any notion of 'innateness'. This is a non-developmental concept that stands in place of an account of how gene activity contributes to cognitive development via brain-cognition relationships at the cellular and molecular level. Similarly, Quartz and Sejnowski (1994) argued that modularity is ultimately a thesis about how information is processed in the brain. The then available data from neurobiology suggested that the nativist position and the related modularity thesis were highly implausible. Shultz (1994) endorsed Annette's growing belief in the importance of formal models, arguing that the latest computational models in the field – connectionist or artificial neural network models – were powerful enough to capture patterns of experience-dependent developmental change. Annette accepted many of these suggestions, but if anything, she was looking for more:

> I have been somewhat disappointed in that, with a few exceptions, many commentators reiterated what I had already stated in Modularity, by simply pointing to the under-specification of my framework rather than suggesting potential solutions from their domain of expertise.
>
> (p. 732)

Nevertheless, the pointers here were clear: the next step was towards an approach that integrated multiple disciplines, embracing developmental cognitive neuroscience, neurocomputation, and genetics.

The theory of RR was not completed in *Beyond Modularity*, but the book represented a monumental effort in attempting to reconcile Fodorian nativism and Piagetian constructivist approaches. A sprinkling of doubts remained: where is the role of culture in Karmiloff-Smith's development theory? Is there no place for domain-general skills such as executive functioning, whose development can constrain emergence of other skills? What about exogenous environmental drivers of development, rather than just the internal processes of modularisation and RR? What limits the rate of RR, such that it can be differentiated from learning and expertise (if indeed they differ)? Why do there remain in adults areas of well-established behavioural mastery where no explicitation has taken place, such as the notorious complexities of syntax? What are the overarching principles revealing why RR should work in the way it does and not some other way?

However, we should note the magnitude of the challenge RR took on – to explain the emergence of cognitive flexibility. The challenge has still not been met. Even in the field of machine learning, with its recent great advances, cognitive flexibility remains out of reach. Cutting-edge AI methods, such as deep neural networks, have learned behavioural mastery in individual domains such as image recognition, voice recognition, and chess playing. Yet they cannot demonstrate flexibility to draw links across domains. As Aaron Sloman, a philosopher and researcher on artificial intelligence and cognitive science, commented on *Beyond Modularity*:

> The theory in Beyond Modularity is a considerable advance both on Piaget's general ideas on development and also an advance on the presuppositions of many of the people working on machines (including robots) that perceive, act, develop, or learn – because most of those researchers think only about how to get robots to achieve behavioural mastery (e.g. catching a ball, juggling, walking, running, following a human, picking things up, carrying things, going through doorways, avoiding obstacles, obeying instructions, answering simple questions, etc.). Such behavioural mastery can be achieved without giving a machine the ability to think about what it has done, what it has not done, what it might have done, what the consequences would have been, what it could not have done, etc. Those additional competences require something like what Karmiloff-Smith calls Representational Redescription, and we need to find ways to get robots to go through such processes if we wish to give them the kind of intelligence young humans, nest-building birds, hunting mammals, monkeys, and other primates seem to have. Developing such mechanisms will help us understand the processes that occur in children and other animals in a new, deep way. The book does not provide mechanisms, but Karmiloff-Smith is clearly aware of the need to do so.

(Sloman, 2015)

Part II: From typical to atypical development

Annette completed *Beyond Modularity* while at the MRC Cognitive Development Unit in London. There, several colleagues were working on autism and Down syndrome, which began to deepen her thinking about atypical development. Previously, she had referred to developmental disorders as possibly informative about domain specificity and modularity by virtue of the uneven cognitive profiles that could be observed, such as particular developmental weaknesses in social cognition or language; or as offering cases such as savant ability where behavioural mastery was not followed by RR and increasing flexibility. But now she was struck by limitations in theorising of the time, which viewed developmental disorders in a static, profoundly non-developmental way.

Another change in her thinking was crystallised by her collaborative book *Rethinking Innateness*, jointly written with Jeff Elman, Elizabeth Bates, Mark Johnson, Dominic Parisi, and Kim Plunkett (Elman et al., 1996). This was an influential volume that married a constructivist view of human development with connectionist modelling and developmental neuroscience. While previously sceptical that connectionist modelling could address anything other than implicit learning, Annette's enthusiasm for it had been spurred by a study visit to San Diego, working with Jeff Elman and Liz Bates. Rethinking Innateness bridges Annette's transition into developmental cognitive neuroscience, representing an attempt to consider development in terms of a complex, multi-level, dynamic process. The period marks her increasing conviction that the study of atypical development was a key avenue to shed light on the nature of the developmental process – and by the same token, that the developmental process itself was the key to understanding atypical development.

