THE CAMBRIDGE ENCYCLOPEDIA OF CHILD DEVELOPMENT

Edited by **BRIAN HOPKINS**
with Ronald G. Barr, George F. Michel
and Philippe Rochat

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The Cambridge Encyclopedia of Child Development

The Cambridge Encyclopedia of Child Development is an authoritative, accessible and up-to-date account of all aspects of child development. Written by an international team of leading experts, it adopts an multidisciplinary approach and covers everything from prenatal development to education, pediatrics, neuroscience, theories, and research methods to physical development, social development, cognitive development, psychopathology, and parenting. It also looks at cultural issues, sex differences, and the history of child development. The combination of comprehensive coverage, clear, jargon-free style, and user-friendly format will ensure this book is essential reading for students, researchers, health-care professionals, social workers, education professionals, parents, and anyone interested in the welfare of children.

Features include:

- Foreword by Jerome Bruner
- Comprehensive coverage
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The companion website for this title can be found at www.cambridge.org/hopkins. It includes an extended glossary, biographical sketches, relevant organizations and links.

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Associate Editors: Ronald G. Barr, George F. Michel, Philippe Rochat

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EDITORIAL PREFACE

The subject matter of child development has grown exponentially over the last fifty years such that its study has become a vast multidisciplinary enterprise. The roots of this enterprise can be traced back to the 1930s, when the likes of Arnold Gesell, Myrtle McGraw, and Jean Piaget embarked on systematic programs of research, each one encompassing a variety of disciplines in different ways.

Common to these pioneering attempts at forging a multidisciplinary approach to the study of child development was an appreciation that ontogenetic development and biological evolution were somehow inextricably linked, and as such it shaped the questions being asked and the answers provided. Subsequently, and perhaps for justifiable reasons at the time, child development was studied bereft of evolutionary considerations and all things 'biological.' With the rise of molecular developmental genetics during the last decade or so, together with renewed insights into the relationships between ontogeny and phylogeny, the landscape of research on ontogenetic development has been changed irrevocably, and as a consequence that on child development will have to take into account newly emerging fields of study such as evolutionary developmental biology.

Another theme that stands out in the book concerns the impact of neuroscience on how child development, both 'normal' and 'deviant,' is presently studied. Ranging from specific animal models through non-invasive neural imaging techniques to computational modeling, the wealth of information generated about the changing nature of brain–behavior relationships during development is truly staggering. The challenge now, and one to which this book is geared, is how to integrate this plethora of new knowledge and that contained in the first theme so that progress can be made toward the provision of more unified theories of ontogenetic development that cross disciplinary boundaries.

A further theme includes the historical roots and controversies that have motivated the study of child development and which form essential reading for understanding the two main issues that continue today: the origin problem and the change problem. The first calls for a better understanding of the ways in which prenatal development relates to that after birth, and the second for the use of longitudinal designs and associated statistical techniques for teasing out the salient features of intra-individual change in whatever domain of development. As an additional theme, this book strives wherever possible to encourage the study of child development across domains (e.g. cognitive, motor, social) rather than within domains as one means of achieving greater theoretical integration.

There is no pretense made of having covered every possible topic that might fall under the heading of 'child development.' Given the limitations of space and those imposed by our own experiences in studying child development, we have endeavored nevertheless to provide a coverage that is as comprehensive as possible. Having said this, there are no separate entries, for example, that deal with 'attachment theory' or 'qualitative research.' Despite not having dedicated slots, such topics are given consideration across a number of entries. Furthermore, the book will have a companion web site by means of which readers will be able to communicate with the editor about the structure of the book and its contents as well as make suggestions for revisions or for correcting any inaccuracies. It will also contain an extended glossary, a large number of web site addresses for relevant scientific organizations, as well as further information relevant to specific entries, and short biographical sketches of additional individuals who have, directly or indirectly, had an influence on the study of child development.

Finally, we wish to thank a number of individuals who enabled this book to come to fruition. To begin, there are the numerous referees whose reviews of the initial proposal helped us to refine both structure and content. In approaching authors for particular topics, the recommendations of Jonathan W. Hill (University of

Liverpool), William P. Fifer (Columbia University), Albert Gramsbergen (University of Groningen), and Claudio Stern (University College London) were particularly helpful. Throughout the whole process of editing the book, Ronald W. Oppenheim (Wake Forest University) was a consistent source of valuable advice, and in the run-in to completion Thomas C. Dalton (California Polytechnic State University, San Luis Obispo) provided a much-needed and coherent description of the term 'consciousness' for the glossary. A number of people kindly accepted the job of reviewing a selection of first drafts, which resulted in some very helpful comments that improved the quality of subsequent versions. These particular individuals have been acknowledged on a separate page. A special debt of gratitude goes to the in-house editorial team at Cambridge University Press: Sarah Caro, Gillian Dadd, Alison Powell, and especially Juliet Davis-Berry. Their advice, patience, and support throughout the arduous task of completing such a large book were unfailing and of the highest professional quality. Another special debt of gratitude goes to Leigh Mueller, copy-editor *par excellence*. To everyone who has helped us in one way or another, we are most grateful.

Brian Hopkins
Lancaster, January 2005

FOREWORD

The course of human development used to be a topic for the specialist – the pediatrician, the development psychologist, the child welfare worker, and even the anthropologist in search of the origins of cultural difference. There was also, to be sure, a wider audience of parents, in search of advice about how best to 'raise' their children, and the better educated among them often browsed in the technical developmental handbooks for clues about how to deal with their children's 'difficulties,' like dyslexia or persistent bedwetting or failure to meet the 'norms' popularized in such widely read manuals as Arnold Gessell's endlessly revised and reissued *Manual of Child Development.*

That degree of specialization is no more. 'Child development' and its course has, in the last quarter-century, become an issue of general, even political concern, a passionate issue. To a degree never before seen, the cultivation of childhood has become central not only in debates about schooling and parenting, but also in discussions of broader policy: anti-poverty programs in our inner cities, budgetary policy nationally, even international policy where aid for the care and education of the young has become a central issue. Indeed, there are few issues that are as publicly scrutinized as, for example, *when* and *how* 'education' should start, even before a child ever gets to school. *What* should schools take as their objective, and *in what ways* might the larger social environment harm or help a child's readiness for later school learning?

Indeed, the introduction of Head Start in America in the 1960s (and comparable programs elsewhere) provoked a blizzard of debate on how and whether poverty disables a young pre-school child for later schooling. In a like vein, intense debates rage about the possibly irreversible effects of childhood 'deprivations' in the Third World. As never before, the adage "The child is father to the man" has emerged into open debate about policy.

All of these concerns make it all the more urgent that there be available not only to the expert, but also to the engaged citizen, some informed and intelligent guidance regarding human growth and development. It is our hope that *The Cambridge Encyclopedia* will fill that function. It is written by distinguished specialists in child development, but written with a view to being accessible to the intelligent reader concerned with the growth and welfare of the young.

One special point needs emphasis. Over the last quarter-century, there has been a remarkable burgeoning of research on early childhood. Inevitably, this research on early growth and the factors affecting it has come to concentrate more than before on neural as well as psychological processes that might be affected by early encounters with the world. Such research is well represented in this volume, and to good effect. For many current debates swirl futilely around the issue, for example, of whether certain early experiences produce 'irreversible' effects on the 'brain.' The reader will find a well-balanced approach to this feverish issue in this *Encyclopedia.*

The contributors to this volume, as well as its editors, are to be congratulated, finally, for maintaining a happy balance between the general and the particular. For, indeed, the details of development cannot be understood without appreciating the broader contexts in which they occur, nor can general trends be grasped without reference to the specific mechanisms that make them possible. The relation between early experience and the state of the brain is, indeed, a two-way street.

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INTRODUCTION

What is development and interdisciplinarity?

The aim of this section is to provide a setting for the rest of the book. This is achieved in two ways. Firstly, by historical overviews and evaluations of the debates about the nature of development, which culminate in contemporary interpretations of ontogenetic development. Secondly, by providing the rudiments of an interdisciplinary framework for studying child development and pinpointing the challenges arising from such a framework.

The concept of development: historical perspectives

CELIA MOORE

Introduction

The concept of development is rooted in the biology of the individual life cycle. It encompasses the subsidiary ideas of growth, differentiation from homogeneous to heterogeneous matter, and morphogenesis (the assumption of ordered form, an idea included as part of differentiation for most of history). Development also comprises the concept of reproduction, in which the origin of an individual from parents is related both to the resemblance of offspring and parents (heredity) and to the observation that species breed true to type. The history of developmental psychology has been fed by many streams, but developmental biology was the wellspring for its origin during the closing decades of the 19th century.

The ancient legacy

Aristotle (384-322 BP) presented the first detailed conception of development, along with a vivid natural history of embryology in diverse life forms, in *On the Generation of Animals*. He replaced the atomistic preformationism of earlier thinkers with an epigenetic conception in which the embryo differentiates progressively from a homogeneous origin, with parts such as heart, lungs, and limbs and their spatial arrangement only gradually taking shape. Both epigenesis (Fig. 1) and preformationism were destined to endure as the two grand synthesizing images that have competed in the minds of developmentalists throughout history.

The three central features of Aristotelian epigenesis derived from his material, efficient, and final causes. These included a distinction between the material cause from which the embryo is produced and nutrients to support the growth and maintenance of the embryo; an explanation of differentiation as the action of a non-material generative principle in the semen of males (the efficient cause) on the formative material from females (menstrual blood of humans, the white of a bird egg, etc.); and an explanation of the particular form taken by an organism and its parts in terms of final causes (purpose or plan). The central epigenetic idea was that there was a male principle that acts on generative material secreted by females, setting developmental processes in motion that progressively actualize potentials inherent in the material. Although his theory of generation mixed metaphysics with science, including as it did both vitalistic and teleological elements, Aristotle nevertheless defined the major developmental questions and led the way for empirically minded successors to continue the inquiry some two millennia later.

Concepts from 17th- and 18th-century embryology

The modern history of developmental science can be started with the 17th-century scientists who resumed the work of the ancients (Needham, 1959). Of these, William Harvey (1578–1657), most celebrated for his discovery of the circulation of blood, stands as an important transitional figure in the history of developmental thought. His work on generation, as it was then still called, took Aristotle's epigenesis as a starting point. Harvey believed that all life begins from an egg. One of the major developmental issues of Harvey's time centered on the nature of embryonic nutrition and the distinction between nutrients and formative matter in the egg. Harvey demonstrated that the distinction was meaningless: nutrients were assimilated by the embryo as it took form. He reconceived epigenesis as the entwined, synchronous processes of growth (increase in mass) and differentiation. This contrasts with Aristotle's equation of epigenesis simply with differentiation of a finite mass of formative material. It also contrasts with the preformationism of Harvey's contemporaries.

Preformation was developed in part out of dissatisfaction with the vitalistic leanings of epigenesis and in part out of the enthusiasm that attends a major technological advance. The newly invented microscope was revealing a previously invisible world and opening the possibility of even smaller worlds awaiting technical improvements in lenses. It prepared a way around the problem of differentiation by making it plausible to deny its necessity. Turning the microscope on eggs revealed a high degree of organization in the tiniest of embryos, giving rise to the ovists; turning it on semen revealed a swarm of active animalcules (spermatozoa), giving rise to the spermists. If such organization was present so early, why not from the very beginning? Although most preformationists were ovists who thought that life was preformed in eggs, the enduring icon of preformation is Nicholas Hartsoecker's 18th-century drawing of what such a human animalcule would look like if only it could be seen clearly. This was not, however, the clearer vision that was to come with improved microscopy. Anatomists such as Caspar Friedrich Wolff (1733–94) saw such things as tubular structures growing out of the folding of two-dimensional sheets, and not from the swelling of miniature tubular structures. The 18th-century debates ended with embryos that were epigenetic in Harvey's sense: simultaneously growing and taking shape. These debates, however, left the problem of heredity unsolved.

As use of the term 'generation' suggests, the concept of development through the 18th century included reproduction along with growth and differentiation. The most salient feature of reproduction in this context is what we would now call heredity. Offspring are of the same type as parents: chickens invariably come from chicken eggs, and ducks from duck eggs. These and similar regularities in nature were taken to reflect the over-arching plan behind the whole of existence. The preformationist concept of emboîtement (encasement), which was promoted by Wolff's adversary Albrecht von Haller (1708–1777), was an attempt to eliminate the problem of heredity. In this conception, progressively smaller embryos were stacked inside one another such that all generations were present from one original creation. This was a plausible idea at the time because of the generally shared presumption of a short history of life on earth.

Qualitative change was established as a central fact of development by the end of the 18th century. However, it is possible to read too much into that victory for epigenesis. Firstly, developmental thought during this formative period was focused on the embryo, which is an early stage of life. By pushing back the time of differentiation far enough, the difference between a preformed and an emergent embryo becomes negligible (Needham, 1959). This is particularly true for developmental psychology, which is concerned with post-embryonic life. Secondly, the conceptions of heredity that came to dominate in the 19th and 20th centuries

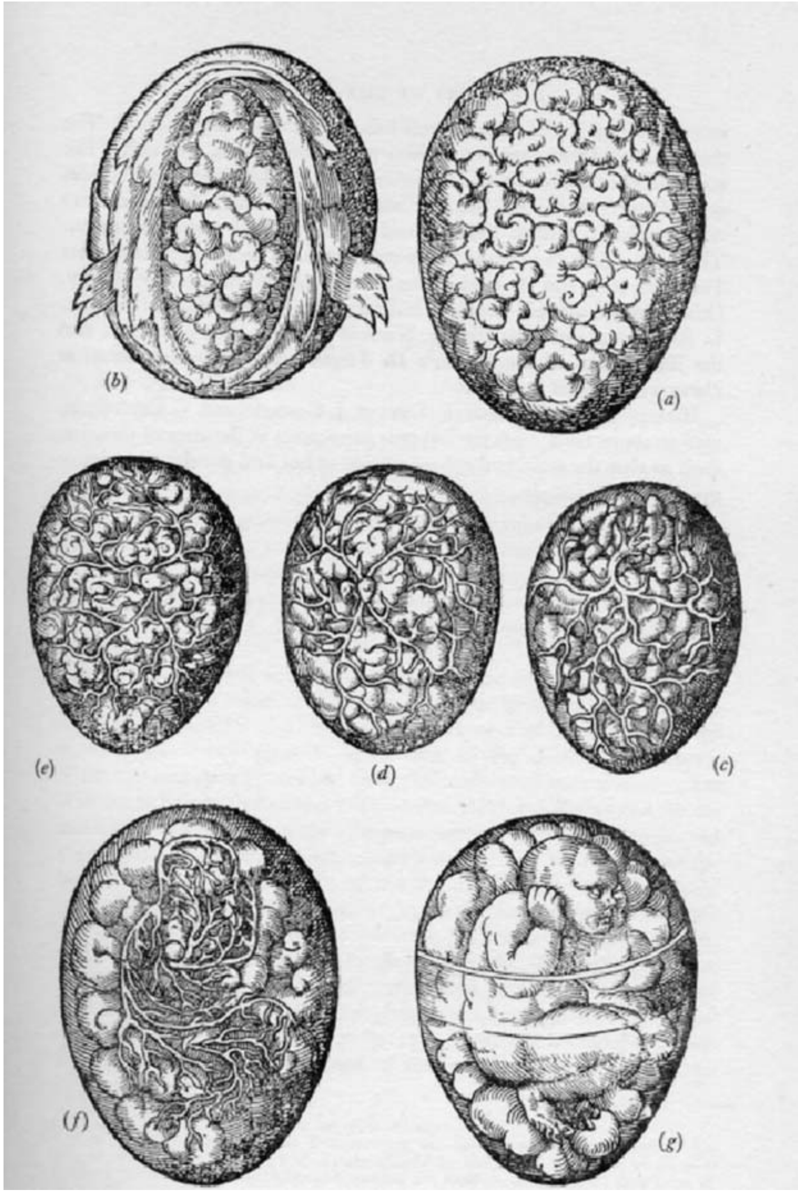

Figure 1. A 16th-century conceptual illustration of what Aristotle's epigenesis might look like if observed. Drawing from Jacob Rueff, as reproduced in J. Needham, 1959. *A History of Embryology*. New York: Abelard-Schuman.

have more in common with the preformationist concept of preexistence than with the epigenetic concept of emergence. Of all the concepts comprised by the ancient idea of generation, heredity was the one that has dominated biology during most of the history of child development.

Development beyond the embryo

Embryology thrived during the early 19th century as a comparative, descriptive science of anatomical development. Its dominance in biology fitted well with the general intellectual climate of the time. The concept of

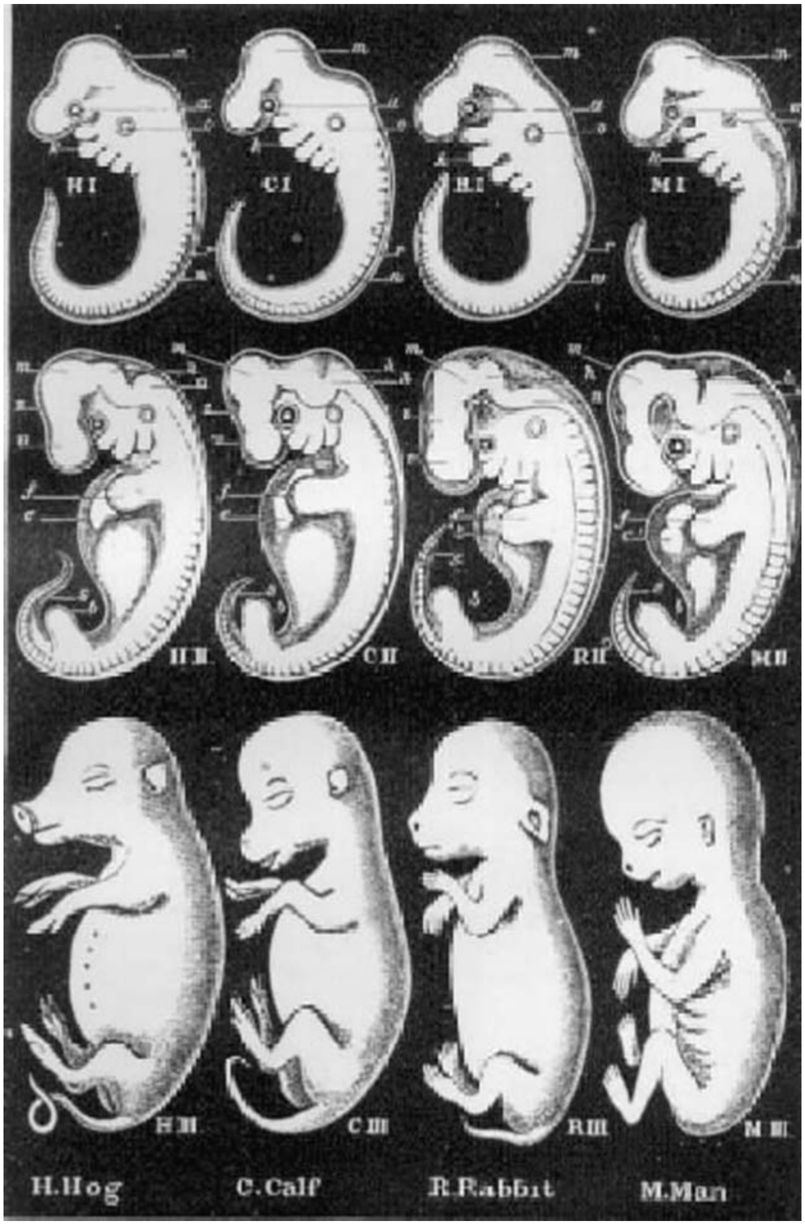

Figure 2. A 19th-century illustration of the relation between ontogeny and phylogeny. From E. Haeckel, 1897. *The Evolution of Man*. New York: D. Appleton and Co. Haeckel's illustrations are presented as empirical, but exaggerate the similarity across species. From S. J. Gould, 1977. *Ontogeny and Phylogeny*. Cambridge, MA: Harvard University Press.

progress was in the air, shaping new ideas in cultural anthropology, sociology, and philosophy as well as those in the natural sciences. This led in natural science to a reconception of the grand plan of nature, that great chain of being, from a static structure to a work in progress and, eventually, to the theory of evolution as the foundation of the life sciences.

Karl Ernst von Baer (1792–1876) synthesized the growing field of anatomical embryology in a set of generalizations that extended the concept of epigenesis beyond the embryo, through the adult stage of a life cycle. This connected embryology with comparative anatomy and taxonomy, allowing von Baer also to extend the concept of development to include diversity of life forms. From this broad array of data, von Baer observed that shared traits in a group of embryos appear earlier than special traits; that more general structural relations in traits appear before the more specific; that embryos of different forms in the same group gradually separate from one another without passing through states of other differentiated forms; and that embryos of higher forms never resemble adults of lower forms, only their embryos. These observations and ideas left a deep mark on Charles Darwin's mid-century theory of evolution. They were seen to support the idea of evolution as descent with modification from ancestral forms.