The first paper in this section is seminal in the field of developmental disorder research. "Development itself is the key to understanding developmental disorders" was published in 1998, the year that Annette moved to become Head of the Neurocognitive Development Unit at the Institute of Child Health in London. During her eight years at the Institute of Child Health, Annette investigated a number of genetic syndromes, including Williams syndrome (WS), Fragile X, and Down syndrome.

Up until this point, the study of cognitive impairments in developmental disorders had proceeded as if they could be viewed as directly analogous to cases of acquired deficits in adults (e.g., Temple, 1997). Selective deficits in adults were viewed as a principal source of evidence for the presence of modules: a selective deficit was explained by damage to a single module. Cognitive deficits in developmental deficits were therefore analogously viewed as damage to an innate module, whereby the relevant ability did not develop typically in the first place.

Annette rejected this view on several grounds. The first was that such an account either takes no account of development at all, or poses a developmental theory that is obviously wrong (that development occurs independently in separate modules). Given that, since *Beyond Modularity*, Annette had rejected modularity as a plausible start state in infancy, the alternative was to view uneven cognitive profiles as the product of an atypical developmental process. The second grounds was that, given the way gene expression tends to have widespread influence on brain development, it was implausible that it would lead to very narrow/specific effects on cognitive outcomes. The alternative was that the effects were widespread, but that this changed properties of the brain which impacted more on the development of some abilities than others.

Beyond Modularity had pitted Fodor's domain specificity against Piaget's domain generality. Here was a new idea, the middle ground of *domain relevance*. In this view, the start state is differentiated to some degree, but processing properties have different degrees of relevance to some abilities than others. Across development, regions and pathways specialise so that domain-relevant properties become domain specific (Box 4.2 of the paper illustrates the idea with respect to a connectionist model of visual cortex). Disruptions to domain-relevant properties would produce greater effects on the development of abilities with greater reliance on those properties, and perhaps more subtle anomalies in other abilities with weaker reliance. The arguments are well captured by Annette's views on Williams syndrome, a disorder showing a markedly uneven cognitive profile:

> Brain volume, brain anatomy, brain chemistry, hemispheric asymmetry, and the temporal patterns of brain activity are all atypical in people with Williams syndrome. How could the resulting cognitive system be described in terms of a normal brain with parts intact and parts impaired, as the popular view holds? Rather, the brains of infants with WS develop differently from the outset, which has subtle, widespread repercussions at the cognitive level.

(p. 393)

Several methodological implications stemmed from these insights. First, the investigation of developmental deficits should proceed by studying infants and then tracing the unfolding of atypical trajectories, rather than by characterising cognitive deficits in the endstate of adulthood. Second, researchers should not focus merely on deficits or weaknesses, but should also use sensitive measures to probe for subtle anomalies in areas of strength. Here we see an idea reappearing from Annette's early work on representational redescription. Recall, U-shaped developmental profiles suggested the same levels of accuracy – each side of the U – could be produced by different types of representation, initially implicitly, later re-represented. In the developmental disorder context, Annette now raised the possibility that similar levels of behavioural accuracy, for instance in domains of apparent strength in a disorder, could be produced by qualitatively atypical underlying representations. And this could particularly be the case where a researcher employs coarse standardised tests to establish cognitive profiles, since such tests are insensitive to the nature of underlying processes. The third methodological implication was that the key data to reveal the constraints operating on development are cross-domain: the longitudinal study of multiple domains can separate domain-general changes from domain-specific ones. Cross-sectional data alone cannot address this crucial issue.

The final methodological implication is also a theoretical one, and corresponds to the laying out of a new framework: *neuroconstructivism* (see Box 4.6 of the paper). Annette argued that plausible cognitive theories of developmental deficits have to be constrained by an understanding of – and therefore data from – genetic influences on brain development and function; and must take into account the history of an individual's dynamic interactions with their environment. Future research in developmental disorders would therefore have to be multi-disciplinary.

The two further papers in this section exemplify these ideas in the research Annette and her team carried out with infants, children, and adults with Williams syndrome. WS is a rare genetic disorder caused by the deletion of a small number of genes from one copy of chromosome 7. It leads to a characteristic pattern of physical and cognitive deficits, including an average IQ of 70. Notably, the WS cognitive profile is uneven, with relative strengths in language and face processing, and relative weaknesses in visuospatial processing and problem solving. In addition to its clinical significance, WS was theoretically important since it had been used by nativist researchers to argue that it represented one part of a genetic dissociation between language and general cognition (Pinker, 1994). Juxtaposed with Specific Language Impairment, a heritable language disorder with relative strength in non-verbal cognition but weakness in language, Pinker (1999) argued that the two represented a genetic double dissociation between language and cognition, and were evidence in favour of innate modularity.

In "Dethroning the myth", Annette marshals a range of empirical evidence to argue forcefully that this is a mischaracterisation of WS, and a misconceived explanation of the uneven cognitive profile. For both language and face processing, development is traced back to early childhood, and evidence presented that skills are atypical from early on, sometimes subtly. In support of her criticism of focusing on adult endstates in developmental disorders, Annette describes a study carried out in her lab that contrasted language and number processing skills in WS and Down syndrome (Paterson et al., 1999). In adults, language skills were shown to be stronger in individuals with WS than DS, while the opposite was true for number skills. However, when these two domains were assessed in infants with the disorders, infants with DS outscored infants with WS on a number task, while there was no difference in language abilities. The respective uneven cognitive profiles were different at different ages. A snapshot of the adult cognitive profile was therefore actively misleading with respect to developmental origins.

In "Exploring the Williams syndrome face-processing debate", Annette shifts to focus on an area of relative strength in the disorder, face recognition skills. There are three points of interest in this paper. First, sensitive tests showed that where children and adults with WS were scoring at chronological age level expectations in a standardised test of face recognition (i.e., showing no deficit), the underlying cognitive processes nevertheless appeared to be atypical, lacking the expected expertise in processing configurations of facial features. Second, the paper showed how atypical development could be described statistically using cross-sectional trajectory analysis, to show how the level, rate, or shape of development could be different, or assess atypicalities in the relationship between skills. These trajectory methods were later developed more fully in Thomas et al. (2009). Third, for the first time, Annette integrates brain-imaging evidence to support the proposal that cognitive level skills develop atypically. Here, notably, electrophysiology is used to argue that processes of face recognition are less localised (to the right hemisphere) and less specialised (to faces but not cars or houses) than in typically developing controls. Since localisation and specialisation would both be expected markers of modular functioning, this evidence suggests that emergent modularisation is disrupted in WS.

Part III: Genetics and computational modelling approaches

The next set of three papers considers the multiple methods and data sets that Annette used to link genotype to phenotype. Here we see more biological terminology present in Annette's writing, as she considers the relationship between sources of genetic variation or mutation in an individual (the genotype) and the subsequent cognitive profile (phenotype). In the first paper, "Different approaches to relating genotype to phenotype in developmental disorders", Annette and her colleagues criticise simplistic one-to-one mappings between genes and specific cognitive outcomes. These simplistic mappings can be found when researchers use phrases like "*a gene (or set of genes) for X* where X is a purported higher level cognitive module such as face processing, grammar, number, or so on" (p. 311), such as those found in the proposals of Pinker (1999) and Marcus (2006). Instead, Annette and colleagues argue that the pathway from genes to cognition is complex and indirect.

The paper then summarises the multiple methods that are required to unpack this pathway. These include quantitative genetics (population level measures of the heritability of phenotypes); molecular genetics (the study of DNA variation correlated with phenotypes); animal models, such as transgenic mice created to have identical or analogous mutations to human disorders; and computational modelling, viewed as an intermediate level at which hypotheses may be generated concerning the link between low-level neurocomputational differences and high-level cognitive outcomes.

In support of the concept of domain-relevance, the example of Fragile X is discussed in some detail. This developmental disorder is caused by the mutation of a single gene, FMR1, yet it leads to an uneven cognitive profile with strengths and weaknesses. Notably, FMR1 appears to impact on experience-dependent plasticity, with lack of this protein affecting dendritic spines, structures involved in the signalling between neurons. Research is described where a mouse model of Fragile X was used to investigate the impact of the mutation on these low-level brain structures. Crucially, the effect of the Fragile X mutation is widespread in the brain yet, through the developmental process, the impact on cognition is uneven.

In line with Piaget, Annette was more inclusive than usual in the different approaches that she took to understand human development. While empirical controlled experiments were a mainstay, individual observations and case studies were also considered important sources of insight. Annette's person-centred approach to atypical development was as rewarding for her science as it was for the children and families that she studied. A particular fascination was why no two children with

Down syndrome, Fragile X, or WS were the same, and to what extent genetic or environmental differences could influence their later outcomes.