In the first textbook of the field, Herbert Spencer (1820–1903) presented psychology as a division of biology, new in its subject matter of the conscious mind, but otherwise using methods and concepts general to the life sciences. Spencer had an abstract concept of development as progress, which he applied across many disciplines. He saw progress as related to the epigenetic tradition of Aristotle, Harvey, Wolff, and von Baer in embryology. This viewpoint was adopted by the influential James Mark Baldwin (1861–1934), who brought the organic tradition of the embryologists into 20th-century developmental psychology. Concepts of assimilation, growth, and differentiation that were first articulated for nutrients and anatomy were re-worked to accommodate experience and the mind. These ideas, in concert with the powerful influence of Darwinian evolutionary theory and the subsequent rise of functionalism, shaped the emergence of developmental psychology and its history well into the 20th century (Kessen, 1983).

It would have been a logical next step for a developmental theory to grow out of von Baer's embryology to explain how evolution works, but efforts in this direction did not flourish (Gould, 1977). Instead, first evolution and then genetics took on the task of explaining development while embryology declined to a marginal field. Ernst Haeckel (1834–1919) popularized the parallel between embryology and evolution (Fig. 2), giving these concepts new names and proposing their relationship in the Biogenetic Law: ontogeny recapitulates phylogeny. Haeckel's recapitulation concept reverted to the old idea of the linear progression of life from monad to man, ignoring von Baer's evidence of the ramified nature of biological diversity and the emergence of diversity in embryonic stages. However retrograde, the idea was very influential for a time. Development came to be seen as pushed by evolution, with adult forms of 'lower' animals as stages in the ontogenetic progression of 'higher' species. This stage conception retained epigenesis of form during ontogeny,

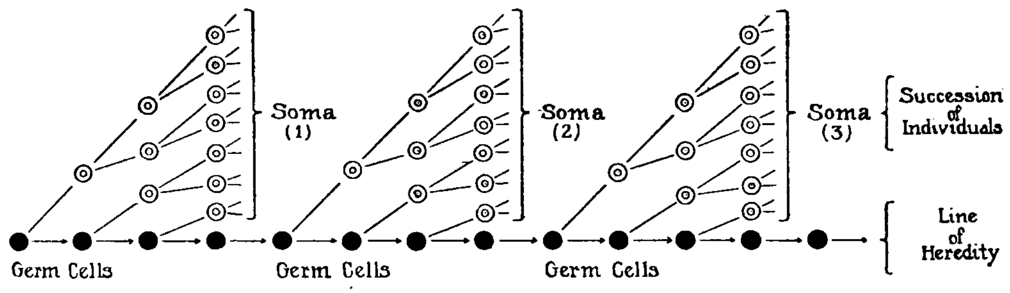

Figure 3. In Weismann's theory, heredity is sequestered in a separate line of germ cells (filled dots) that cross generations. Somatic cells (open dots) originate from inherited germ cells but cannot cross generations. From E. B. Wilson, 1925. *The Cell in Development and Heredity*, 3rd. edn. New York: MacMillan, p. 13.

but placed the cause of change in a preexistent phylogeny.

The schools of developmental psychology that arose early in the 20th century derived core conceptions from 19th-century embryology and evolutionary biology, but each took something different from these sources. The stage conceptions of development elaborated by G. Stanley Hall and Sigmund Freud built on Haeckel's flawed concept. These theorists proposed that human development recapitulated the history of human evolution and that healthy development required support of this predetermined sequence through childhood. Heinz Werner's orthogenetic principle of development as progress from a global, undifferentiated state to an articulated, hierarchically integrated state was an abstract statement meant to distinguish development from other temporal change. It was Spencerian in the breadth of its application and Aristotelian in its view of epigenesis.

William Preyer (1841–1897) was a physiological embryologist in the epigenetic tradition of von Baer who brought both concepts and methods from this field to the study of behavioral development. His 1882 book (*The Mind of the Child*), often used to date the birth of developmental psychology, demonstrated a way to transform empirical approaches from embryology for use in postnatal mental development. Preyer's concept of development, shaped by his physiological work, included an active organism contributing to its own development and the idea that achievements from early stages provide substrates for later stages. This concept had a major influence on James Mark Baldwin, who integrated Preyer's ideas with von Baer's principles and Darwin's natural selection into a developmental theory that served as a foundation for many schools of 20th-century developmental psychology, including those associated with Lev Vygotsky, Jean Piaget, Heinz Werner, Leonard Carmichael, and T. C. Schneirla.

Baldwin's concept of development focused on the relationship between the active organism and its social milieu as the source of developmental transformation. Applied to the mind of the child, this led him to notions of circular reaction and genetic epistemology that were later to be extensively elaborated by Piaget. Vygotsky and Werner applied the ideas broadly, including cultural and phyletic evolution in their conceptions, along with ontogenetic development that served as their primary focus. Comparative developmentalists, such as Carmichael and Schneirla who used experimental methods to study behavioral development in diverse animals, remained closest to their roots in physiological embryology. They mirrored early 20th-century experimental embryology with experimental approaches to behavioral development.

Heredity and development

The fact of organic evolution and Darwin's theory of natural selection to explain how it works were widely accepted by the end of the 19th century. This made a mechanism of heredity the most important missing link in biology. Evidence for Lamarckian inheritance had been found wanting, which was disappointing in the light of the adaptability of organisms through use and disuse. The search for a genetic mechanism took a decisive turn away from the organism with the introduction by August Weismann (1834–1914) of the germ plasm concept at the close of the century (Fig. 3). The cell had been established as the basic unit of life by 1838. Egg and sperm were subsequently identified as cells, and the first step in ontogeny was reconceived as their fusion. Weismann demonstrated that the cell divisions giving rise to egg and sperm occurred in a specialized population of cells sequestered from the rest of the body. This had the effect of separating the concepts of reproduction and heredity from that of development, and making the hereditary material preexistent to development.

If the 19th century was the age of progress, the 20th century was the age of information. The metaphors used to discuss development were drawn from the cultural well of cybernetics and computers (Keller, 1995). In keeping with this new orientation, the concept of plan was reintroduced to guide the progressive emergence of form during epigenesis. However, the 20th-century plan was written in a digital code inherited from a line of ancestors, not an idea carried on the informing breath of an agent in semen as it was for Aristotle.

The search for a hereditary mechanism led to the rediscovery of Gregor Mendel's non-blending hereditary particles, the location of these particles on chromosomes in the cell nucleus, the discovery of the DNA molecule, and the definition of a gene as a code that specifies phenotype. In 1957, Francis Crick (1916–2004) stated the central dogma of biology as the one-way flow of information from gene to product. The central dogma had taken its place alongside Darwinian evolution as one of the twin pillars of biology. The study of development thus became incidental to the major biological agenda. Indeed, molecular geneticists adopted single-celled bacteria as their organism of choice, in part because they do not undergo the irrelevant complications of metazoan development. The term 'developmental biology' came into wide use as a replacement for embryology by the middle of the 20th century to describe a field that was now largely focused on cytoplasm in cells rather than on either organisms or the hereditary molecules found in cell nuclei.

Conclusions

The success of genetics fostered a new generation of predeterminists who conceived development as differentiation under the control of plans inherited in genes. They took a biologically differentiated organism as their starting point, using mainstream genetic ideas to explain biological development. Predeterminists and environmentalists debated developmental theory in terms of the nature–nurture dichotomy. The predeterminists claimed a major informative role for nature, which they equated with inherited plans; the environmentalists claimed a major informative role for nurture acting on a *tabula rasa* organism. The ascendancy of the central dogma had the effect of putting constructivists in the Baldwinian tradition outside mainstream biological thought for most of the 20th century. Constructivists have an organic conception of epigenesis as emergent differentiation entwined with growth, achieved through organism–environment transactions. This conception is not compatible with either preexistent plans or the nature–nurture dichotomy.

There are signs that the long reign of the central dogma is coming to an end in biology. Developmental genetics has focused attention on the activation of genes and made cytoplasmic elements at least equal in importance to an increasingly passive DNA molecule. The embryo has re-emerged as a central figure in both development and evolution. With some irony, the age of information that gave us simplifying genetic codes has now given us the science of complexity, making it not only possible but fashionable to study complex, developing organisms with new tools. It remains to be seen what lasting changes in the concept of development will follow these current trends.

Acknowledgments

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See also:
Understanding ontogenetic development: debates about the nature of the epigenetic process; Constructivist theories; Dynamical systems approaches; Conceptions and misconceptions about embryonic development; Behavioral embryology; Behavior genetics; Developmental genetics; James Mark Baldwin; Jean Piaget; Wilhelm T. Preyer; Lev S. Vygotsky; Heinz Werner

Further reading

Oyama, S. (2000). *The Ontogeny of Information: Developmental Systems and Evolution*, 2nd edn. Durham, NC: Duke University Press.
Peters, R. S. (1965). *Brett's History of Psychology*. Cambridge, MA: MIT Press.
Pinto-Correia, C. (1997). *The Ovary of Eve: Egg and Sperm and Preformation*. Chicago: University of Chicago Press.

Understanding ontogenetic development: debates about the nature of the epigenetic process

GILBERT GOTTLIEB

Introduction

The debates concerning individual development go back 2,500 years to the time of Aristotle in the fourth century before the present era. During his investigations of the embryo and fetus in a wide variety of species, Aristotle opened up fertilized eggs at different stages of incubation and noted that new structures appeared during the course of incubation. He was the first to perceive the antithesis between *epigenesis* (novel structures emerge during the course of development) and *preformation* (development is the simple unfolding or growth of preexisting structures). All subsequent debates about the nature of the developmental process are founded to some extent on this dichotomy. I say 'to some extent' because when one surveys the history of embryological thought, as, for example, embodied in Joseph Needham's (1959) marvelous work, *A History of Embryology*, there is a second debate of utmost importance that is really at the heart of all debates about the nature of the developmental process: what causes development? What causes development to happen?

By the late 1700s and early 1800s, the debate over preformation and epigenesis was resolved in favor of epigenesis. Before proceeding to a review of the debates about the causes of epigenetic development, it is informative to go a bit deeper into the notions of preformation and epigenesis.

Preformation: ovists and animalculists

There were two main versions of preformation. Since, according to this view, the organism was preformed in miniature from the outset, it was believed by some to lie dormant in the ovary of the female until development was started by fertilization. This view was held by the ovists. To other thinkers, the preformed organism resided in the semen of the male and development was unleashed through sexual union with the female. These were the animalculists.

Many of the preformationists, whether ovists or animalculists, tended to be of a religious persuasion. In that case they saw the whole of humankind having been originally stored in the ovaries of Eve if they were ovists or in the semen of Adam if they were animalculists. Based upon what was known about the population of the world in the 1700s, at the time of the height of the argument between the ovists and animalculists, Albrecht von Haller (1708–1777), the learned physiologist at the University of Göttingen, calculated that God, in the sixth day of his work, created and encased in the ovary of Eve 200,000 million fully formed human miniatures. Von Haller was a very committed ovist.

The sad fact about this controversy was that the very best evidence to date for epigenesis was at hand when von Haller made his pronouncement for preformation: "There is no coming into being! [*Nulla est epigenesis.*] No part of the animal body was made previous to another, and all were created simultaneously . . . All the parts were already present in a complete state, but hidden for a while from the human eye." Given von Haller's enormous scientific stature in the 1700s, we can only assume that he had an overriding mental set about the question of ontogenesis (development of the individual), and that set caused him to misinterpret evidence in a selective way. For example, the strongest evidence for the theory of encasement, as the theory of preformation was sometimes called, derived from Charles Bonnet's observations, in 1745, of virgin plant lice, who, without the benefit of a male consort, reproduce parthenogenetically (i.e., by means of self-fertilization). Thus, one can imagine the ovist Bonnet's excitement upon observing a virgin female plant louse give birth to ninety-five females in a 21-day period and, even more strikingly, observing these offspring themselves reproduce without male contact. Here was Eve incarnate among the plant lice!

Epigenesis: emergent nature of individual development

The empirical solution of the preformation–epigenesis controversy necessitated direct observation of the course of individual development, and not the outcome of parthenogenetic reproduction, as striking as that fact itself might be. Thus it was that one Caspar Friedrich Wolff (1733–1794), having examined the developmental anatomy and physiology of chick embryos at various times after incubation, provided the necessary direct evidence for the epigenetic or emergent aspect of individual development. According to Wolff's observations, the different organic systems of the embryo are formed and completed successively: first, the nervous system; then the skin covering of the embryo; third, the vascular system; and finally, the intestinal canal. These observations not only eventually toppled the doctrine of preformation but also provided the basis for the foundation of the science of embryology, which took off in a very important way in the next 150 years.

Fortunately, the microscopes of the late 1800s were a significant improvement over those of the late 1600s, whose low power allowed considerable reign for the imagination. Figure 1 shows the drawing of a human sperm cell by Nicholas Hartsoeker in 1694. Needless to say, Hartsoeker was a convinced animalculist prior to looking into the microscope.

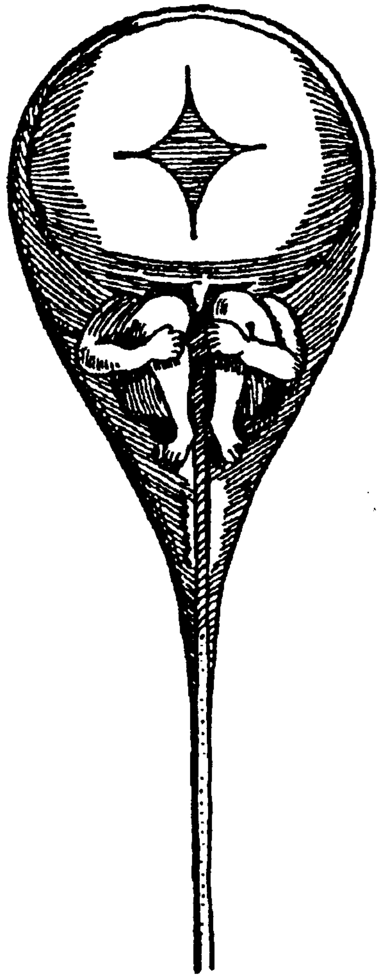


Figure 1. Drawing of the contents of a human sperm cell by the preformationist Nicholas Hartsoeker in 1694. From J. Needham (1959). *A History of Embryology*. New York: Abelard-Schuman.

Nature versus nurture: the separation of heredity and environment as independent causal agents

The triumph of epigenesis over preformation eventually ushered in the era of experimental embryology, defined as the causal-analytic study of early structural development, which unhappily coincided with the explicit separation of the effects of heredity and environment in Francis Galton's formulation of the nature-nurture dichotomy in the late 1800s.

Francis Galton's influential legacy

Francis Galton (1822–1911) was a second cousin of Charles Darwin and a great admirer of Darwin's concept of natural selection as a major force in evolution. Galton studied humans and advocated selective breeding or non-breeding among certain groups as a way of, respectively, hastening intellectual and moral evolution and saving humankind from degeneracy. Galton coined the term *eugenics*, and its practice in human populations eventually resulted from his theories, among others. He advocated positive eugenics, which encouraged people of presumed higher moral and intellectual standing to have larger families. (Negative eugenics, which he did not explicitly advocate, resulted in sterilization laws in some countries, including the United States, so that people judged unfit would have fewer children.)

Galton failed completely to realize that valued human traits are a result of various complicated kinds of interactions between the developing human organism and its social, nutritional, educational, and other rearing circumstances. If, as Galton found, men of distinction typically came from the upper or upper-middle social classes of 19th-century England, this condition was not only a result of selective breeding among 'higher' types of intelligent and moral people, but was also due in part to the rearing circumstances into which their progeny were born. This point of view is not always appreciated even today; that is, the inevitable correlation of social class with educational, nutritional, and other advantages (or disadvantages) in producing the mature organism. Negative eugenics was practiced in some European countries (e.g., Sweden, Switzerland) and in some states in the USA for much of the twentieth century.

Galton's dubious intellectual legacy was the sharp distinction between nature and nurture as separate, independent causes of development, although he said in very contemporary terms, "The interaction of nature and circumstance is very close, and it is impossible to separate them with precision" (Galton, 1907, p. 131). While it sounds as if Galton opts for the interpenetration of nature and nurture in the life of every person, in fact he means that the discrimination of the separate causal effects of nature and nurture is difficult only at the borders or frontiers of their interaction. Thus, he wrote:

> Nurture acts before birth, during every stage of embryonic and pre-embryonic existence, causing the potential faculties at the time of birth to be in some degree the effect of nurture. We need not, however, be hypercritical about distinction; we know that the bulk of the respective provinces of nature and nurture are totally different, although the frontier between them may be uncertain, and we are perfectly justified in attempting to appraise their relative importance.
>
> (Galton, 1907, p. 131)

Since we still retain, albeit unknowingly, many of Galton's beliefs about nature and nurture, it is useful to examine his assumptions more closely. He believed that nature, at birth, offered a potential for development, but that this potential (or reaction range, as it is sometimes called) was rather circumscribed and very persistent. In 1875, he wrote: "When nature and nurture compete for supremacy on equal terms . . . the former proves the stronger. It is needless to insist that neither is self-sufficient; the highest natural endowments may be starved by defective nurture, while no carefulness of nurture can overcome the evil tendencies of an intrinsically bad physique, weak brain, or brutal disposition." One of the implications of this view was, as Galton wrote in 1892: "The Negro now born in the United States has much the same natural faculties as his distant cousin who is born in Africa; the effect of his transplantation being ineffective in changing his nature." The conceptual error here is not merely that Galton is using his upper-middle class English or European values to view the potential accomplishments of another race, but it is rather that he has no factual knowledge of the width of the reaction range of African blacks – he assumes it not only to be inferior, but to be narrow and thus without the potential to change its phenotypic expression.

This kind of assumption is open to factual inquiry and measurement. It requires just the kind of natural experiment that Galton would have marveled at, and perhaps even enjoyed, given its simple elegance, namely, the careful monitoring and measurement of presumptively in-built traits *within generations* in races that have migrated to such different habitats, sub-cultures, or cultures that their epigenetic potential would be allowed to express itself in previously untapped ways. Thus, we can draw a line of increasing adult stature as Oriental groups migrate to the United States and substantially change their diet. More importantly we can measure the increase in IQ of blacks (within as well as between generations) as they move from the rural southern United States to the urban northeast, and its further increase the longer they remain in the urban northeast (Otto Klineberg's book, *Negro Intelligence and Selective Migration*, published in 1935). The same is true for lower-class whites coming from the rural south to the urban northeast. Galton's concept of 'like begets like,' whether applied to upper-class Englishmen or poor blacks and whites, requires that their rearing circumstances and opportunities remain the same.

Galton's dubious intellectual legacy is notoriously long-lived, no matter how many times the nature-nurture controversy has been claimed to be dead and buried. An analysis of psychology textbooks reveals the heartiness of Galton's dichotomous ideas up to the late 20th century (Johnston, 1987).

Dichotomous thinking about individual development in early experimental embryology

In the late 1800s and early 1900s, the main procedure of experimental embryology, as a means of implementing a causal analysis of individual development, was to perturb normal development by deleting cells or moving cells to different places in the embryo. Almost without exception, when normal cellular arrangements were changed developmental outcomes were altered, giving very strong empirical support to the notion that cell–cell or cell–environment *interactions* are at the heart of individual development: interactions of one sort or another make development happen (i.e., make development take one path rather than another path).

This major conceptual advance was only incompletely realized because of the erroneous interpretation of one of the earliest experiments in the new experimental embryology. In 1888, Wilhelm Roux (1850–1924), one of the founders of experimental embryology, used a hot needle to kill one of the two existing cells after the first cleavage stage in a frog's egg and observed the development of the surviving cell. The prevalent theory of heredity at the time held that one-half of the heredity determinants would be in each cell after the first cleavage, and, indeed, as called for by the theory, a roughly half embryo resulted from Roux's experiment.

However, when Hans Driesch (1867–1941), another of the founders of experimental embryology, performed a variation of Roux's experiment by separating the two cells after cleavage by shaking them completely loose from one another, he observed an *entire* embryo develop from the single cells. Eventually, Roux accepted that the second, dying cell in his experiment interfered with the development of the healthy cell, thus giving rise to the half-embryo under his conditions.

Before he accepted that, however, Roux had begun theorizing on the basis of his half-embryo results and came up with a causal dichotomy that continues to haunt embryology to the present day: *self-differentiation* versus *dependent differentiation*. These two terms were coined by Roux as a consequence of his half-embryo experiment, which he believed erroneously to be an outcome of self-differentiation, implying an independent or non-interactive outcome, in contrast to dependent differentiation where the interactive component between cells or groups of cells was necessary to, and brought about, the specific outcome. The concept of self-differentiation is akin to the concept of the *innate* when the term is applied to an outcome of development, as in the innate (hereditary) – acquired (learned) dichotomy that is prevalent in much of psychological theorizing.