In the next paper, “Using case study comparisons to explore genotype-phenotype correlations in Williams-Beuren syndrome”, Annette and her colleagues focus on the specific case of relating the genetic mutation in WS to its characteristic uneven cognitive profile. Recall, WS is caused by the deletion of a small number of genes from one copy of chromosome 7. By the time of publishing this paper, 19 had been characterised within the deleted region of DNA, while that number now stands at 27 (Broadbent et al., 2014). Annette addressed a particular argument present at the time that the mapping between genes and physical and cognitive outcomes might be straightforward. Specifically, deletion of one of the genes, elastin (ELN) is associated with the connective-tissue abnormalities and cardiovascular disease (supravalvular aortic stenosis [SVAS]). Deletion of another gene, LIM kinase-1 (LIMK1) would account for the particular weakness in visuospatial cognition.

This simple mapping was evaluated via two case studies. The first was a 43-year-old adult with WS who was particularly high functioning, recording an overall IQ of 93. She had the typical genetic deletion of WS and correspondingly, exhibited the characteristic visuospatial deficit. The second case was an 11-year-old girl who had a deletion of 60% of the region of DNA normally deleted in WS, including both ELN and LIMK1. While the girl exhibited SVAS, her cognitive profile was in the normal range, and there was no evidence of a deficit in visuospatial cognition. LIMK1 alone could not explain the spatial deficit. Together, the case studies reveal the scale of the challenge in relating uneven cognitive profiles to specific genes. Indeed, a decade later, Annette and her team reported two further case studies of children with partial deletions of the stretch of DNA associated with WS (Broadbent et al., 2014). Here, visuospatial cognition was explored in greater depth, distinguishing between small-scale and large-scale space. Notably, different partial deletions revealed contrasting profiles across these scales, suggesting a “complex, dynamic, and combinatorial role of different genes within the WS critical region on disparate phenotypic expression within the visuospatial domain” (Broadbent et al., 2014). The complexity only increased!

The third paper in this section exemplifies Annette's belief that formal models represent an important tool to link data from multiple levels of description within causal mechanistic accounts. The paper, "Mechanisms of developmental regression in autism and the broader phenotype: a neural network modeling approach" presents a connectionist model of developmental regression in autism. In a minority of children with autism (20%–40%), cognitive skills decline in the second year of life after a period of apparently normal-looking early development. The paper, co-authored with Thomas and Knowland, considers the hypothesis that such regression is caused by the exaggeration of an otherwise normal phase of brain development, synaptic pruning. Computer modelling is firstly used to establish the mechanistic viability of the idea, linking a low-level neurocomputational property to a high-level deficit in behaviour via an implemented developmental process. Secondly, it is employed to explore the idea that individual differences in other neurocomputational parameters can add risk or protective factors in determining whether the pathology, atypical synaptic pruning, results in atypical cognitive development, thereby accounting for variation in the atypical phenotype and patterns of family inheritance (see also Thomas et al., 2016). For Annette, this model linked with her ideas of specialisation and localisation of function (generated here by pruning), combined with the crucial importance of timing in development. Should the brain commit too rapidly to specialisation and localisation of function, the result would be less flexibility for processing novel stimuli. Moreover, the pivotal role of the time course of developmental change demonstrated once more the need to progress theory beyond the simple metaphor of static intact and impaired modules (Karmiloff-Smith, 2015).

Part IV: Taking the brain seriously

In 2006, Annette left the Institute of Child Health to join Birkbeck, University of London, as a Professorial Research Fellow. At Birkbeck, she was based in the Developmental Neurocognition Lab in the Centre for Brain and Cognitive Development. The papers in this and the next section exemplify Annette's continued broadening of her multi-level, dynamic approach to development, embracing epigenetics, brain structure/function, network connectivity, cognition, behaviour, and the environment. "Neuroimaging of the developing brain: taking 'developing' seriously" considers the utility of functional brain imaging for studying developmental change. Paradoxically, in this paper she views many current brain imaging studies of infants and children as non-developmental, and as merely portraying snapshots of brain function at different ages, instead of revealing processes of progressive change. In a review of the strengths and weaknesses of the main brain imaging methodologies (functional magnetic resonance imaging, function near-infrared spectroscopy, event-related electrophysiology), her key themes emerge. Imaging must be hypothesis-driven and test mechanistic accounts (or as she says, "as a tool, brain imaging is no better than a pencil or a fishing trip, unless it is hypothesis driven", p. 934). Neural data can be most informative when it shows that similar-looking behaviour is generated by alternative underlying circuitries, as in the case of atypical development, or the case of compensatory changes in healthy ageing. Given limits in spatial or temporal resolution, development is best studied by a multi-method converging approach, combining imaging methods and the study of trajectories of change. In this paper, Annette also looks to the future: the possibility that brain imaging can test her RR hypothesis through studying emerging hierarchical network structure in 'resting state' brain networks; and the possibility that advances in wireless technology will eventually allow imaging to move beyond a child lying flat in a scanner into the real world, with the child interact naturally in their environment.