Roux, himself, gave up the self- and dependent-differentiation dichotomy as he came to accept Driesch's procedure as being a more appropriate way to study the two post-cleavage cells. Unfortunately, Roux's concepts lived on in experimental embryology in disguised form as *mosaic development* versus *regulative development*. In the latter, the embryo or its cells are seen as developing in relation to the *milieu* (environment), whereas the former is understood as a rigid and narrow outcome fostered by self-differentiation or self-determination, as if development were non-interactive. Here is the way the American embryologist W. K. Brooks (1902, pp. 490–491) expressed concern about the notion of self-differentiation:

> A thoughtful and distinguished naturalist tells us that while the differentiation of the cells which arise from the egg is sometimes inherent in the egg, and sometimes induced by the conditions of development, it is more commonly mixed; but may it not be the mind of the embryologist, and not the material world, that is mixed? Science does not deal in compromises, but in discoveries. When we say the development of the egg is inherent, must we not also say what are the relations with reference to which it is inherent?

This insight that developmental causality is relational (interactive or coactive) has eluded us to the present time, as evidenced in the various causal dichotomies extant in the developmental-psychological literature of today: nature-nurture, innate-acquired, maturation-experience, development-evolution, and so forth. We need to move beyond these dichotomies to understand individual development correctly.

Predetermined and probabilistic epigenesis

At the root of the problem of understanding individual development is the failure to truly integrate biology into developmental psychology in a way that does empirical justice to both fields. The evolutionary psychologists, for example, are still operating in terms of Galton's legacy, as witnessed by the following quotations. They start off seemingly on the right foot, as we saw in Galton's introductory remarks about nature and nurture: "The cognitive architecture, like all aspects of the phenotype from molars to memory circuits, is the joint product of genes and environment . . . EPs [evolutionary psychologists] do not assume that genes play a more important role in development than the environment does, or that 'innate factors' are more important than 'learning.' Instead, EPs reject these dichotomies as ill-conceived" (Cosmides & Tooby, 1997, p. 17). However, several pages later, when they get down to specifics, the nature-nurture dichotomy nonetheless emerges: "To learn, there must be some mechanism that causes this to occur. Since learning cannot occur in the *absence* of a mechanism that causes it, the mechanism that causes it must *itself* be unlearned – must be innate" (Cosmides & Tooby, 1997, p. 19). Since one must certainly credit these authors (as well as others who write in the same vein) with the knowledge that development is not preformative but epigenetic, in 1970, extending Needham's (1959, p. 213, note 1) earlier usage, I employed the term 'predetermined epigenesis' to capture the developmental conception of the innate that is embodied in the above quotation. (Cosmides and Tooby do not stand alone; other evolutionary theorists such as the ethologist Konrad Lorenz (1903–1986) posited an 'innate schoolmarm' to explain the development of species- specific learning abilities.) The predetermined epigenesis of development takes this form:

Predetermined Epigenesis
Unidirectional Structure – Function Development
Genetic activity (DNA $\rightarrow$ RNA $\rightarrow$ Protein) $\rightarrow$ structural maturation $\rightarrow$ function, activity, or experience (e.g. species-specific learning abilities)

In contrast to predetermined epigenesis, I put forward the concept of probabilistic epigenesis:

Probabilistic Epigenesis
Bidirectional Structure – Function Development
Genetic activity (DNA $\leftrightarrow$ RNA $\leftrightarrow$ Protein) $\leftrightarrow$ structural maturation $\leftrightarrow$ function, activity, or experience

In this view, prior experience, function, or activity would be necessary for the development of species-specific learning abilities. Epigenesis is probabilistic because there is some inevitable slippage in the very large number of reciprocal coactions that participate in the developmental process, thereby rendering outcomes probable rather than certain.

By way of defining the terms and their relationships, as it applies to the nervous system, *structural maturation* refers to neurophysiological and neuroanatomical development, principally the structure and function of nerve cells and their synaptic interconnections. The unidirectional structure-function view assumes that genetic activity gives rise to structural maturation that then leads to function in a non-reciprocal fashion, whereas the bidirectional view holds that there are reciprocal influences among genetic activity, structural maturation, and function. In the unidirectional view, the activity of genes and the maturational process are pictured as relatively encapsulated or insulated, so that they are uninfluenced by feedback from the maturation process or function, whereas the bidirectional view assumes that genetic activity and maturation are affected by function, activity, or experience. The bidirectional or probabilistic view applied to the usual unidirectional formula calls for arrows going back to genetic activity to indicate feedback serving as signals for the turning on and turning off of genetic activity.

The usual view in the central dogma of molecular biology calls for genetic activity to be regulated by the genetic system itself in a strictly feed-forward manner, as in the unidirectional formula of DNA → RNA → Protein above. Thus, the central dogma is a version of predetermined epigenesis. Note that genetic activity is involved in both predetermined and probabilistic epigenesis. Thus, what distinguishes the two conceptions is not genes versus environment, as in the age-old nature-nurture dichotomy, but rather the unidirectional (strictly feed-forward or -upward influences) versus the bidirectional nature of the coactions across all levels of analysis. There is now evidence for all of the coactions depicted in the probabilistic conception, including those at the genetic level of analysis (Gottlieb, 1998). Given that genes, however remotely, are necessarily involved in all outcomes of development, it is dismaying to see that that fact is not universally recognized, but rather is seen as some outdated relict of hereditarianism: ". . . although genetic effects of various kinds have been conclusively demonstrated, hereditarian research has not produced conclusive demonstrations of genetic inheritance of complex behaviors . . . The behaviorists' approach . . . should be – and generally is – to accept a genetic basis only if research designed to identify effects of social or other environmental variables does not reveal any effects" (Reese, 2001, p. 18). This is a particularly blatant example of either/or dichotomous causality: developmental outcomes are caused either by genes or by environment. Given the recent date of the quotation, this is evidence that the nature-nurture dichotomy is not dead and, if it is buried, it has been buried alive.

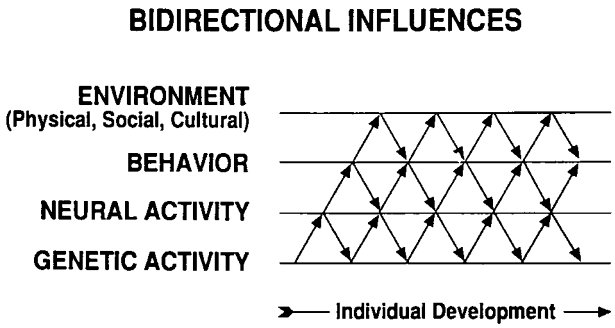


Figure 2. Probabilistic-epigenetic framework: depiction of the completely bidirectional and coactional nature of genetic, neural, behavioral, and environmental influences over the course of individual development. From G. Gottlieb, 1992. *Individual Development and Evolution*. Oxford: Oxford University Press, with permission.

From central dogma of molecular biology to probabilistic epigenesis

In addition to describing the various ramifications of the nature-nurture dichotomy, the other purpose of this entry is to place genes and genetic activity firmly within a developmental-physiological framework, one in which genes not only affect each other and mRNA (messenger RNA that mediates between DNA and protein), but are affected by activities at other levels of the system, up to and including the external environment. This developmental system of bidirectional, coactional influences is captured schematically in Figure 2. In contrast to the unidirectional and encapsulated genetic predeterminism of the central dogma, a probabilistic view of epigenesis holds that the sequence and outcomes of development are probabilistically determined by the critical operation of various endogenous and exogenous stimulative events (Gottlieb, 1997).

The probabilistic-epigenetic framework presented in Figure 2 not only is based on what we now know about mechanisms of individual development at all levels of analysis, but also derives from our understanding of evolution and natural selection. As everyone knows, natural selection serves as a filter and preserves reproductively successful phenotypes. These successful phenotypes are a product of individual development, and thus are a consequence of the adaptability of the organism to its developmental conditions. Therefore, natural selection has preserved (favored) organisms that are adaptably responsive to their developmental conditions, both behaviorally and physiologically. As noted above, genes assist in the making of protein; they

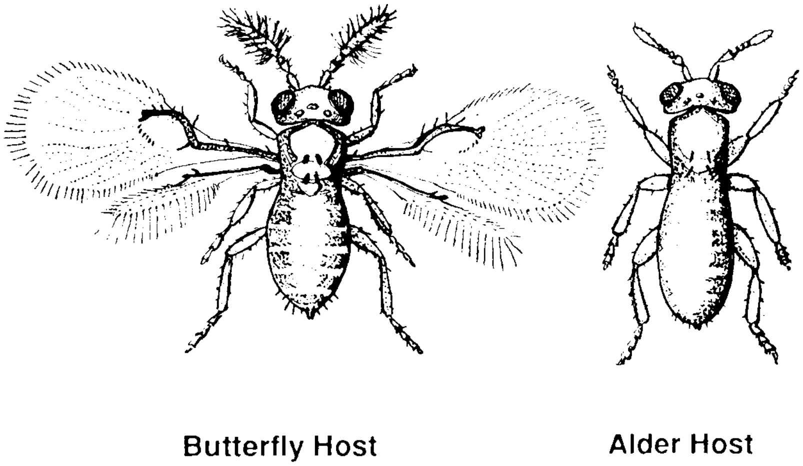


Figure 3. Two very different morphological outcomes of development in the minute parasitic wasp. The outcomes depend on the host (butterfly or alder fly) in which the eggs were laid. The insects are of the same species of parasitic wasp (*Trichogramma semblidis*). Adapted on the basis of V. B. Wigglesworth, 1964. *The Life of Insects*. Cleveland, OH: World Publishing Co.

do not predetermine or make finished traits. Thus, organisms with the same genes can develop very different phenotypes under different ontogenetic conditions, as witness the two extreme variants of a single parasitic wasp species shown in Figure 3 and identical twins reared apart in the human species (Fig. 4).

Since the probabilistic-epigenetic view presented in Figure 2 does not portray enough detail at the level of genetic activity, it is useful to flesh that out in comparison to the previously mentioned central dogma of molecular biology.

As shown in Figure 5, the original central dogma explicitly posited one-way traffic from DNA → RNA → Protein, and was silent about any other flows of 'information' (as Francis Crick wrote in 1958). Later, after the discovery of retroviruses (RNA → DNA information transfer), Crick (1970) did not claim to have predicted that phenomenon, but, rather, that the original formulation did not expressly forbid it. At the bottom of Figure 5, probabilistic epigenesis, being inherently bidirectional in the horizontal and vertical levels (Fig. 2), has information flowing not only from RNA → DNA but between Protein ↔ Protein and DNA ↔ DNA. The only relationship that is not yet supported is Protein → RNA, in the sense of reverse translation (protein altering the structure of RNA), but there are other influences of protein on RNA *activity* (not its structure) that would support such a directional flow. For example, a process known as *phosphorylation* can modify proteins such that they activate (or inactivate) other proteins (Protein → Protein) which, when activated, trigger rapid association of mRNA (Protein → RNA activity). When mRNAs are transcribed by DNA, they do not necessarily become immediately active but require a further signal to do so.

The consequences of phosphorylation could provide that signal (Protein → Protein → mRNA activity → Protein). A process like this appears to be involved in the expression of 'fragile X mental retardation protein' under normal conditions and proves disastrous to neural

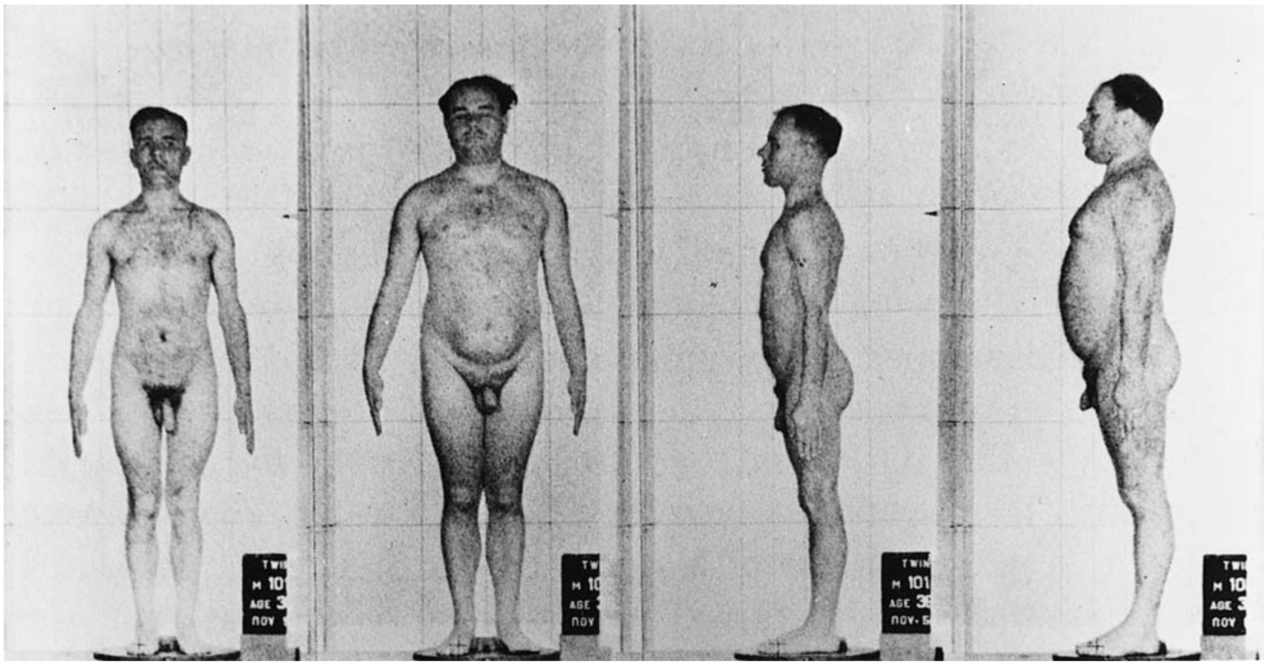
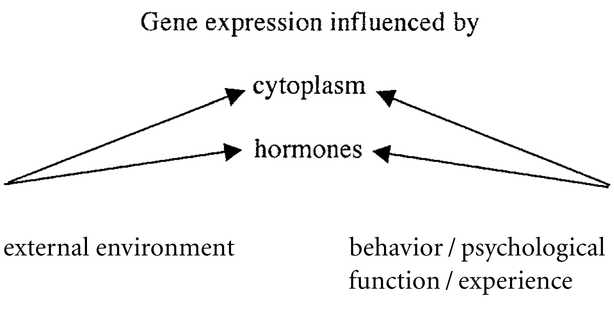


Figure 4. Remarkable illustration of the enormous phenotypic variation that can result when monozygotic (single egg) identical twins are reared apart in very different family environments from birth. From J. M. Tanner, 1978. *Foetus Into Man*. Cambridge, MA: Harvard University Press.

and psychological development when it does not occur. The label of 'fragile-X mental retardation protein' makes it sound as if there is a gene (or genes) that produces a protein that predisposes to mental retardation whereas, in actual fact, it is this protein that is *missing* (absent) in the brain of fragile X mental retardates, and thus represents a failure of gene (or mRNA) expression rather than a positive genetic contribution to mental retardation. The same is likely true for other 'genetic' disorders, whether mental or physical: these most often represent biochemical *deficiencies* of one sort or another due to the lack of expression of the requisite genes and mRNAs to produce the appropriate proteins necessary for normal development. Thus, the search for 'candidate genes' in psychiatric or other disorders is most often a search for genes that are not being expressed, not for genes that are being expressed and causing the disorder.

So-called cystic fibrosis genes and manic-depression genes, among others, are in this category. The instances that I know of in which the presence of genes causes a problem are Edward's syndrome and trisomy 21 (Down's syndrome), wherein the presence of an extra, otherwise normal, chromosome 18 and 21, respectively, causes problems because the genetic system is adapted for two, not three, chromosomes at each location. In some cases, it is of course possible that the expression of mutated genes can be involved in a disorder, but, in my opinion, it is most often the lack of expression of normal genes that is the culprit. Most mutations impair fitness. In one of the very rare cases of benefit, in sickle-cell anemia (a defect in red blood cells), the bearer is made resistant to the malaria parasite. Amplifying the left side of the bottom of Figure 5, it is known that gene expression is affected by events in the cytoplasm of the cell, which is the immediate environment of the nucleus and mitochondria of the cell wherein DNA resides, and by hormones that enter the cell and its nucleus. This feed-downward effect can be visualized thusly:



According to this view, different proteins are formed depending on the particular factors influencing gene expression. Concerning the effect of psychological functioning on gene expression, we have the evidence of decreased interleukin 2 receptor mRNA, an immune system response, in medical students taking academic

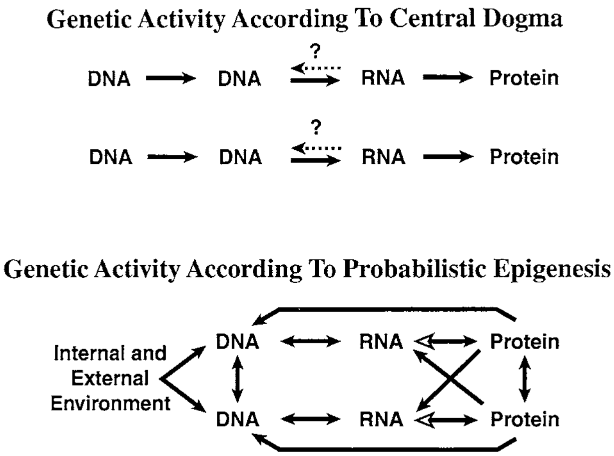


Figure 5. Different views of influences on genetic activity in the central dogma and probabilistic epigenesis. The filled arrows indicate documented sources of influence, while the open arrow from Protein back to RNA remains a theoretical possibility in probabilistic epigenesis and is prohibited in the central dogma (as are Protein ↔ Protein influences). Protein → Protein influences occur (1) when prions transfer their abnormal conformation to other proteins and (2) when, during normal development, proteins activate or inactivate other proteins as in the phosphorylation example described in the text. The filled arrows from Protein to RNA represent the activation of mRNA by protein as a consequence of, for example, phosphorylation, and the reshuffling of the RNA transcript by a specialized group of proteins called spliceosomes ('alternative splicing'). DNA ↔ DNA influences are termed 'epistatic,' referring to the modification of gene expression depending on the genetic background in which they are located. In the central dogma, genetic activity is dictated solely by genes (DNA → DNA), whereas in probabilistic epigenesis internal and external environmental events activate genetic expression through proteins (Protein → DNA), hormones, and other influences. To keep the diagram manageable, the fact that behavior and the external environment exert their effects on DNA through internal mediators (proteins, hormones, etc.) is not shown; nor is it shown that the protein products of some genes regulate the expression of other genes. (Further discussion in text.) Reprinted in modified form from G. Gottlieb, 1998. Normally occurring environmental and behavioral influences on gene activity: from central dogma to probabilistic epigenesis. *Psychological Review*, 105, 792–802; with permission of the American Psychological Association.

examinations (Glaser *et al.*, 1990). More recently, in an elegant study that traverses all levels from psychological functioning to neural activity to neural structure to gene expression, Cirelli, Pompeiano, & Tononi (1996) showed that genetic activity in certain areas of the brain is higher during waking than in sleeping in rats. In this case, the stimulation of gene expression was influenced by the hormone norepinephrine flowing from locus coeruleus neurons that fire at very low levels during sleep, and at high levels during waking and when triggered by salient environmental events. Norepinephrine modifies neural activity and excitability, as well as the expression of certain genes. So, in this case, we have evidence for the interconnectedness of events relating the external environment and psychological functioning to genetic

Table 1. Developmental–behavioral evolutionary pathway.

I: Change in behavior	*II: Change in morphology*	*III: Change in gene frequencies*
First stage in evolutionary pathway: change in ontogenetic development results in novel behavioral shift, which encourages new environmental relationships.	Second stage in evolutionary change: new environmental relationships bring out latent (already existing epigenetic) possibilities for morphological–physiological change.	Third stage of evolutionary change resulting from long-term geographic or behavioral isolation (separate breeding populations). It is important to observe that evolution has already occurred phenotypically before stage III is reached.

expression by a specifiable hormone emanating from the activity of a specific neural structure whose functioning waxes and wanes in relation to the psychological state of the organism.

Role of ontogenetic development in evolution

Though not a debate about the nature of ontogenetic development or the epigenetic process as such, the role of development in evolution takes two very different forms. In its most conventional form, a change in genes (via mutation, sexual recombination, or genetic drift) brings about an enduring change in development that results in the appearance of different somatic, behavioral, and psychological features. That is the standard sequence of events in bringing about evolution in what is called the 'Modern synthesis' in biology. A change in genes results in a change in development in this scenario. Since evolution need not occur in only one mode, in another, more recent, scenario, the first stage in the evolutionary pathway is a change in ontogenetic development that results in a novel behavioral outcome. This novel behavior encourages new organism–environment relationships. In the second stage, the new environmental relationships bring out latent possibilities for somatic-physiological change without a change in existing genes. The new environmental relationships activate previously quiescent genes that are correlated with a novel epigenetic process, which results in new anatomical and/or physiological arrangements. This evolutionary scenario is based on two facts: firstly, the empirical fact that specific kinds of changes in species-typical development result in the appearance of behavioral novelties (e.g., increased exploratory behavior, changes in learning ability or preferences, enhanced coping with stress), and, secondly, there is a relatively great store of typically unexpressed genetic (and, therefore, epigenetic) potential that can be accessed by changing developmental conditions.

As long as the changed developmental circumstances prevail, in generation after generation, the novel behavior will persist without any necessary change in genes. Now, eventually, long-term geographic or behavioral isolation (separate breeding populations) may result in a change in gene frequencies in the new population, but the changes in behavior and morphology will already have occurred before the change in genes. No one is denying that genetic mutations, recombination, or drift can bring about evolution; the point is that those are not the only routes to evolutionary change. The three-stage developmental-behavioral evolutionary scenario is shown in Table 1.

That a developmental change in behavior can result in incipient speciation and in genetic change has recently been demonstrated in the apple maggot fly, *Rhagoletis pomonella*. The original native (USA) host for the female apple maggot fly's egg laying was the hawthorn, a spring-flowering tree or shrub. Domestic apples were introduced into the USA in the 17th century. Haws and apples occur in the same locale. The first reported infestation of apple trees by apple maggot flies was in the 1860s. There are now two variants of *R. pomonella*, one of which mates and lays its eggs on apples and the other of which mates and lays its eggs on haws (Table 2). The life cycles of the two variants are now desynchronized because apples mature earlier than haws. Incipient speciation has been maintained by a transgenerational behavior induced by early exposure learning: an olfactory acceptance of apples for courting, mating, and ovipositing based on the host in which the fly developed (Bush & Smith, 1998).

The cause of the original shift from hawthorns to apples as the host species for egg laying can only be speculated upon. Perhaps the hawthorn hosts became overburdened with infestations or, for other reasons, died out in a part of their range, bringing about a shift to apples in a small segment of the ancestral hawthorn population that did not have such well-developed olfactory sensitivity or an olfactory aversion to apples. This latter supposition is supported by behavioral tests, in which the apple variant accepts both apples and haws as hosts, whereas in the haw variant only a small percentage will accept apples and most show a strong preference for haws. As indicated by single host acceptance tests, the apple-reared flies show a greater percentage of egg-laying behavior on the apple host than do the hawthorn-reared flies. Thus, the familiarity-inducing rearing experience (exposure learning) makes the apple-reared flies more accepting of the apple host, although they still have a preference for the hawthorn host.

Given the ecological circumstances, the increased likelihood of acceptance of the apple host, even in the face of a preference for hawthorn, would perpetuate the transgenerational courting, mating, and laying of eggs in apple orchards. Apple maggot flies hatch out at the base of the tree in which their mother had laid their egg the previous summer. While becoming sexually mature, even though they have wandered tens or hundreds of yards, they are still in the vicinity of the apple orchard, if not still in the orchard. The scent of the apples attracts them, and the early rearing experience having rendered the apple scent acceptable, the cycle renews itself, because of the high probability that the early maturing apple maggot fly will encounter the odor of apples rather than hawthorns (see Table 2). In support of incipient speciation, the two variants are now genetically somewhat distinct and do not interbreed freely in nature, although they are morphologically the same and remain interfertile.

Table 2. An example of the developmental behavioral basis of evolution: incipient speciation in two variants of apple maggot fly (Rhagoletis pomonella).

Time	*Apple host*	*Hawthorn host*
Year 1	Eggs laid	Eggs laid
	↓ Fruit matures earlier than haw	↓ Fruit matures later than apple
Year 2	Hatch late summer	Hatch early fall
	↓ 5–12 days	↓ 5–12 days
Year 3	OFFSPRING court and mate on or near host, and female lays eggs on same host	OFFSPRING court and mate on or near host, and female lays eggs on same host
	↓	↓
	Cycle repeats	Cycle repeats

Adapted from G. L. Bush and J. J. Smith, 1998. The genetics and ecology of sympatric speciation: a case study. *Research in Population Ecology*, 40, 174–187; and R. Prokopy and G. L. Bush, 1993. Evolution in an orchard. *Natural History*, 102, 4–10.

In contrast to the transgenerational behavioral scenario being put forward here, conventional evolutionary biological thinking would hold that "most likely some mutations in genes coding for larval/pupal development and adult emergence" brought about the original divergence and maintain the difference in the two populations (Ronald Prokopy, personal communication, August 2000). Although we cannot know with certainty, present evidence (below) would suggest a genetic mutation was not necessary. This is not a behavior versus genes argument; the transgenerational behavioral initiation requires genetic compatibility, otherwise it would not work. The question is whether the original interaction (switch to the apple host) required a genetic mutation or not. The developmental timing change in the life histories of the two forms (Table 2) has resulted in correlated genetic changes in the two populations. That finding is consonant with the evolutionary model presented here (i.e., gene frequencies change some time after the behavioral switch).

From the present point of view, another significant feature of the findings is that, when immature hawthorn flies (pupae) are subjected to the pre-wintering environment of the apple flies (pupae), those that survive have a genetic make-up that is similar to the apple flies, signifying that environmental selection is acting on already-existing developmental-genetic variation. Most importantly, this result shows that there is still sufficient individual developmental-genetic variation in the hawthorn population, even at this late date, to support a transgenerational behavioral initiation of the switch from hawthorns to apples without the necessity of a genetic mutation.

To summarize, a developmental-behavioral change involving the apple maggot fly's choice of oviposition site puts it in a situation where it must be able to withstand certain pre-wintering low temperatures for given periods of time, and that differ between the apple and hawthorn forms (Table 2). This situation sets up the natural selection scenario that brings about changes in gene frequencies that are correlated with the pre-wintering temperature regimen. The change in egg-laying behavior leads the way to genetic change in the population, the genetic change thus being a consequence of the change in behavior.

Conclusions

After hundreds of years of debate, epigenesis triumphed over preformation. Thus, the nature of the process of individual development was finally understood to be of an emergent character, wherein new structures and functions appear during the maturation of the organism. The next debates concerned the sources of these new structures and functions, and these were partitioned into nature (heredity or genes) and nurture (environment or learning). Recently, as probabilistic epigenesis has more or less triumphed over predetermined epigenesis, the cause of development is now understood to be relational (coactive), in which genetics, neurology, behavior, and environmental influences are all seen as essential and as acting in concert to bring about developmental outcomes, whether physical or psychological. Finally, ontogenetic development, particularly changes in behavioral development, can have a role in initiating evolution prior to genetic changes in the population.

See also:
The concept of development: historical perspectives; Neuromaturational theories; Ethological theories; Cross-species comparisons; Twin and adoption studies; Conceptions and misconceptions about embryonic development; Normal and abnormal prenatal development; Sleep and wakefulness; Behavioral and learning disorders; Down's syndrome; Behavior genetics; Developmental genetics

Further reading

Johnston, T. D. and Edwards, L. (2002). Genes, interactions, and the development of behavior. *Psychological Review*, 109, 26–34.

Lerner, R. M. (2002). *Concepts and Theories of Human Development*, 3rd edn. Mahwah, NJ: Erlbaum.

Moore, D. S. (2001). *The Dependent Gene: The Fallacy of "Nature vs. Nurture."* New York: Henry Holt.

Wahlsten, D. and Gottlieb, G. (1997). The invalid separation of nature and nurture: lessons from animal experimentation. In R. J. Sternberg and E. Grigorenko (eds.), *Intelligence, Heredity, and Environment.* New York: Cambridge University Press, pp. 163–192.

Acknowledgments

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One section of this entry, "From central dogma of molecular biology to probabilistic epigenesis," was taken from Gottlieb (1998), with permission of the American Psychological Association.

What is ontogenetic development?

BRIAN HOPKINS

Introduction

Take any textbook on human development and then look for whether it provides a definition of 'development.' You will probably find that such a definition is absent or that it is provided in a couple of unenlightening sentences. In fact, most of these textbooks provide only a cursory definition of the term. The reason is not hard to find: development is one of those terms that we freely use in everyday language and yet when we try to pin it down with a precise definition it assumes an almost evanescent-like quality. As the satirist and evolutionist Samuel Butler (1835–1902) wrote in his Note-Books (1912), published posthumously, "Definitions are a kind of scratching and generally leave a sore place more sore than it was before." Scratching the surface of the term development exposes a host of seemingly related terms such as differentiation, evolution, growth, and phylogeny. Scratch a bit more and up pops 'ontogenetic development.'

In what follows, there is no pretense made to distinguish between all these terms, as space limitations do not permit that. The main focus is on comparing ontogenetic development with ontogeny. This brings with it the need to distinguish development from evolution and evolution from phylogeny. Finally, mention will be made of the long-standing pursuit to bring ontogenetic development and biological evolution into a scientifically credible relationship, which is currently leading to the emergence of a new discipline called evolutionary developmental biology.

Ontogeny and development

Ontogeny

Like phylogeny, this is a term created by Ernst Haeckel (1839–1919) from combining the Greek word for 'being' with that for 'birth' or 'born of.' Typically, ontogeny is defined as the life history of an individual from the zygote to the mature adult. Thus, it concerns the description of a historical path (i.e., the life cycle) of the 'common' individual of a particular species from fertilization to sexual maturity. In the past, it was restricted to the time between conception and birth, with the term ontogenesis being reserved for the history of a particular individual as in, for example, case studies. In either case, ontogeny or ontogenesis, such a history is conveniently broken down into periods, phases, or stages according to some metric of chronological age in order to indicate major age-specific changes and to describe the products of these temporal delineations.

Development

A more general and abstract concept than ontogeny, development has assumed a number of different meanings such that it was treated as being synonymous with the terms differentiation, growth, and evolution. As a concept, particularly prior to the 20th century, it was intended to indicate organized change toward some certain end condition or hypothetical ideal. Thus, like evolution, it was represented as a progressive process of 'improvement' applicable to all levels of organization.

The distinction between growth and differentiation, with both serving as synonyms for development, continued to separate the preformationists (development is growth) from the epigeneticists (development is differentiation) throughout the 19th century. However, during the same century, growth started to become something different from development, with the advent of cell theory as formulated by Theodor H. A. Schwann (1810–1887) following Matthias Schleiden (1804–1881). While much of Schwann's theory proved to be untenable, it led to growth being restricted to quantitative change (viz., increase in cell number by cell division and increase in cell size), and thus continuing compatibility with preformationism. Subsequently termed

Table 1. Examples of quantitative and qualitative regressions during ontogenetic development at different levels of organization.

Level	*Quantitative*	*Qualitative*
Behavioral	Decrease in associated movements	Fetal GMs, rooting, suckling, and some reflexes, imitation, swimming in human newborn
Morphological		Egg-tooth
Physiological		Yolk-sac, placenta
Neuromuscular	Poly- to monoinnervation	
Neural	Apoptosis, synapse elimination	Cajal-Retzius cells, axon and dendrite retraction, radial glia, neurons in the dorsal horn of spinal cord

Quantitative regressions involve a decrease in the number of elements (e.g. neurons; synapses). Qualitative regressions consist of replacements of existing structures and behaviors, or their disappearance, once their adaptive functions have been fulfilled. The quantitative change from poly- to monoinnervation occurs with a change from many to just one axon innervating a muscle fiber, which seems to occur both prenatally and during early postnatal life in humans. The egg-tooth is found in birds and crocodiles at the end of their beaks or snouts, respectively. Together with spontaneous and rather stereotyped head movements, it enables the hatchling to be born by breaking open the eggshell. Once it has served this function, it drops off. GMs: general movements of the whole body that are expressed in the healthy fetus and infant with variations in amplitude, speed, and force, and give the impression of being fluent and elegant in performance. Evident at about 10 weeks after conception, they remain in the behavioral repertoire until about 2–3 months after birth. After this age, they are replaced by more discrete movements that have a voluntary-like appearance (e.g., reaching). All told, convincing evidence for qualitative regressions in behavioral development is less easy to come by than at the other levels.

appositional or isocentric growth, it was contrasted with allometric growth (i.e., change in shape) in order to account for qualitative change, largely through the work of Julian Huxley (1887–1975). Treating growth as manifesting both types of change led to a blurring of distinctions between it and development that continues today.

With the rise of systems thinking during the 20th century, further attempts were made to discriminate development from other sorts of change such as growth and metabolism. One such attempt was made by Nagel (1957) who defined the concept of development as involving: ". . . two essential components. The notion of a system possessing a definite structure and a definite set of pre-capacities; and the notion of a sequential set of changes in the system yielding relatively permanent but novel increments not only to structure, but to its modes of operation as well" (p. 17). The core of Nagel's definition is that development consists of changing structure-function ('modes of operation') relationships at all levels of organization, an issue that goes to the heart of attempts to explain ontogenetic development at the individual level.

Ontogenetic development

When, in 1870, Herbert Spencer (1820–1903) suggested that the development of the individual was analogous to embryonic growth, the way was open to combine ontogeny with development to give ontogenetic development. Once done, it was not long before individual development was divided up into successive, time-demarcated periods, phases, or stages. The result was an even more difficult term to pin down unambiguously. What then do we mean by 'ontogenetic development'? One definition, capturing those given in some textbooks on developmental (psycho-) biology, is the following: "Species-characteristic changes in an individual organism from a relatively simple, but age-adequate, level of organization through a succession of stable states of increasing complexity and organization."

Defined as such, we are confronted with what is meant by 'relatively simple,' 'organization,' and 'stable,' as well as the previously mentioned term 'differentiation.' Moreover, the definition alludes to ontogenetic development being progressive, while at the same time ignoring the possibility of transitional periods between the stable states. Evidence from avian and non-human mammalian species, and to a lesser extent for humans, indicates both quantitative regressions (e.g., cell death) and qualitative regressions (e.g., the replacement of one set of cells by another) as being a normal part of 'normal' development (Table 1). Such evidence forces us to consider ontogenetic development as being both progressive and regressive, and in which there are both quantitative (continuous) and qualitative (discontinuous) changes (Fig. 1). If there is qualitative change (i.e., the emergence of new properties), then there must be transitional periods during which the

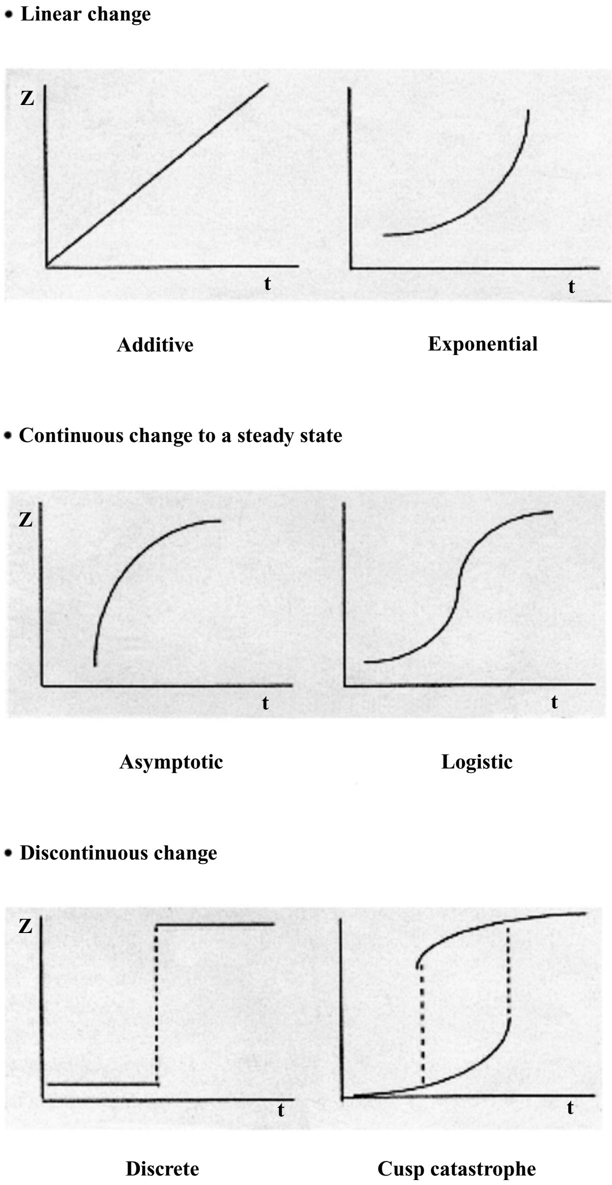


Figure 1. A classification of a variety of developmental functions. Quantitative and continuous changes can reveal linear or exponential functions as well as ones that are asymptotic or comply with a logistic growth function (i.e., there is an initial exponential trajectory that gives way to deceleration and the achievement of a final steady state). Qualitative and discontinuous changes may be manifested in one of two ways. The first consists of a discrete step or sudden jump from one stable state to another, but more complex, state with no intermediary ones. The second, termed a cusp catastrophe, has the same properties but additionally includes a hysteresis cycle, which can be interpreted as a regressive phenomenon. Hysteresis is a strong indication that a developing system is undergoing a transition between two qualitatively different states. With special thanks to Raymond Wimmers for permission to use the plots of the developmental functions.

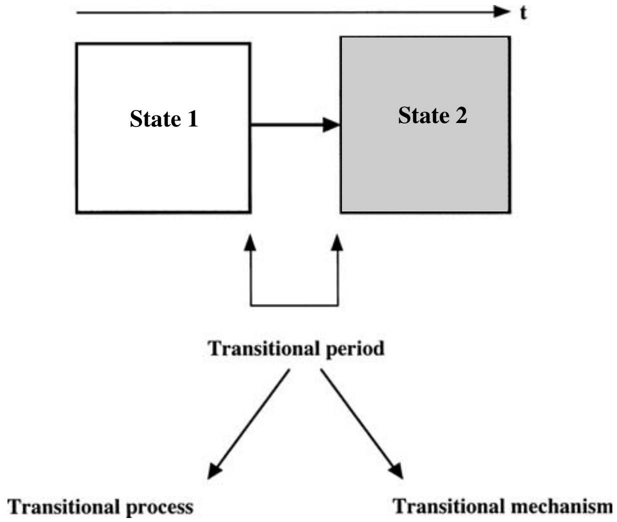


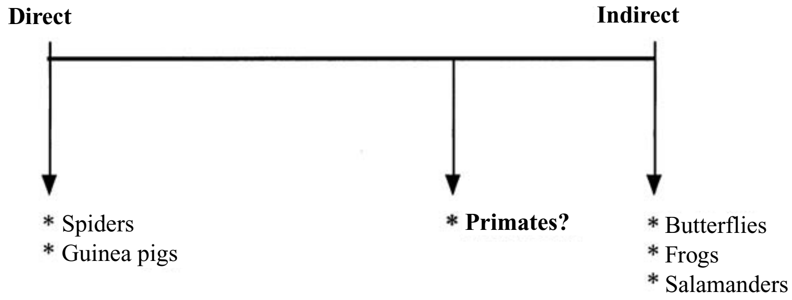
Figure 2. A transition in the behavior of a linear system (e.g., a thermostat) is gradual and continuous. For non-linear systems such as living organisms, change can be abrupt and lead to a qualitatively different and more complex state. As illustrated for such systems, that part of the time (t) taken to complete a transition (the transitional period) should be shorter than that spent in the preceding and subsequent states. In the first instance, what one wants to know is how behavior is organized during the period of transition (the transitional process) relative to the preceding and subsequent states. In dynamical systems terminology, this is captured by an order parameter, an example of which might be movement units in studying the development of reaching. The next step would be to identify the event that triggered the transition (the transitional mechanism). Using the same terminology, this is referred to as control parameter, which in the case of reaching could be the degree of postural stability when performing this action.

developing organism undergoes transformation (Fig. 2). Thus, ontogenetic development is typified by progressions and regressions, quantitative and qualitative changes, and instabilities (i.e., transitions) between stable states that become increasingly complex by some criteria. Furthermore, it takes on two forms, one direct and the other indirect or metamorphic (Fig. 3).

In suggesting metamorphosis as a metaphor for non-metamorphic development, Oppenheim (1982a) makes his point as follows:

> Destruction followed by a dramatic reorganization or even the appearance of entirely new features are familiar themes of development in such forms, and the nervous system and behavior are no exceptions. Although I do not wish to offend my colleagues in developmental psychology by claiming that the ontogeny of the nervous system and behavior in 'higher' vertebrates is metamorphic in nature, I would argue that even some of the regressions and losses, and other changes that occur during human development are only slightly less dramatic than the changes that amphibians undergo in their transformation from tadpoles into frogs.
>
> (p. 296)

Comparing ontogenetic development across phyletic levels in this way brings us to the distinction between phylogeny and evolution.



• **Direct development**: newborn or hatchling resembles adult form and mainly undergoes *growth* to achieve adult-end state.

• **Indirect (or metamorphic) development**: newborn or hatchling differs markedly from adult in terms of behavioral, morphological, physiological and other traits.

Figure 3. The differences between direct and indirect forms of ontogenetic development, taken to be two extremes of a continuum of possibilities. Direct development is more or less synonymous with growth. Indirect development, which is the defining feature of metamorphosis, involves radical transformations at different levels of organization, including the behavioral level. It has been suggested that the ontogenetic development of non-metamorphic species such as primates may in fact be better characterized as lying closer to the indirect end of the continuum. In developmental psychology, there is an ongoing debate about whether infants are born with innate cognitive structures for acquiring physical knowledge and thus that subsequent development is analogous to the growth of these structures. Those who oppose this view argue that such structures are emergent properties of the developing cognitive system. Thus, the first view is consonant with the direct form of development and the latter with its indirect counterpart.