Part V: Taking the environment seriously

Annette's neuroconstructivist framework for explaining developmental disorders stressed the importance of considering the environment as much as the internal causes of the disorders. In the paper in this section, "Genetic and environmental vulnerabilities in children with neurodevelopmental disorders", Annette and her colleagues work through this idea in greater detail. They focus on the methodological approach of tracing cognitive level functions back to their basic level roots in infancy and then probing their ontogenetic progression. The importance of interaction with the environment is considered in three examples. In the first, numeracy skills are contrasted in two disorders, WS and DS. In adults with WS, there are difficulties with large approximate number discrimination, whereas in DS there are difficulties with small exact numbers. The origins of the profiles are traced to a single basic level problem for each syndrome. During infancy, visual attention shifting deficits in WS lead to difficulties in discriminating large approximate quantities, while visual sustained attention deficits produce difficulties in individuating objects in small displays in DS. The low-level deficits alter the history of experience in number processing in each disorder, leading to later diverging patterns of deficit in high-level numeracy skills. In the second example, Annette and colleagues consider the possibility that social deprivation can sometimes produce cognitive impairments that show similarities to those observed in genetics disorders. The authors describe an experimental paradigm designed with the ambition to distinguish syndrome-specific versus general and modality-specific versus general characteristics of deficits originating in genetic versus environmental causes (see also Karmiloff-Smith et al., 2014). In the third example, the authors present evidence to suggest that, when a child has a genetic disorder, aspects of their environment are simultaneously changed. Developmental profiles are a product of the combination and interaction of these effects. Evidence comes from how parents constrain their infant's exploration of the physical environment, and how parents respond to errors in their toddler's productive naming skills. As the authors say, "nothing is static in biology or psychology, and this finding holds equally for the environment" (p. 17264).

Part VI: And, always, taking development seriously

The three papers of the final section represent the fruition of Annette's neuroconstructivist approach, and the multiple lines of research it spawned. In "Ontogeny, genetics, and evolution: a perspective from developmental cognitive neuroscience", Annette demonstrates how the accumulating body of empirical evidence led away from the simple notion of innate modularity to an emergentist account of adult specialisation of function, considered, respectively, in the fields of evolution, genetics, and development. In "Nativism versus neuroconstructivism: rethinking the study of developmental disorders", Annette revisits her seminal 1998 paper some ten years later, reviewing progress in the field of disorder research and validation of its primary methodological lessons. In "An alternative to domain-general or domain-specific frameworks for theorizing about human evolution and ontogenesis", Annette focuses on the notion of domain-relevance, the intermediate position between domain generality and specificity. She grounds the idea more firmly at computational, neural, genetic, and evolutionary levels. She then shows how it synthesises with contemporary accounts, such as Dehaene's *neuronal recycling hypothesis* (Dehaene, 2009). In the neuronal recycling hypothesis, cultural inventions such as reading and writing invade older cortical circuits, thereby inheriting their structural constraints. As Annette says, "the notion that these new functions seek out a ‘neuronal niche’, i.e., a cortical area in the brain *relevant* to the processing required, is clearly along the same lines as the domain-relevant approach” (p. 6). Finally, in the context of Dehaene’s proposal of a global workspace for flexible use of knowledge (and indeed, conscious access), Annette sees the possibility of a brain basis for her concept of RR (Dehaene et al., 2014). Domain-specific systems enable plasticity and flexibility through a process of cross-domain interactions in a global workspace, where information is available to conscious access.

Conclusion

The history of Annette’s ideas also charts the history of the emergence of developmental cognitive neuroscience as a field. What started as observations about the behaviour of children at different ages became the study of mechanisms of change in a multi-level dynamic framework, embracing neuroscience, genetics, and evolution. Rudimentary concepts of modularity were replaced with neurally grounded concepts of increased localisation and specialisation, while clunking metaphors of procedures, data structures, and subroutines were replaced by the language of brain-inspired computation. A research career that began with a chance meeting with Jean Piaget in a bookshop in Geneva, and ended with a sophisticated multidisciplinary investigation of Down syndrome as a molecular model for Alzheimer’s disease almost half a century later, has set the stage for a future understanding of development that unifies the many disciplines of the cognitive and biological sciences.

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