Phylogeny and evolution

Phylogeny

Phylogeny (or phylogenesis) refers to the historical paths taken by evolving groups of animals or plants. More precisely, it is a history made up of the histories of a class of organisms in which every member is the ancestor of some identifiable class of organisms. The key to understanding this more precise definition is identifying what is meant by 'histories of a class of organisms.'

One interpretation derives from Haeckel's theory of recapitulation, later amended to the Biogenetic Law: phylogeny is a successive build up of adult stages of ontogeny, with descendants adding on a stage to those 'bequeathed' them by their ancestors. Accordingly, organisms repeat the adult stages of their ancestors during their own ontogeny. They do so, however, such that previous adult stages appear increasingly earlier during the ontogeny of descendants thereby allowing for the terminal addition of a new stage. Over the years, Haeckel's brainchild was summarized and handed down with the felicitous phrase 'ontogeny recapitulates phylogeny.'

Recapitulation theory became discredited when Thomas H. Morgan (1866–1945) showed it to be

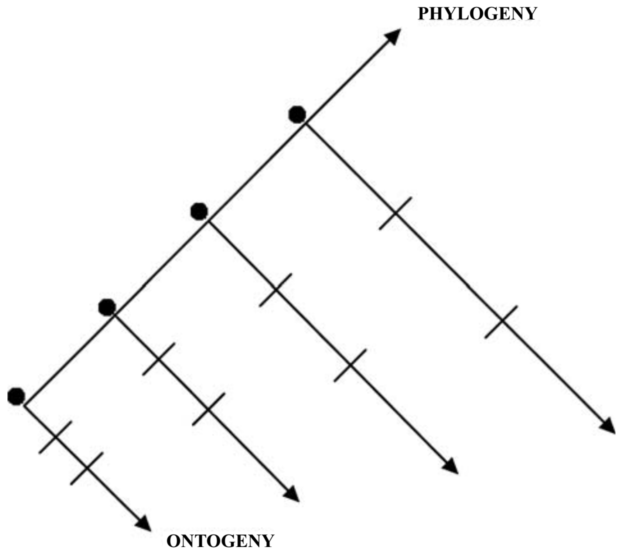


Figure 4. Phylogeny refers to the histories of a class of organisms in which every member is the ancestor of some identifiable class of organisms. These histories can be considered as a successive series of ontogenies that begin with fertilization (•). In this idealized reconstruction, each succeeding ontogeny becomes longer. Furthermore, identifiable stages (–) become proportionally extended with each ensuing ontogeny. Thus, heterochronic alterations in the mechanisms that regulate the process of ontogeny can precipitate phylogenetic change in the form of, for example, speciation.

incompatible with Mendelian genetics. In its place came a diametrically opposed interpretation articulated by Walter Garstang (1868–1949) and Gavin de Beer (1899–1972). Now, 'histories of a class of organisms' was interpreted as phylogeny consisting of a succession of *complete* ontogenies across many generations (Fig. 4). The crucial point about this interpretation is that phylogenetic change occurs through heterochronic alterations in the timing of ontogeny (i.e., by retardation as well as through the acceleration of ontogeny). More specifically, it involves alterations in the timing of somatic growth relative to reproductive maturation (Gould, 1977).

Evolution

When the controversy between supporters of epigenesis and preformationism was in full flow during the 18th century and into the second half of the 19th century, evolution (from the Latin word 'evolutio' meaning the unfolding of existing parts) was treated as being synonymous with development. Seemingly introduced by Charles Bonnet (1720–1793) or Albrecht von Haller (1708–1777), both radical preformationists, it was taken to denote any process of change or growth. Once again, it was Spencer who changed things. In his essay the 'Developmental hypothesis,' published seven years before Darwin's *Origin of Species* (1859), he offered it as a metaphor for organic change, while still retaining the notion of improvement. Although Darwin avoided the term 'evolution' in his theory of descent with modification (except as the very last word in the first edition of the *Origin*), he was, together with the geologist Charles Lyell (1797–1875), instrumental in restricting its scientific usage to biological evolution as distinguished from cultural evolution.

Biological evolution

It is sometimes not fully appreciated that Darwin had two theories of biological evolution: descent with modification and natural selection. In the 20th century, these two master theories spawned a number of associated theories (Fig. 5). His theory of descent with modification, which concerned phylogenetic change or macroevolution (i.e., speciation), led to disputes between proponents of phyletic gradualism and punctuated equilibrium. In contrast, the theory of natural selection, which addresses evolutionary change or microevolution (i.e., continuous small changes in gene frequencies within a population), was united with the theory of population genetics to give rise to the Modern synthesis. In formulating the theory of descent with modification, Darwin accorded ontogenetic development (embryology in his terms) a role in creating phylogenetic change and a chapter in the *Origin*, although he never spelt out in detail how this might occur. The Modern synthesis, for its part, dispensed with ontogenetic development as being irrelevant to an understanding of evolutionary change, in part because its supporters regarded embryology as still harboring remnants of vitalistic thinking and anti-materialistic doctrines (Mayr, 1982). As a consequence, Darwin's two master theories have proved to be difficult to integrate. The emergence of evolutionary developmental biology in the last decade is yet another attempt to provide such an integration. Before considering this discipline-in-the making, a few final comments on the distinction between biological evolution and phylogeny are needed.

To begin with, evolution in the biological sense is a theory proposing a number of mechanisms (e.g., natural selection, mutations, genetic drift) that can be made to account for micro- and macroevolutionary changes. Unlike the study of phylogeny as pursued by paleontologists, evolutionary theory is ahistorical and concentrates on the determinants that bring about these changes. Thus, there is a distinction to be made between the reconstruction of a phylogenetic history and the mechanisms of events that can explain the processes implicated in that history. Put another way, the study of phylogeny involves the description of a succession of products while evolutionary theory addresses the processes and mechanisms underlying such successive products. In this sense, the distinction between phylogeny and evolution parallels that between ontogeny

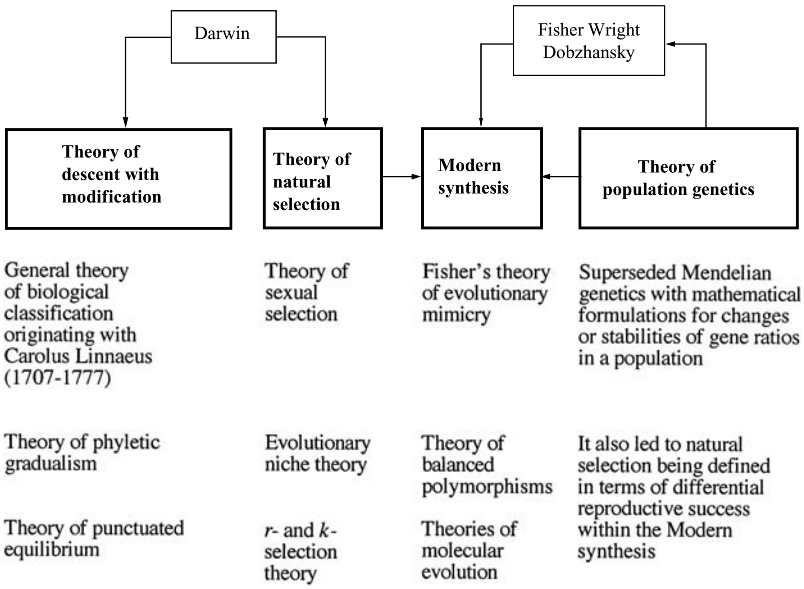


Figure 5. A summary of some of the many adjunct theories derived from Darwin's master theories of descent with modification and natural selection. The Modern synthesis arose from an integration of the theories of natural selection and population genetics during the first half of the 20th century, chiefly, but not only, through the work of Ronald A. Fisher (1890–1962), Sewall Wright (1889–1988), and Theodosious Dobzhansky (1900–1975). In turn, the synthesis gave rise to a number of adjunct theories. The theories of punctuated equilibrium and molecular evolution are difficult to classify exclusively: the former because it incorporates *r*- and *k*-selection theory and the latter in that they attempt to address phylogenetic descent. Punctuated equilibrium, more than the other theories, tries to take account of the nexus between ontogeny and phylogeny. More specifically, it rests on the assumption that alterations in the timing of ontogenetic development can lead to phylogenetic changes.

and development (i.e., ontogenetic development is not a function of time, but rather a system of processes and related mechanisms that take place over time).

To round off the comparisons, it was claimed in the past that the basic difference between ontogenetic development and biological evolution was that the former relies on deterministic processes and the latter on stochastic processes. Now, however, both are regarded as being based on determinism (i.e., 'necessity') and on (constrained) stochasticity (i.e., 'chance'). With this distinction in mind, we can turn to evolutionary developmental biology.

Evolutionary developmental biology

Haeckel's recapitulation theory had the effect of driving a wedge between developmental and evolutionary biology for many years thereafter. Nevertheless, individuals such as Richard Goldschmidt (1878–1958), with his 'hopeful'

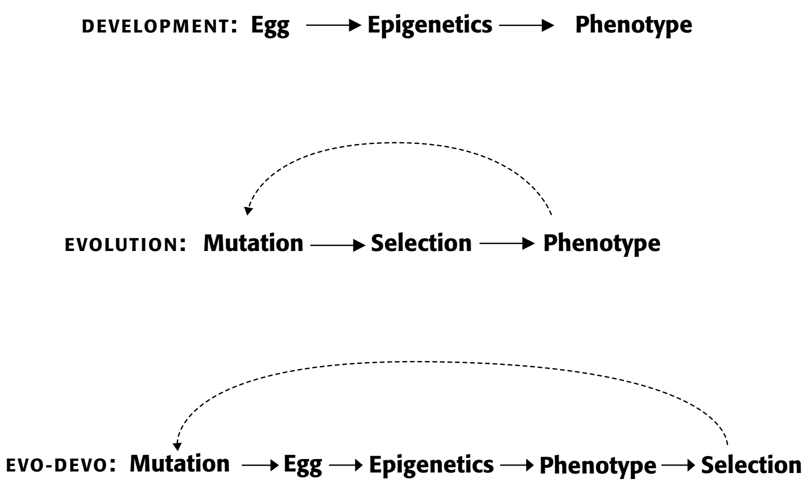


Figure 6. In ontogenetic development, epigenetics serves to mediate the connections between genotype and phenotype (top). Such an intermediary agent is replaced by selection in the Modern synthesis, which acts on the variation created by mutations (middle). Until recently, and most notably with Edelman's theory of neuronal group selection, the concept of Darwinian selection has not been ascribed a prominent role in the study of ontogenetic development. Evolutionary developmental biology attempts to go beyond the Modern synthesis in accounting for the role of epigenetics in biological evolution as well as for selection processes acting on ontogenetic development at any stage (bottom). The solid arrows indicate events within a generation and the dashed ones those that take place between generations. Adapted from B. K. Hall, 2003. Unlocking the black box between genotype and phenotype: cell condensations as morphogenetic (modular) units. *Biology and Philosophy*, 18, 219–247.

monsters arising as a consequence of small changes in the timing of embryonic development, and Conrad H. Waddington (1905–1975), with his diachronic biology and its associated concept of epigenetics, made valiant efforts to overcome the neglect of ontogenetic development in the Modern synthesis. What they lacked was the present day array of techniques in molecular biology that would have allowed them to test their ideas more fully. In recent years, there has been a renewal of interest in forging closer links between developmental and evolutionary biology with the arrival of what promises to be a new synthesis, namely, evolutionary developmental biology (or evo-devo for short).

The starting point for evo-devo is credited to the Dahlem Workshop (1981) on evolution and development (Bonner, 1982). At that time, there were major advances in molecular biology such as recombinant DNA technologies that enabled cross-species comparisons of developmental mechanisms at the molecular level. In addition, a distinction had been made between developmental regulator genes and structural genes, starting with the François Jacob - Jacques Monod (1910–1976) operon model (1961). Whereas the Modern synthesis, or more correctly population genetics, assumed that ontogenetic development was stable and resistant to change, and therefore irrelevant for understanding evolutionary change, evo-devo treats it as a major agent of such change.

What are the defining features of evo-devo? They can be summarized as follows:

1. Genes alone can explain neither development nor evolution.
2. Developmental processes (i.e., epigenetics) link genotype to phenotype (Hall in Sarkar & Robert, 2003). Due to the stochastic nature of such processes, there is no one-to-one relationship between genotype and phenotype.
3. Developmental mechanisms evolve.
4. Developmental constraints act on particular kinds of phenotypic variation and thus restrict the availability of evolutionary pathways. According to Gilbert (2003), these consist of physical constraints (e.g., elasticity and strength of tissues), morphogenetic constraints (e.g., there are only a limited number of ways a vertebrate limb can be formed), and phyletic constraints (e.g., due to the genetics of a species' development). In these respects, ontogenetic development exerts deterministic influences on biological evolution.
5. Evolutionary biology should not persist in trying to explain adaptation, but instead should try to account for evolvability (i.e., the potential for evolution). Stated otherwise, this means accounting for the possibility of complex adaptations via transformations in ontogenetic development. And finally, the key feature of evo-devo:
6. Most evolutionary changes are initiated during ontogenetic development. The implication here seems to be that alterations in the actions of regulator genes rather than structural genes give rise to macroevolutionary changes.

If all of the above signal a new synthesis, how then does it differ from the Modern synthesis? Figure 6 attempts to encapsulate the main differences.

Evo-devo is one of at least three current initiatives to integrate ontogenetic development with biological evolution in a testable and unifying theory. Another is developmental evolutionary biology (abbreviated to devo-evo) and a third is dynamical systems theory (DST). At the present time, there is a lack of clarity as to the essential differences between them. Both devo-evo and DST have been criticized for underplaying the roles of genes in evolution, while at the same time emphasizing those for developmental constraints (Gilbert in Sarkar & Robert, 2003). For example, DST, as represented in Brian Goodwin's book *How the Leopard Changed its Spots* (1994), accords explanatory equality to all levels of organization, and thus does not assign instructive or at least permissive roles to genes. Such differences in emphasis between scientists engaged in a common cause are perhaps a hallmark of the first stages in forming a new discipline. If this is achieved, then we will have a foundation for promoting new insights into ontogenetic development that Waddington and his contemporaries could only have dreamed about.

Conclusions

The main thrust of this entry has been to capture the phenomenological features of ontogenetic development that distinguish it from other terms such as evolution, ontogeny, and phylogeny. Furthermore, evolution was contrasted with phylogeny in order to prepare the ground for an introduction to evolutionary developmental biology with its promise of unifying the developmental and evolutionary sciences. To quote Samuel Butler again, it is to be hoped that we have not left ". . . a sore place more sore than it was before."

With regard to ontogenetic development, two related points can be emphasized. Firstly, we still need a theory of developmental transitions that is sufficiently detailed to guide us toward teasing out the processes and mechanisms involved in specific instances. Secondly, if the primary aim of studying ontogenetic development is to describe and explain change *within* individuals over time, then we also require a better understanding of the functional significance of the considerable variability that typifies intra-individual change. If such variability both increases and decreases over time, what does this mean? Does, for example, increasing variability herald the onset of a developmental transition and a decrease its offset? Most grand theories of development have either ignored or paid insufficient attention to such issues.

Finally, a comment on the new arrival evolutionary developmental biology. It has resulted in reuniting ontogenetic development with biological evolution through the aegis of molecular biology. While appearing to hold great promise for understanding the causal relationships between genotype and phenotype both within and between generations, it remains to be seen what impact it will have on the practice of studying child development. As the saying goes, "In theory, there is no difference between theory and practice, but in practice there is a great deal of difference." Hopefully, this will not be the case if the theoretical implications of evolutionary developmental biology become more widely appreciated amongst those of us who study child development.

See also:
The concept of development: historical perspectives; Understanding ontogenetic development: debates about the nature of the epigenetic process; Dynamical systems approaches; Conceptions and misconceptions about embryonic development; Brain and behavior development (II): cortical; Anthropology; Developmental genetics

Further reading

Ford, D. H. and Lerner, R. M. (1992). *Developmental Systems Theory*. Newbury Park, CA: Sage.
Hall, B. K., Pearson, R. D. and Müller, G. B. (eds.) (2003). *Environment, Development and Evolution: Toward a Synthesis*. Cambridge, MA: MIT Press.
Hopkins, B. (2004). Causality and development: past, present and future. In A. Peruzzi (ed.), *Causality and Mind*. Amsterdam: John Benjamins, pp. 1–17.
McNamara, K. J. (1997). *Shapes of Time: The Evolution of Growth and Development*. Baltimore: Johns Hopkins University Press.
van der Weele, C. (1999). *Images of Development: Environmental Causes in Ontogeny*. Albany, NY: State University of New York Press.

The challenge of interdisciplinarity: metaphors, reductionism, and the practice of interdisciplinary research

BRIAN HOPKINS

Introduction

Go to Google and type in 'interdisciplinary' as a search word. What do you get? In the first instance, the answer is almost 1.8 million entries or 'hits.' Not quite as many as for George W. Bush at almost more than 3.4 million hits or Manchester United at just 2 million, but nevertheless an impressive number. Combining 'interdisciplinary' with 'psychology' delivers over 360,000 entries, 20.2 percent of the total number for 'interdisciplinary' alone, and noticeably more (in descending order) than for 'sociology,' 'anthropology,' 'developmental biology,' and 'behavior genetics.' Within psychology, 'social psychology' results in many more hits than, for example, 'cognitive psychology' and 'developmental psychology' when combinations with 'interdisciplinary' are made. Nevertheless, each one provides an imposing numerical outcome. Repeating the whole exercise with 'interdisciplinary research' and 'interdisciplinarity' does little to alter by very much any of these relative comparisons (Table 1).

At first flush, this trawl through the Internet would seem to suggest that interdisciplinarity is well established in some areas of study represented in this volume. Unfortunately, the quantitative findings do not tally with qualitative considerations. Why not? First of all, because there is a lack of clarity about the meaning of interdisciplinarity or what constitutes interdisciplinary research. Further confusion is engendered when attempting to distinguish among interdisciplinarity, cross-disciplinarity, multidisciplinarity, and transdisciplinarity. Yet we now appear to be in the age of the inter-discipline prefixes and suffixes, with proliferations of bio-, etho-, psycho-, and socio-, together with the recent arrival of scientific endeavors dubbed 'social neuroscience' and 'neuroeconomics.' As for 'child development,' the number of Google entries is relatively large (Table 1). Once again, however, the numbers game masks a range of different designations as to the meanings of interdisciplinarity and interdisciplinary research. Certainly, interdisciplinarity has had something of a bad press in the past.

The up and downs of interdisciplinarity

If it appears that something of an interdisciplinary Zeitgeist is upon us, it has been achieved in the face of some strong pockets of resistance in the past. One example is epitomized by the remark of Leslie A. Smith (1900–1975) in his book *The Science of Culture* (1949) to the effect that cultural anthropologists ". . . have sold their culturological birthright for a mess of psychiatric pottage" (p. xix). During the 1960s, some leading biologists opposed what they saw as the threat of their discipline being reduced to the laws and principles of physics, or more specifically to classical mechanics. The same mistrust is still evident in attempting to preserve disciplinary boundaries (e.g., that between psychology and neuroscience).

Why then has interdisciplinarity (ID) become the mantra of current scientific policy? Before getting anywhere near answering that question, we need to address a number of converging issues: the meaning of ID relative to cross- and multidisciplinarity as well as to transdisciplinarity, levels of (biological) organization and the associated problem of reductionism, and the use of metaphors and other tropes (e.g., analogy) in science more generally. What follows is essentially a personal view derived from the experience of being a member of so-called interdisciplinary programs of research in child development. Undoubtedly, this view will have its dissenters, particularly with regard to the restricted meaning accorded to ID. Such an imposition should be seen as a debating point, rather than a firmly held belief as to how interdisciplinary research (IDR) should be construed. The hope is that it will highlight some of the structures and processes needed for IDR in child development that go beyond mere cross-disciplinarity and multidisciplinarity.

The discipline of interdisciplinarity

In 1996, the final report of the US Gulbenkian Commission on the Reconstruction of the Social Sciences was published. While favorably disposed to IDR, it did little more than recommend it could be achieved by granting academics tenure in two departments. Nowhere in the report was there a systematic attempt to distinguish ID from the other three similar terms. In short, among other things, it is a shared language (or what might be termed a scientific Esperanto) between the participating disciplines that embraces both theory and method (Table 2).

With the establishment of such a linguistic 'trading zone' at the frontiers of disciplines, the task of dissipating barriers to ID has begun. If this first step is seen as a 'mission impossible,' there are examples in science to suggest otherwise. For instance, the interdiscipline of biophysics was established through the combined efforts of physicists, biochemists, and computer scientists to learn each other's theoretical vocabulary in order to gain fresh insights into biomolecular mechanisms involving, for example, protein synthesis in membranes. Nearer to home, cognitive neuroscience arose from a lack of models in clinical neuropsychology that could be used to address the effects of focal brain injuries. During the 1960s, such models were sought in cognitive psychology, with the result that the neuropsychologists began to share the language and methods of cognitive psychologists.

Even more germane were the efforts of Arnold Gesell and Myrtle McGraw in the 1930s and 1940s to found the study of child development on principles drawn from embryology and particular branches of physics such as thermodynamics. Other pertinent examples are: the birth of biochemistry through François Magendie (1783–1855) bringing together organic chemists and physiologists to study collectively the relevance of nitrogen for animal nutrition, and the way in which Walter Nernst (1864–1941) and collaborators integrated what was then known about electrochemistry with thermodynamics during the early 20th century to give birth to what is now inorganic chemistry.

To label a scientific activity as an ostensive example of IDR is a common occurrence and a source of some obfuscation. IDR can take on at least three types, with, for example, one discipline coming to subordinate the others brought together to address a common problem beyond the bounds of a single discipline. Once more, what makes a distinction is a commonly shared language that 'cracks' the linguistic codes of the participating disciplines (Table 3).

If only it were that simple. For example, disciplines can share identical words, but they can have contrasting meanings in each one. Examples include different interpretations of growth and individuation across the developmental sciences and even that pertaining to causality. When one gets down to this level of discussion, proposed IDR projects can eventuate in disarray and the loss of a common cause. The interdisciplinary gap widens instead of closing.

Table 1. Approximate number of Google entries for interdisciplinary, interdisciplinary research, and interdisciplinarity. These terms are then combined with psychology, followed by doing the same for developmental, cognitive, and social psychology. The procedure is repeated for what might be regarded as 'sister' disciplines (sociology; anthropology), for two others that have a bearing on theorizing and research in developmental psychology (developmental biology; behavior genetics), and for child development.

Search word	*Interdisciplinary*	*Interdisciplinary research*	*Interdisciplinarity*
On its own	1,790,000	1,590,000	46,000
Psychology	362,000	414,000	9,150
Developmental psychology	954,000	189,000	1,940
Cognitive psychology	108,000	117,000	6,170
Social psychology	284,000	267,000	5,330
Sociology	284,000	224,000	6,170
Anthropology	237,000	224,000	4,520
Developmental biology	76,800	120,000	1,160
Behavior genetics	30,600	51,600	341
Child development	189,000	243,000	2,610

Bridging the gap: levels of organization and reductionism

Levelism

One way in which disciplinarity is portrayed is to arrange disciplines along a hierarchy of levels of organization and then at each level to pigeon-hole them under 'structure,' 'function,' and 'evolution.' Table 4 depicts such a hierarchy for the life sciences, broadly defined.

It should be evident that the number of levels and how they are labelled is, together with the disciplines included, an arbitrary exercise (e.g., ecology could have been allocated to the top and particle physics to the bottom of the hierarchy). Nevertheless, one person's hierarchy looks very much like another's demarcation of

Table 2. Starting from a consideration of what constitutes disciplinarity, interdisciplinarity (ID) is compared to three other forms of scientific collaboration. There is still confusion and a general lack of agreement about the meaning of ID and how it should be practiced. The defining features of ID are deliberately presented in conservative terms so as to draw distinctions with the other forms of scientific collaboration that are often taken as being synonyms. Transdisciplinarity is the most vague term used to denote cooperation between disciplines. It appears to be an attempt to get science galvanized into focusing on the provision of solutions to a variety of social and economic concerns that may be national or, more commonly, worldwide in scope (e.g., environmental pollution, and its effects on child development).

	Defining features	*Comments*
Disciplinarity	During the early part of the 20th century, there was a 'drive for disciplinarity': establishment of 'bounded' disciplines, with their own theories, methods, and standards of scientific rigor. Gave rise to modern-day discipline structures having their own scientific societies and accreditation committees	Until the late 19th century, disciplines as they existed were more loosely 'bounded' in that science was pursued as an enterprise based on a broad-ranging critical reflectivity across many areas of knowledge. Such was the case, for example, in descriptive embryology. With the 'push for specialization,' new disciplines were founded (e.g., pediatrics, which became a 'bounded' discipline in the 1930s). Largely as a result of the Cold War, area studies and systems approaches to science began to emerge in the late 1950s which ultimately gave rise to what have been termed 'interdisciplines' (e.g., cybernetics)
Interdisciplinarity (ID)	Well-established disciplines working together on a common problem, but with the express aim of adjusting their theories and methods so that they can be integrated into a new discipline or interdiscipline. It involves generalizing from multidisciplinary settings so that a common language covering theory and method can be established	In the past, there have been a number of unsuccessful attempts to establish a common scientific language (e.g., behaviorism; logical positivism; General system theory) and the quest continues (e.g., on a more restricted scale with the theory of embodiment). Apart from that, most individuals participating in this 'strong' form of scientific collaboration do so not only to contribute to another field, but also to take back new ideas to their own disciplines (thus preserving discipline independence)
Multidisciplinarity	Disciplines working together on a common problem, but not changing their approaches or adjusting to the knowledge base or techniques of other disciplines. Participating disciplines then tend to present their findings in discipline-dedicated conferences and journals	Most so-called ID research takes on this 'weak' form of scientific collaboration
Cross-disciplinarity	Takes on two forms: 1. researchers in one discipline (e.g., physics) choose to work in another discipline (e.g., biology)[1] 2. researchers trained in two disciplines (e.g., psychology and neuroscience or psychology and anthropology)	Two noticeable and increasing features of modern-day science are: 1. cross-appointments between departments (e.g., between computer science and psychology) 2. cross-disciplinary training programs (e.g., within the context of the neurosciences)
Transdisciplinarity	A sort of half-way house between disciplinarity and ID in which the aim is to provide a forum or platform for the generation of new ideas that can then be applied across a number of disciplines	If properly understood, it seems to be a medium created so that non-scientists, can have a say in the decision-making process as to which scientific problems need to be addressed. Consequently, it tends to lead to calls for science to tackle issues such as diseases and discrimination, and to providing a better standard of living for all

[1] Outstanding examples of this type of cross-disciplinarity are Max Delbrück (1906–1981) and Leo Szilard (1898–1964), both trained in quantum mechanics, who applied their knowledge acquired in physics to the study of cell reproduction. Their work made a significant contribution to the discovery of the DNA double helix attributed to John D. Watson and Francis H. C. Crick.

Table 3. Three types of interdisciplinary research, which ultimately depend on whether or not the participating disciplines share a common language, and for which possible examples involving psychology and possible common problems are given.

Type	*Interpretation*	*Possible example*	*Possible common problem*
Communality in vocabulary	Two or more disciplines focusing on a common problem, with a common scientific language and set of concepts and techniques as well as shared standards of rigor and proof. While a common shared language may be assumed, it could turn out that some terms have different meanings between the participating disciplines	Psychology and Behavioral biology	Development of attachment
Disparity in vocabulary	Two or more disciplines with different languages and concepts as well as techniques, and standards of proof. The problem to be tackled is divided up so that each part can be dealt with by relevant disciplines. Findings from the parts then have to be integrated in some way	Psychology and Anthropology	Cross-cultural comparisons of parent-child communication
Disparate in vocabulary and subordination of one discipline to another	Two or more disciplines with very different languages, research methods techniques, and standards of proof. There is a search for a common language, which requires major adjustments in concepts, methods, and techniques. The outcome can be a hierarchically arranged research strategy in which one discipline is subordinated to another in tackling a common problem.	Psychology and Pediatrics	Development of very preterm infants

Table 4. Levels of organization in relation to structure (being), function (acting), and evolution (becoming) and the (sub-)disciplines that address each one. Evolution is meant to denote the study of change over different time scales (viz., real, developmental, and geological time).

Level	*Structure*	*Function*	*Evolution*
Macro-societal	Cultural anthropology	Sociology	History
Institutional	Management science	Political science	Cultural anthropology
Micro-societal	Social psychology	Social psychology	Developmental psychology[1]
Individual	Linguistics	Psychology	Developmental psychology
Organic	Anatomy	(Neuro-)physiology[2]	Embryology
Cellular	Histology	Biochemistry	Embryology
Sub-cellular	Molecular biology	Molecular biophysics	Developmental genetics

[1] Developmental psychologists carry out research at this level when, for example, it involves the analysis of family dynamics

[2] Neurophysiology can be interpreted as covering neuroscience and developmental neuroscience and thus can feature, for example, at both the organic and cellular levels under 'Evolution'

levels and assignment of disciplines. What is this stratified hierarchy meant to convey? There are two responses. One is that as you move up the hierarchy, disciplines have to address increasingly complex phenomena, together with the emergence of properties not manifested at the lower levels. The other is that as you move down it, increasing explanatory power can be gained, which has led to the claim that science should be unified from the bottom up rather than top down. Whichever way you move, you are confronted with a task of almost Sisyphean dimensions, namely, climbing the slippery slopes of reductionism.

Reductionism

Here is not the place to embark on a detailed diatribe about the provenance of reductionism in science in general and for IDR in particular, and which assumes not one, but a number of slippery slopes. Instead, we focus just on theoretical reductionism. To begin with, what is meant by theoretical reductionism?

Termed intertheoretic reductionism by Churchland (1986), it concerns the explanation of the reduced theory (e.g., the theory of gases) by the reducing theory (e.g., statistical mechanics). On a grander scale, it encompasses the pursuit of a Theory of Everything as strived for by General system theory in the past and by such as string theory, superstring theory, and M-theory at present. In the context of the deductive-nomological model of scientific explanation originating with Carl Gustav Hempel (1905–1997) and Paul Oppenheim in 1948, theoretical reductionism is supposed to work through the implementation of bridge laws or principles. These devices act as transformation rules for linking two distinct linguistic expressions with two theories at different levels. Self-organization is sometimes treated as possessing the potential to become a bridge law as are Piaget's functional universals (viz., assimilation, accommodation, and equilibration). The problem with bridge laws is that they can become too cumbersome to put into practice such that they defeat the purpose of ever attempting theoretical reductionism in the first place (a case in point being the way in which Piaget attempted to operationalize equilibration). If this is so, and which appears to be borne out by the fact that the most successful reductions in the history of science (e.g., of Mendelian to molecular genetics) did not have recourse to bridge laws, then an alternative strategy is needed.

If not bridge laws, then what? Let's put this question to one side for a minute and consider two classic problems of theoretical reductionism. These are genetic determinism and the relationship between psychology and neuroscience.

1. Genetic determinism: with the success of the Human Genome Project, there is an increasing tendency to regard genes as the ultimate determinants of development and of developmental disorders. Knowing the sequence of many human genes, however, is not going to be particularly revealing about development, given the protein-folding problem and continuing ignorance of the pathways between genotype and phenotypes during development. Genetic determinism brings with it the danger of reification: reducing something that is a dynamical process to a static trait and then searching for its single (genetic) determinant. Examples include aggression, intelligence, and syndromes such as ADHD. Without doubt, genes influence virtually all behavior, but virtually no behavior is determined by them. Structural genes manufacture proteins and enzymes whose translation and regulation are critical to phenotypical changes in ontogenetic development (and biological evolution). However, the environment can inject some degree of developmental specificity as well (e.g., the sex of a turtle depends on the temperature of incubation and not on the dictates of chromosomes). In this example, the environment is instructive and the genotype permissive.
2. Psychology and neuroscience: without doubt, one of the most enduring themes in the history of science is how to conflate psychology and neuroscience into a unified theory of behavior or cognition. Can psychology be reduced to neuroscience as some contend (Churchland, 1986)? Or is neuroscience irrelevant to psychology as maintained by others who see their task as defending the autonomy of psychology from intrusions by other sciences (Fodor, 1975)? The nub of the issue is whether mental states (e.g., emotions, feeling, and consciousness more generally) can be reduced to corresponding neural states. Recent attempts that have been made to resolve this issue include Gerald Edelman's theory of neuronal group selection. Churchland's (1986) response, in a pro-reductionist mode, has been to argue that a psycho-neuro symphysis can be achieved by what she calls theoretical co-evolution: theories at different levels may co-evolve such that they inform and correct each other, thus bringing them ever closer to assuming a common theory. As Churchland herself realizes, while concordant development has worked for the marriage of thermodynamics and statistical mechanics as well as for physics and chemistry more generally, there are still formidable problems to be overcome in fusing psychology with neuroscience. Why? Because it is still unclear how knowledge of the brain exerts constraints on theorizing about psychological functions. Ultimately, clarity can only be achieved through further insights into structure-function relationships. For developmental psychology, understanding such constraints seems at best remote given the ever-changing relationships between structure and function during development. Thus, psycho-neuro IDR concerned with child development faces considerable hurdles, not just because of linguistic disparities between the two fields of study (Table 3), but rather due to the lack of a common theory that goes beyond correlating changes in structure and function.

So, if not bridge laws, then what? An alternative to such laws is the use of analogies to connect two or more different levels of organization. Perhaps the most frequently cited example of the value of analogies in promoting scientific advancement is how Darwin arrived at his theory of natural selection. To begin with, he drew an analogy between artificial selection as used by animal and plant breeders and the process of natural selection. He then addressed another analogy, namely, that between the theory of population pressure developed by Thomas R. Malthus (1766–1834) and the process of speciation. In combining these two analogies, Darwin created the very foundation of modern biology.

If analogical reasoning worked as a first step for Darwin, then we can ask if it serves the same function in getting IDR off the ground (i.e., whether it provides a starting point for the development of a common language). Asking this question raises the more general issue of the role of tropes in science. To begin with, let's take a trip to Milton Keynes.

Headline news: "Milton Keynes is to double in size over the next 20 years" (*Guardian* newspaper, January 6, 2004)

Metaphor, analogy, and homology

Milton Keynes (MK), like Basildon, is one of the so-called new towns built in the UK during the late 1940s. Apart from having the longest shopping mall in the world according to the *Guinness Book of Records*, it was built on a grid network system of roads and is now home to a range of light industries. Doubling its size will make it comparable to Pittsburgh in terms of the number of inhabitants. One of these inhabitants might say:

1. MK is paradise on earth
2. Although designed differently, MK has the same functions as Basildon, which also has a number of light industries
3. Although both have a grid system, MK has different functions than Pittsburgh, with its traditional base of heavy industries

Admittedly, these comparisons stretch credulity a bit, but they do raise some relevant points. What are these points? They are that:

1. is a metaphor (note it is not a simile as our inhabitant would have said: "MK is *like* paradise on earth")
2. is an analogy (viz., two different structures have similar functions)
3. is a homology, which is not a trope (viz., two corresponding structures have different functions). Relatedly:
4. Asking whether MK will have the same structures or functions in 2024 as now is a question about serial homology (viz., with development or evolution, whether or not organisms retain the same structures or functions).

A metaphor is a figure of speech in which an expression about an object or action is used to refer to something it does not literally denote in order to suggest a similarity. It is one of two master tropes, with analogy being a sub-class of metaphors. To complete the picture, the second master trope is metonymy, with synecdoche as a sub-class.

Like a metaphor, an analogy is a linguistic device or form of reasoning that logically assumes that if two things agree in some respects (mainly their relations), then they probably agree in others. To this extent, an analogy is regarded as an extended metaphor or simile. And like a 'metaphor,' it gives insights into the unfamiliar and unknown by comparison with something familiar and known. Furthermore, analogies are made explicit by similes and are implicit in metaphors. In practice, it is hardly feasible to delimit the use of metaphors, analogies, and similes in science. Thus, for the time being, these tropes will not be distinguished further, with the term 'metaphor' being used for all three.

Aristotle (384–322 BP) in his *Poetics* stated that the greatest thing by far was to be master of the metaphor and that to have achieved mastery is a sign of genius. A bit of an overstatement perhaps, but it is widely accepted that the functions of metaphor are indispensable to science, with a minority who think otherwise. Its acknowledged functions are: aids to communication, resources for the discovery of novel insights and the generation of new theories, and in applying a theory to data by means of metaphorical redescription (i.e., in mediating its application to real-life phenomena). Examples abound, across many branches of science, about the theory-invigorating properties of metaphors (Table 5).

Having championed metaphors as a first-staging post in implementing IDR, it is well to consider what has been said about their limitations. In short, according to some, there is a price to pay for using metaphorical identifications (Table 6). Despite such pitfalls, it is questionable whether there can be a metaphor-free knowledge of whatever phenomenon we are striving to explain.

What about homologies? What role, if any, can they be accorded in IDR? Posing this question brings in its wake the more general concept of isomorphisms between levels of organization.

Homologies and isomorphisms

While homology is one of the most important concepts in biology, it is used for quite different purposes (e.g., some morphologists define homology with reference to

Table 5. Examples of theories and concepts that emerged from particular metaphors (or analogies) in terms of who used them ('Source'), where they came from originally, and to what field of study they were applied. Freud and Piaget are renowned for their use of metaphors in generating their respective theories. James Clerk Maxwell was openly honest about the sources of his metaphors and another one who used them widely in his work. ? = Could it have been Aristotle?

Example	*Source*	*From*	*To*
Theory of natural selection	Darwin	Animal breeding	Evolutionary biology
Theory of electricity and magnetism	Maxwell	Fluid mechanics	Electromagnetic fields
Epigenetic landscape	Waddington	Geology	Embryology
Emotion	Freud/Lorenz	Hydraulics	Psychology/Ethology
Assimilation and accommodation	Piaget	Digestive system functioning	Genetic epistemology/Developmental psychology
Differentiation	?	Psychology	Embryology

Table 6. Three problems put forward as being associated with the use of metaphors (and analogies) in science. Lewontin's metaphorical distortion is by far the most problematic.

Pitfall	*Description*	*Comment*
Misplaced metaphor or Lavoisier's problem	Proposing a metaphor that turns out to have no value in understanding the target phenomenon	Antoine L. Lavoisier (1743–1794) proposed that a living organism is like a combustion engine. While subsequently shown to be completely incorrect, it brought together chemistry and biology, thereby encouraging physiologists of the time to take account of chemistry in their work. This eventually gave rise to modern insights and formed the basis for the initial establishment of biochemistry. Thus, misplaced metaphors can lead to advances in science, even when they are shown to be wrong, by means of testing them out
Metaphorical distortion[1]	A theory provides explanations and a model the related analytical techniques. In applying the model to a real-world phenomenon, the latter needs to be associated with some metaphor. Such metaphorical identification can give rise to metaphorical distortion (or what others have termed 'sort-crossing')	An example of a metaphorical distortion is treating evolution as though it were a process of trial and error. Doing so runs the risk of imposing concepts such as 'intention' and 'will' on what is seen as generally being a random process
Overreliance on metaphors	"Major reasons for psychology's lack of progress in accounting for brain-behavior relationships stem from a reliance on metaphorical explanations as a substitute for a real understanding of neural mechanisms"[2]	Such a statement is not supported by the vast literature on metaphors in general and their use in science in particular. For example, if Charles S. Sherrington (1857–1952) had not put forward his notion of a (then unseen) synapse as metaphor for neural connectivity, then S. Ramón y Cajal (1832–1934) would probably never have fully developed the neuron doctrine

[1] R. C. Lewontin, 1963. Models, mathematics and metaphors. *Synthese*, 15, 222–244.
[2] V. S. Ramachandran and J. J. Smythies, 1997. Shrinking minds and swollen heads. *Nature*, 386, 667–668.

a common developmental origin and although a different concept it is sometimes the case that the two homologies can be congruent). In evolutionary biology, it stands for correspondences between species in parts of morphological structure, a segment of DNA, or an individual gene. It becomes controversial when applied to behavior and development. Why? Because, in principle, homology is a qualitative concept (viz., something is homologous or not) and thus it can only be applied with considerable difficulty to phenomena that show a great deal of variability such as behavior and development. Despite this problem, there are ongoing attempts to convert homologies into mathematical isomorphisms and to account for development in terms of serial homologies.

The distinction between homology and analogy is embedded within the more general concept of isomorphisms. There are three sorts of isomorphisms to be drawn between different levels of organization:

1. Analogical isomorphisms: also known as the 'soft' systems approach, the concern is to demonstrate similarities in functioning between different levels. However, they say nothing about the causal agents or governing laws involved.
2. Homological isomorphisms: also known as the 'hard' systems approach, the phenomena under study may differ with regard to causal factors, but they are governed by the same laws or principles based on mathematical isomorphisms. The latter can be derived, for example, from allometry, game theory, and linear or non-linear dynamics, as well as a broad range of frequency distributions (e.g., Poisson distribution).
3. Explanatory isomorphisms: the same causal agents, laws, or principles are applicable to each phenomenon being compared.

The interdisciplinary exercise of approaching ontogenetic development as a process of interacting dynamical systems in developmental psychology has been mainly confined to (1), but it strives to attain (2), and for which there are some recent examples (e.g., in applying chaos theory to the study of how fetal and infant spontaneous movements are organized).

A serial homology addresses the issue of whether repetitive structures within the same organism are the same or different. When brought to bear on development, it results in questions such as: in what ways is behavior pattern A at time T_1 the same as or different from that at T_2? Are they served by homologous or analogous structures at the two ages or by those that are partially homologous and partially analogous? Such questions confront what in essence calls for IDR, namely, the evergreen topic concerning the development of structure-function relationships.

We now turn from the abstract to things more pragmatic: the practicalities of doing IDR (with the remark that the *OED* defines 'pragmatic' as dealing with things sensibly and realistically in a way that is based on practical rather than theoretical considerations).

News flash: "Pushing the frontiers of interdisciplinary research: an idea whose time has come" (*Naturejobs*, March 16, 2000)

This five-year-old news flash was a blurb for a number of US research initiatives that were accorded the adjective "interdisciplinary." In particular, coverage was given to the Bio-X project housed in the Clark Center at Stanford University, which gathers together researchers from engineering, the chemical and physical sciences, medicine, and the humanities. What is the project meant to achieve? One senior academic associated with the project answered as follows: "What's really interesting is the possibility that we have no clue what will go on in the Clark Center. That's the point. Much of what we think works is this random collision that has a physics person talking to somebody interested in Alzheimer's" (p. 313).

The Bio-X project, as with others of the same ilk, is an example of 'big science,' largely concerned with the development of new (biomedical) technologies. In its present instantiation, it is best labeled as a cross-disciplinary program of research that, perhaps with more of the random collisions, could evolve into a series of IDR projects. Certainly, it is a more expensive way of achieving truly IDR than 'small science.' The latter, as an ID enterprise, begins with a focus on a commonly defined problem emanating from negotiated theoretical settlement arrived at through the medium of metaphorical reasoning and the like. How small should 'small' be though? If forming an across-discipline group to establish guidelines for achieving desired outcomes in patient care is of any relevance, then the recommendation is not to exceed twelve to fifteen members, with a minimum of six (Shekelle *et al.*, 1999). Too few members restrict adequate discussion and too many disrupt effective functioning of the group.

Assuming that a common problem has been identified, what are the further practical considerations to be borne in mind when attempting to carry out IDR? Some, but by no means all, can be captured under three headings: preliminary questions, having clarity about general guidelines and goals, and overcoming threats to IDR.

- Preliminary questions
  1. What does IDR achieve that would not be attained by a single discipline?
  2. In what ways would IDR give rise to improved and more powerful explanations?
  3. What disciplines should be included and excluded (or at least held in abeyance)?
  4. Does a new vocabulary interpretable by all participating disciplines need to be developed?
  5. Do new methods and techniques need to be developed?
- General guidelines and goals
  1. The main aim of IDR should be to predict and explain phenomena that have not been studied previously or are only partially understood and resolved.
  2. Establish criteria for judging what counts as good quality IDR. As yet, there are no well-defined

(i.e., operationalized) criteria for making such a judgment. On a personal note, at least one good indication that an IDR project is proceeding well is if a member of the team (e.g., psychologist) is able to report findings relevant to another from a different discipline (e.g., pediatrician) coherently at a conference mainly for colleagues of the latter.
3. The publications stemming from IDR should report not just the methods of data collection and analysis, but also how ID collaboration was achieved. Incorporating how this was done can be of benefit to others attempting to initiate IDR, as well as providing a source of reference for developing and improving the practice of such research.
4. At all costs, avoid the 'Humpty-Dumpty' problem: allowing participants to pursue their own discipline-related research agendas without regard to what has been defined as the common problem, such that at a later stage the pieces have to be put together to form a coherent whole. In order to prevent this:
5. Constantly ask what the common problem and related questions are in the first instance. Are we still 'on track' or are we losing sight of the original plan for achieving the desired outcomes? What were the desired outcomes and do we need to alter them in some way, given how things have gone?

◦ Threats to IDR: apart from one discipline riding atop a hierarchy of subordinated disciplines as mentioned previously, others are –
1. Continuation of research funding that endorses existing disciplinary boundaries
2. Career paths in academia continue to be dependent on discipline-best performance criteria
3. Not encouraging technical staff (the lifeblood of most research activities) to publish in their own right. However:
4. Ensuring that the research is not primarily driven by the availability of technological innovations. While the development of new techniques is a laudable goal in IDR, they can assume a life of their own in that they permit questions to be pursued across disciplines that would not otherwise be answered. The opposite of this and another threat is:
5. Technical inertia: as pointed out by Paul Galison in his book *Image and Logic* (1998) for the case of particle physics, techniques, instruments, and experimental expertise can possess an inertia that determines the course of the research. And last, but not least:
6. *The First Law of Scientific Motivation*: "what's in it for me?"

As a final comment on the practicalities of IDR, its defining character is to have a shared common problem that can only be addressed by two or more disciplines working closely together. In tackling it, Hodges' Law of Large Problems has a very practical implication: inside every large problem is a small (and more manageable) problem struggling to get out.

Conclusions

Research in child development has long been distinguished by multidisciplinarity, if not interdisciplinarity. In the 1930s and 1940s, both Gesell and McGraw had embarked on research programs addressing core issues about the nature of infant development that were both theoretically and in practice steadfastedly committed to the ethos of interdisciplinarity. McGraw, for example, brought together an interdisciplinary team consisting of researchers from biochemistry, neurophysiology, nursing, pediatrics, physiology, and psychology as well as requisite technicians during her time at the Babies' Hospital of Columbia University (Dalton & Bergenn, 1995b, p. 10). Her studies were sponsored by the Rockefeller Foundation, which had a special commitment to the promotion of IDR.

Times have changed and nowadays it is less common to find such an array of disciplines collectively focused on resolving a common set of problems concerning child development using a judicious interplay of cross-sectional and longitudinal methods. This is not to imply that IDR is a good thing and specialization a bad thing for research on child development. Many breakthroughs have been achieved (e.g., in studying cognitive development) from within a more or less monodisciplinary framework. IDR is mandated by the start point for any sort of research: "What's the question?" What is at issue is whether the question, when pared down so as to render more specific ones that are methodologically tractable, unequivocally carries with it the necessity of crossing disciplinary borders.

The success of IDR depends initially on the thoroughness of attempts to develop a common language of communication framed around a common problem. Achievement of a common language should suggest isomorphisms between levels of organization representative of the disciplines involved and which emerge from the skillful use of metaphors and analogies, and perhaps ultimately homologies. The power of metaphorical reasoning to achieve communication between individuals from different backgrounds has been demonstrated, for example, in research on consultations between pulmonary physicians and their patients (Arroliga *et al.*, 2002). If it works so successfully in this sort of setting in which such a marked disparity in language use has to be overcome, then this is surely an indication of its potential for fostering IDR.

Inevitably, reductionism in one form or another looms large in the context of IDR. Despite the rise of radical reductionism in the guise of genetic determinism during recent years, there is little evidence to suggest it has any real significance for the way in which most developmental scientists conduct their research. What one finds is that reductive analysis (i.e., induction) is combined with holistic synthesis (i.e., deduction), which have commonly (and mistakenly) been represented as mutually exclusive types of scientific explanation. Embryologists such as Paul A. Weiss (1898–1989), a staunch defender of holism, long ago argued for the necessity of maintaining both approaches in research on living systems. Put another way, it is an argument that both upward and downward causation should be accounted for in IDR.

Organizational structures need to be in place in order for IDR to flourish and in this regard the USA is still ahead of the game. On the one hand, there are agencies that continue to promote and support IDR networks, such as the MacArthur Foundation, some of which are committed to the study of child development (e.g., Network on Early Experience and Brain Development). On the other hand, there is considerable encouragement for the establishment of interdisciplinary teaching, at least with respect to the undergraduate level, through the activities of the Association for Integrative Studies. In order to overcome the confusion about the meaning of interdisciplinarity, this organization commissioned a task force whose work culminated in a report entitled "Accreditation Criteria for Interdisciplinary Studies in General Education" (2000). While a first step in identifying good practice in interdisciplinary teaching, this document also helps in removing some of the ambiguities surrounding the use of the term interdisciplinarity more generally.

Why has interdisciplinarity become the mantra of scientific policy? The optimist might answer that it is because it provides the sort of intellectual challenge that leads to scientific breakthroughs. Apart from mentioning the potential financial savings to be gained from replacing a diverse multidisciplinarity with a more unified interdisciplinarity (or in other words, amalgamating departments when there are cash-flow problems), the pessimist would point out that the policy makers have overlooked Barr's Inertial Principle: asking scientists to revise their theory is like asking a group of police officers to revise the law. Now there's a challenge.

See also:
Understanding ontogenetic development: debates about the nature of the epigenetic process; Neuromaturational theories; Constructivist theories; Dynamical systems approaches; Conceptions and misconceptions about embryonic development; Behavioral embryology and all other entries in Part VII; Jean Piaget

Further reading

Bickle, J. (1998). *Psychoneural Reduction: The New Wave.* Cambridge, MA: MIT Press.

Brown, T. L. (2003). *Making Truth: Metaphor in Science.* Champaign-Urbana: University of Illinois Press.

Klein, J. T. (1996). *Crossing Boundaries: Knowledge, Disciplinarities and Interdisciplinarities.* Charlottesville, VA: University of Virginia Press.

Sarkar, S. (1998). *Genetics and Reductionism.* Cambridge: Cambridge University Press.

Weingardt, P. and Stehr, N. (eds.) (2000). *Practising Interdisciplinarity.* Toronto: Toronto University Press.

PART I
Theories of development

The aim of this part is to explain the main features of theoretical approaches to development that have shaped contemporary developmental sciences in general and developmental psychology in particular. The strengths and weaknesses of each approach will be indicated. The final section on the application of dynamical systems approaches to development enables further details to be added to the interdisciplinary framework outlined in the Introduction.

Neuromaturational theories

BRIAN HOPKINS

Introduction

Ontogenetic development occurs as a consequence of genetically determined structural changes in the central nervous system that can in turn give rise to orderly modifications in function. Thus, whatever the function, development conforms to an inevitable and invariable linear sequence of achievements (or milestones), with little or no assistance from the prevailing environment.

Redolent of the theory of the immortal germ plasm designed by August Weismann (1834–1914) to account for the genetic mechanisms of inheritance, this depiction of development continues to persist in textbooks on human development that devote a section (rarely a chapter) to what has become known as neuromaturational theories. Typically, two names have been associated with such theories: Arnold L. Gesell (Fig. 1) and Myrtle B. McGraw (Fig. 2). Consequently, the history of so-called neuromaturational accounts of development is restricted to brief, and as a result distorted, descriptions of the research endeavors of these two eminent developmental scientists. Such descriptions inevitably go on to report the demise of neuromaturational theories of development, with the epitaph "of historical interest, but no longer relevant." Nothing could be further from the truth, and it leaves one pondering whether some writers of developmental textbooks have ever read the original (as in 'source' and 'originality') writings of Gesell and McGraw.

Previewing the conclusions

Scientists, unlike hermits, do not work in a vacuum divorced from contemporary and historical influences on their research interests. As Isaac Newton (1642–1727) wrote to fellow physicist Robert Hooke (1635–1703) in a letter dated February 5, 1675: "If I have seen further it is by standing on the shoulders of giants." Who were the influential 'giants' with regard to the research and writings of Gesell and McGraw? Answers to this question lead to the conclusion that neuromaturational theories as depicted above are a caricature when applied to influences that motivated the wide-ranging works of Gesell and McGraw.

It becomes further evident that neither was a 'neuromaturationist' in the strictest sense when one considers what they actually wrote. Even though both frequently used the term maturation, they did so as a means of combating the excesses of behaviorism and its doctrinal insistence that the human newborn was nothing more than a tabula rasa. Thus, perhaps we should conclude that 'neuromaturational' is an inappropriate adjective with which to qualify their respective theoretical stances – a conclusion they reinforced by the fact that they not only converged, but also most noticeably diverged, in their speculations about the determinants of development.

Historical and contemporary influences

From Comenius to Dewey

The intellectual heritage implicit in the writings of both Gesell and McGraw can be traced back to Jean-Jacques Rousseau (1712–1778) and before him John Amos Comenius (1592–1670). Rousseau offered the first psychological theory of child development in his book *Emile* (1762). While he portrayed development as an internally regulated process, he was by no means a strict maturationist as he emphasized that the spontaneously active child is ultimately a product of his own exploratory behavior and the environmental challenges it creates.

The intermediary link between Rousseau's ideas on the nature of the child and those of Gesell and McGraw was John Dewey (1859–1952). Fascinated by the latter's theory of enquiry and related research on infant and child development, the teenaged McGraw corresponded with Dewey from 1914 to 1918, and subsequently followed his courses at Columbia University. Dewey had

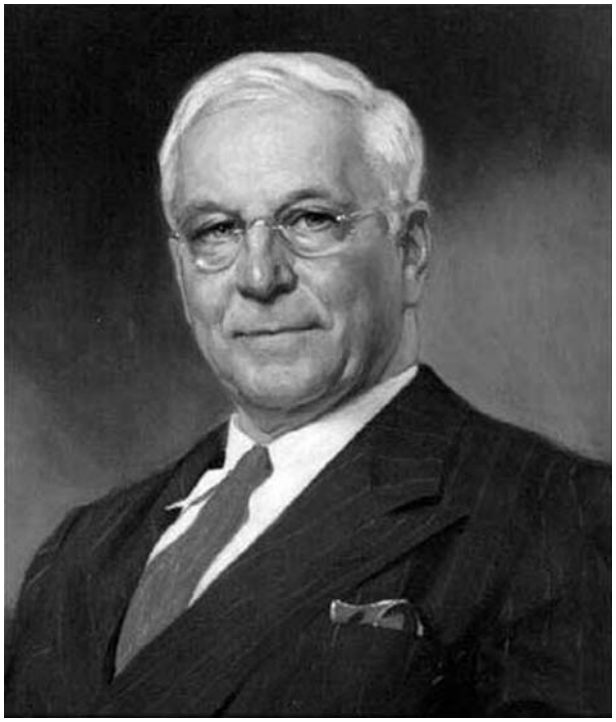


Figure 1. Arnold Lucius Gesell (1880–1961).

Figure 2. Myrtle Byram McGraw (1899–1988), photograph by Victor Bergenn.

a crucially important influence on McGraw's research agenda and in turn his theorizing substantially benefited from her findings (Dalton & Bergenn, 1995b, pp. 1–36). As for Gesell, he was influenced by Dewey's theory from two sources. Firstly, through the writings of G. Stanley Hall (Fig. 3) on child education, and secondly by his wife and some time co-author Beatrice Chandler who was a devotee of Dewey's pragmatic philosophy.

Dewey's rich and complex theory as expressed in his ideas on the development of judgment was an attempt to resolve the mind-body problem such that a static 'being' could be reconciled with a dynamical 'becoming.' Important in this respect were the related theories of Michael Faraday (1791–1867) and James Clerk Maxwell (1831–1879) on electrical and magnetic forces. Dewey believed that the laws of energy derived from these theories could be applied to the study of infant development. This step was taken by McGraw in one of her most detailed investigations on the development of bipedal locomotion, which for its time was technically sophisticated (Fig. 4).

For Dewey, and for McGraw, infants devote a considerable expenditure of kinetic energy in their first attempts at counteracting the gravitational field and subsequently in sitting, prehension, and the various forms of locomotion. For bipedal locomotion, at least, the dissipation of kinetic energy is expressed in a non-linear fashion, with the transition from unsupported to supported walking as shown by McGraw (Fig. 4). In general, however, development involves a

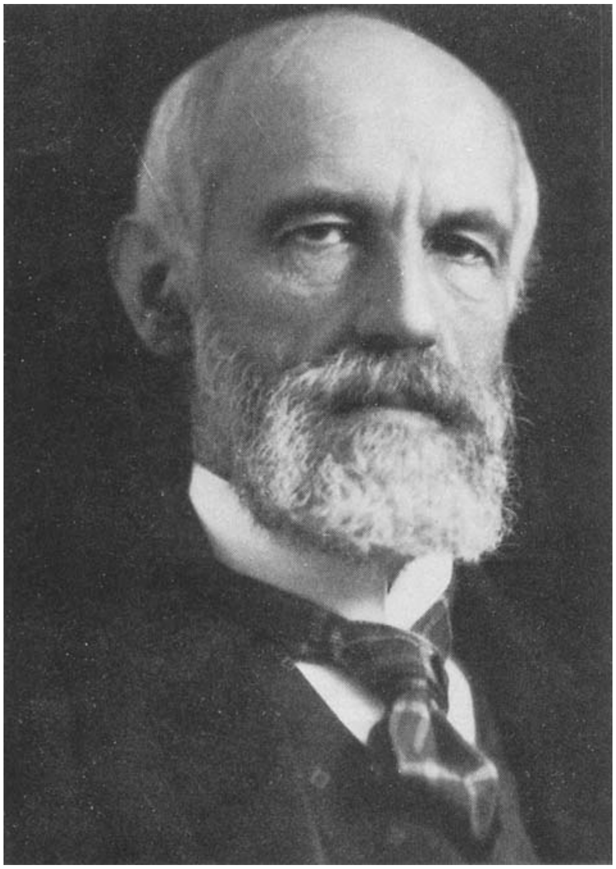


Figure 3. Granville Stanley Hall (1844–1924).

gradual reduction in this expenditure through improvements in the transformation and redistribution of energy by the brain (and presumably by the musculoskeletal system in interaction with the central

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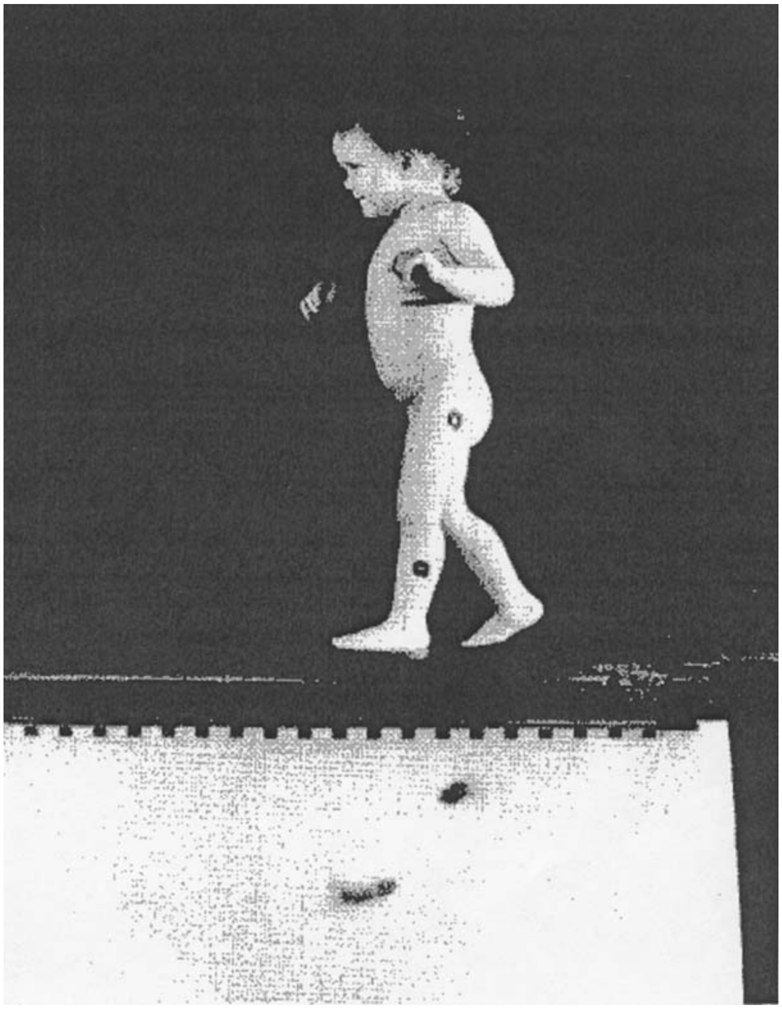

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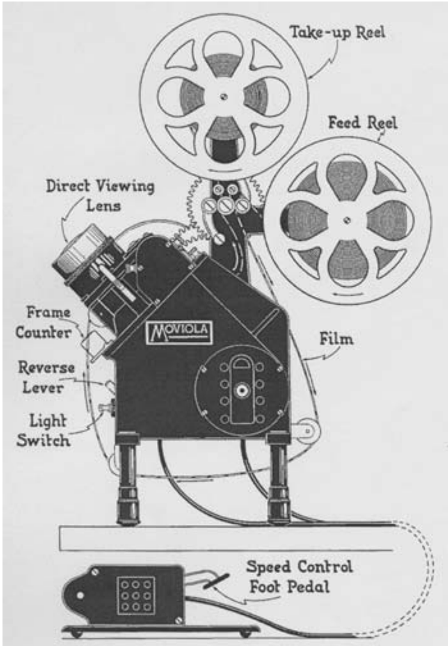

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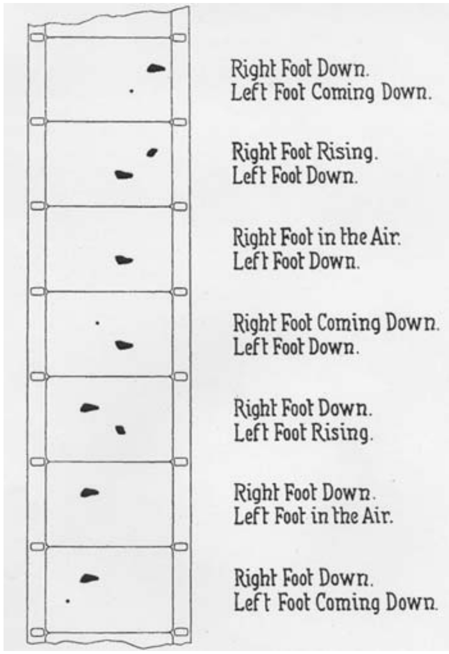

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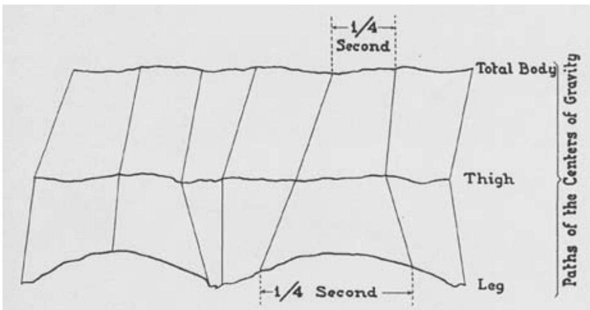


Figure 4. Methodological aspects of the study by McGraw and Breeze (1941) on the energetics of unsupported and supported walking in fifty-two infants. (A) Infants walked across a glass-topped table covered in evaporated milk and on top of which was placed a rubber mat. Positioning a mirror below the table at an angle of 45° enabled images of footprints to be recorded. Black markers were attached to the lower legs and thighs and another to that ". . . corresponding to the level of the center of gravity as a whole" (p. 276). Successive footprints and displacements of the markers on both sides of the body were registered by means of a 16mm camera at a sampling rate of 32 frames per second. (B) An editing camera was used to to project recordings onto a screen so that single and double stance times as well as changes in marker displacements could be plotted frame-by-frame. (C) A frame-by-frame plot of footprints indicating single and double stance phases. (D) A frame-by-frame plot of paths followed by the centers of gravity of the whole body, thigh, and lower leg. A number of measures to capture the 'energetic efficiency of locomotion' were derived. One was based on translational kinetic energy: average kinetic energy of a projectile / average kinetic energy of the leg moving over the same horizontal distance. This ratio revealed little change throughout supported walking and a sudden increase with the onset of unsupported walking. Subsequently, there was evident variability, both between and within infants, in the amount of kinetic energy expended. From M. B. McGraw and R. W. Breeze, 1941. Quantitative studies in the development of erect locomotion. *Child Development*, 12, 267–303.

nervous system). The outcome is a series of overlapping phases during which there is a selective elimination of unnecessary movements in such actions. During these phases, movements become increasingly integrated and coordinated, thereby allowing more stable energy-efficient states of 'being' to be achieved.

The notions of integration and coordination, according to Dewey, were evident in the continuing bidirectional relationships between motor and cognitive functions. Consequently, it was for him an artificial exercise, and thus biologically inappropriate, to compartmentalize development into separate functions. Doing so would undermine our understanding of how consciousness developed as it involves not just the mind, but also the mind in interaction with the body. To use Dewey's terminology, the development of consciousness was the "awareness of difference in the making."

Dewey, like Baldwin and Piaget, took account of Darwin's impact on psychology in his theory building, as did Gesell through his exposure to the arch-Darwinist and avid supporter of recapitulation theory, Stanley Hall. While Dewey never fully ascribed to Darwin's claim that development abided by a universal sequence, Gesell adopted it as a cornerstone of his theory. Apparently, McGraw displayed some hesitancy in applying Darwinian thinking to her work, feeling that it diverted attention away from a proper understanding of proximate mechanisms in development (Dalton & Bergenn, 1995a, pp. 207–214). Nevertheless, both she and Dewey can be read as subscribing to Darwin's theory of natural selection, at least in terms of a metaphor applicable to development. Dewey's selectionist account of development is echoed in McGraw's (1935) conclusion that developing infants are engaged in a process of selecting and refining combinations of movements and postures best suited to gaining ascendancy over a new task or challenge. In this sense, they foreshadowed a key feature of Gerald Edelman's theory of neuronal group selection.

Embryology

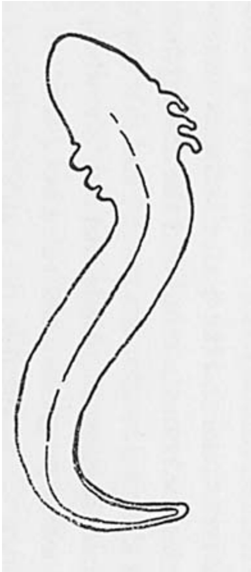
An important contemporary influence on Gesell and McGraw was the rise of experimental embryology, which reached a peak during their most research-intensive period (viz., the 1930s and 1940s). Figures in this field such as Ross G. Harrison (1873–1959) had already expressed the view that embryogenesis was not predetermined, but instead relied on interactions between cells and between them and the extracellular environment, a view in keeping with Gottlieb's concept of probabilistic epigenesis. By the time Gesell and McGraw embarked on their respective programs of research, such a view had become a commonly held principle among embryologists. For certain, they were keenly aware of such embryological principles and readily incorporated them into their work. Thus, we find Gesell writing: "The organismic pattern of one moment, responsive to both internal and external environments, influences the pattern of succeeding moments. In a measure, previous environmental effects are perpetuated by incorporation with constitution" (Gesell & Thompson, 1934, p. 294). For her part, McGraw expressed her indebtedness to embryology in the following way: ". . . it is the experimental embryologists and not psychologists who deserve credit for formulating the most adequate theory of behavior development. It is they who are revealing the process of morphogenesis, and it is they who are bringing the most convincing experimental evidence to bear upon an evaluation of the intrinsic and extrinsic factors in the process of growth" (McGraw, 1935, p. 10). She then goes on to state in a manner equally applicable to Gesell: "In many ways development as manifest in the early metamorphosis of the germ cells is extraordinarily similar in principle to that shown in the development of behavior in the infant and young child" (p. 10). Undoubtedly, the embryologist with the greatest impact on Gesell and McGraw was George E. Coghill (Oppenheim in Dalton & Bergenn, 1995a, pp. ix–xiv). Coghill had embarked on an intensive study of changes in the swimming movements of salamander larvae and embryos in 1906, with the aim of identifying the neural mechanisms underlying their behavioral development. His theoretical approach and findings influenced Gesell and especially McGraw in a variety of ways (Fig. 5). Three of these relevant to both of them can be mentioned. Firstly, behavioral development stemmed from an orderly sequence of changes in the nervous system (a standpoint perhaps shared more by Gesell than McGraw). Secondly, from the beginning, behavior is expressed as a total integrated pattern and from which individual functions emerge during development (Coghill's principle of the integration and individuation of behavior, according to which experience and learning make significant contributions to development). Thirdly, behavioral development does not originate in a bundle of reflexes triggered into a chain-like response to external stimulation. Instead, it commences as a coordinated pattern generated by a spontaneously active nervous system (another standpoint perhaps shared more by Gesell than McGraw). This last point reveals something about Coghill's strong opposition to behaviorism and its close cousin in neurophysiology, reflexology (Fig. 6).

Behaviorism

If embryology, with its emphasis on reciprocal structure-function relationships during development,

Figure 5. A specific instance of Coghill's influence on McGraw's research. (A) The S-stage in the development of swimming movements in the salamander larva, one of three stages identified by Coghill, with the prior two being termed the Early Flexure and Coil stages. (From Coghill, 1929, as cited in George E. Coghill, this volume.) These observations provided McGraw with the motivation for studying developmental changes in the swimming movements of human infants. (B) Phases in the swimming movements of the human newborn (A), at about 2–3 months (B) during which they become more variable, and approximately coinciding with the achievement of unsupported bipedal locomotion (C). The newborn movements, no longer present when the infant is placed in water after phase B, suggest that they are ontogenetic adaptations to the intrauterine environment, with their 'reappearance' at phase C having to do with practice effects as in her co-twin study. They also demonstrate the effects of decreasing gravitational constraints on the behavior of the newborn and McGraw considered them to be better organized than either neonatal crawling or stepping movements. From M. B. McGraw, 1943. *The Neural Maturation of the Human Infant*. New York: Columbia University Press.

(A)



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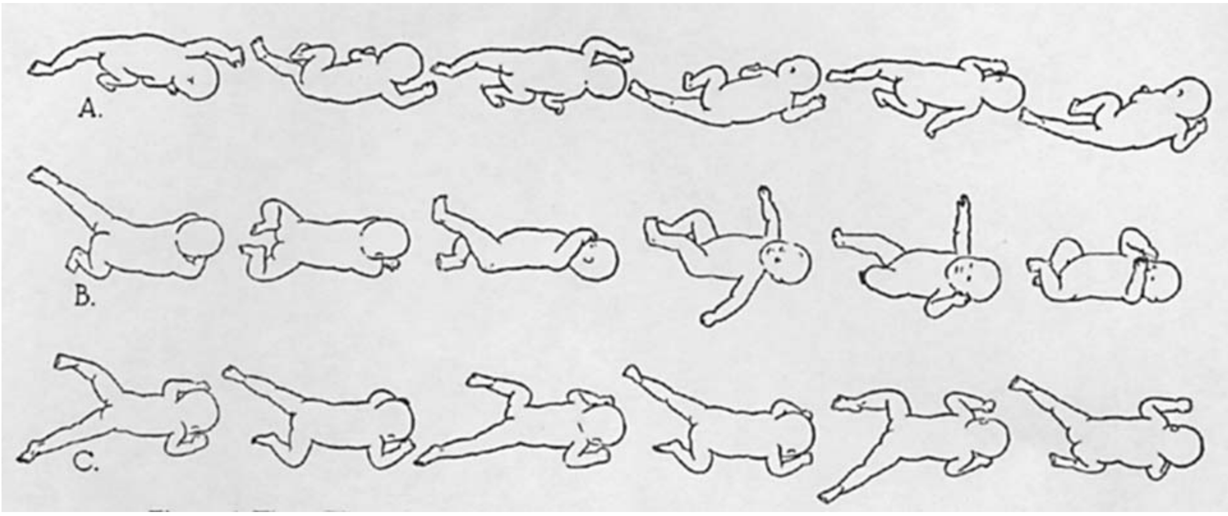

was a source of inspiration for Gesell and McGraw, then behaviorism posed a definite threat to the future of their research. Of course, we are not talking about just any sort of behaviorism, but rather the radical formulation promulgated by John B. Watson (1878–1958). Attaining the apex of its dominance during the 1930s and 1940s, Watson's radical environmentalism banned not only the use of the introspective method, but also concepts having to do with the internal regulation behavior that were so essential to the visions of development held by Gesell and McGraw. Why he espoused such an extreme view is not entirely clear. His Ph.D. thesis (1903) concerned the issue of how behavior and cortical myelination co-developed in the rat, and subsequently he carried out ethological research together with his student Karl S. Lashley (1890–1958) on the behavioral development of terns. Perhaps the turning point was his justifiable dissatisfaction with the concept of instinct as could be found in the writings of William McDougall (1871–1938) at the time. Whatever the case, Watson never studied child development, except for an abortive attempt to classically condition the human newborn. He did manage, however, to divorce mainstream (American) developmental psychology from its roots in biology that had been established by the likes of Baldwin and Stanley Hall before him.

Given their affinity with Coghill and Dewey, it is not surprising that Gesell and McGraw also opposed radical behaviorism as a means of understanding development. Certainly, Gesell was more outspoken in this respect and both he and McGraw were forced by Watson's polemics to defend and refine their own theoretical stances on

Table 1. Gesell's seven morphogenetic principles, with their interpretations, examples taken from his own writings and analogous terms used by others. Most of them were derived from embryology and some of them have interdependent meanings. The overriding principle is that of self-organization.

Principle	*Interpretation*	*Gesellian example*	*Similar terms*
1. Individuating fore-reference	Two aspects: 1. organism develops as a unitary whole from which differentiated functions arise (i.e., 'being' is sustained in the face of 'becoming'); 2. neural mechanisms present before they are functionally expressed	Neural 'machinery' for locomotion is developed before the child can walk	Systemogenesis and environmentally or experience-expectant development of structures and functions
2. Developmental direction	Development proceeds in invariant cephalo (proximal) – caudal (distal) direction as well as following a proximo-distal trend	Infant gains control over muscles of the eyes, neck, upper trunk, and arms before those of the lower trunk and legs	Gradients in morphogenetic fields
3. Spiral reincorporation	Loss and (partial) recurrence of behavioral patterns (regressions as well as progressions) that lead to emergence of new ones, with development appearing to repeat itself at higher levels of organization	As the infant changes from being able to move in prone, elevated, and finally the upright position, there is a partial repetition of previous forms of leg activity.	Repetition (of abilities at increasingly higher levels of organization)[1]
4. Reciprocal interweaving	Periodic fluctuations in dominance between functions, and between excitation and inhibition. Applied not only to the changing dominance between flexor and extensor muscles, but also to perceptual and emotional development. Similarity with Piaget's concept of *décalage* and thus to the process of equilibration	Alternations in hand preference during infant development that include a period of no preference.	Heterochrony and systemogenesis
5. Functional asymmetry	Development begins in a symmetrical state that has to be 'broken' in order to achieve lateralized behavior	Symmetry is 'broken' initially with the appearance of the asymmetrical tonic neck posture in neonatal life, which forms the origin of a subsequent hand preference	Symmetry breaking (in physics)
6. Self-regulatory fluctuation	Developing system in state of formative instability in which periods of equilibrium alternate with periods of disequilibrium. Accordingly, development is a non-linear process	Evident in changes in the developing relationships between sleep and wakefulness	Self-organization
7. Optimal tendency	Achievement of end-states in development through the action of endogenous compensatory mechanisms, which serve to 'buffer' the developing organism from undue external perturbations	Most infants achieve independent bipedal locomotion without any specific training at about the same age, despite temporary setbacks such as illnesses	Canalization and the mechanism of homeorhesis, both of which stem from the concept of equifinality

[1] Derived from T. G. R. Bower and J. G. Wishart, 1979. Towards a unitary theory of development. In E. B. Thoman, ed., *Origins of the Infant's Social Responsiveness*. Hillsdale, NJ: Erlbaum, and a feature of Bower's model of descending differentiation applied to both perceptual and motor development.

child development. What were the defining features of their respective theories?

Arnold Gesell the theoretician and tester

On the possibility of a behavioral morphogenesis

The anchor point of Gesell's theory of development was morphogenesis, the study of change in the physical shape or form of the whole organism by means of growth and differentiation across ontogenetic (or phylogenetic) time. In this respect, he was greatly influenced by the Scottish zoologist D'Arcy Wentworth Thompson (1860–1948) and his book *Growth and Form* (1917). Today the mechanisms of growth and differentiation are couched in terms of symmetry breaking following the seminal work of Alan Turing (1912–1954) on modeling the effects of chemical gradients in morphogenetic fields, something that Gesell was aware of toward the end of his working life.

According to Gesell, behavior had a changing morphology, and development, like physical growth, was a morphogenetic process that was revealed in transformations of the ". . . architectonics of the action system" (Gesell & Amatruda, 1945, p. 165). Morphogenesis was more than just a metaphor for Gesell: behavioral development conformed to the same processes of pattern formation as for the growth of anatomical structures, and its study required a topographical approach (partly via cinematography) in order to capture age-related alterations in the patterns of movement (e.g., prehension) and posture (e.g., the asymmetrical tonic neck configuration of head, arms, and legs). He endeavored to encapsulate these processes in his seven morphological principles or laws of growth (Table 1) and to depict their most salient features with the aid of spatial-temporal illustrations (Fig. 7).

What is clear from reading the later publications of Gesell (e.g., Gesell & Amatruda, 1945) is that his theory of behavioral morphogenesis complied with one overarching principle: self-regulation or what is now referred to as self-organization in open systems. He, like McGraw, was acquainted with General system theory as propounded by Ludwig von Bertalanffy (1901–1972) in his attempt to provide a theoretical framework for the unification of biology and physics through the agency of irreversible thermodynamics. Gesell was also becoming familiar with the approach of Ilya Prigogine (1917–2003) to this branch of physics and thus to how living systems evade the maximum entropy created by the Second law of thermodynamics. One can only speculate how Gesell would have incorporated the non-linear dynamics of irreversible thermodynamics and related theories into his own morphogenetic theory, but it is indisputable that for him development was a self-organizing process.

On the meaning of maturation

If development was a process imbued with self-organizing capacities, what then was the mechanism of ontogenetic change in Gesell's theory? It is in this regard that we confront the most persistent representation of his theory, namely, that the 'motor' driving such change was maturation. Originating in embryology, the meaning of maturation was restricted there to the formation of gametes (ova and spermatozoa) from the oogonia and spermatogonia of the female and male gonads, respectively. As such, it refers to the first of the major stages in metazoan embryological development that is followed by fertilization, cleavage, and the stages of the blastula and neurula. In Gesell's theory, maturation was not only a formative agent in development, but also even more so a stabilizing mechanism that ensured the ontogenetic achievement of species-characteristic end states. Thus, it has considerable kinship with the notion of canalization as advanced by the geneticist-cum-embryologist Conrad H. Waddington (1905–1975).

The obdurate misrepresentation of Gesell's theory stems not only from a neglect of how he conceptualized development, which he used to replace the by-then-outmoded instinct concept. What tends to be overlooked is that he accorded both learning and experience equality with maturation as is evident in the previous citation from Gesell & Thompson (1934). What united learning, experience, and maturation in Gesell's theoretical edifice was his concept of growth (Oppenheim, 1992). Growth for him was the functional enhancement of behavioral adaptations that included responses to internal and external environments, with the rider that the distinction between 'internal' and 'external' was ultimately an inexpedient exercise. Over the years, and perhaps as a debating point to counteract the excesses of radical behaviorism, he subtly altered his stance on the maturation versus learning debate that came to replace the hereditary-environment controversy. So, by the middle of the 1940s, he expressed the following, much-quoted, statement: "The so-called environment, whether internal or external, does not generate the progressions of development. Environmental factors support, inflect, and specify; but they do not engender the basic forms and sequences of development" (Gesell, 1946, p. 313). Such a statement is strikingly reminiscent of the roles of experience in development delineated by Gottlieb: maintenance (cf., support), facilitation (cf., inflect), and induction (cf., specify).

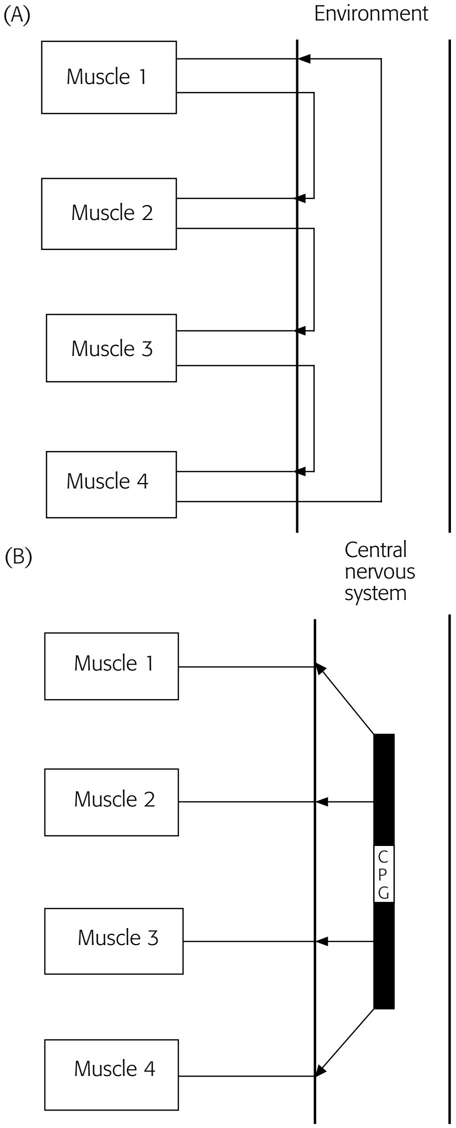

Figure 6. (A) Reflexology: a schematic representation of the chain-reflex model. When the first reflex associated with a muscle is elicited by external stimulation, its output triggers the next reflex and so on. With elicitation of the last reflex in the chain, its output serves to re-elicit the first one and thus the movement is repeated as in locomotion. Opposed by Coghill, this model was also severely criticized by Lashley in 1930 as an unrealistic model of motor control. (B) Coghill's approach to behavioral development was akin to the Preyer-Tracy hypothesis of autogeneous motility, which today is reflected in the central pattern generator (CPG) theory. A CPG is taken to be a network of of spontaneously active interneurons situated, for example, in the spinal cord and which emits modulated rhythmical electrical discharges that activate muscles in coordinated fashion, such as those involved in locomotion. With thanks to Hans Forssberg for both illustrations.

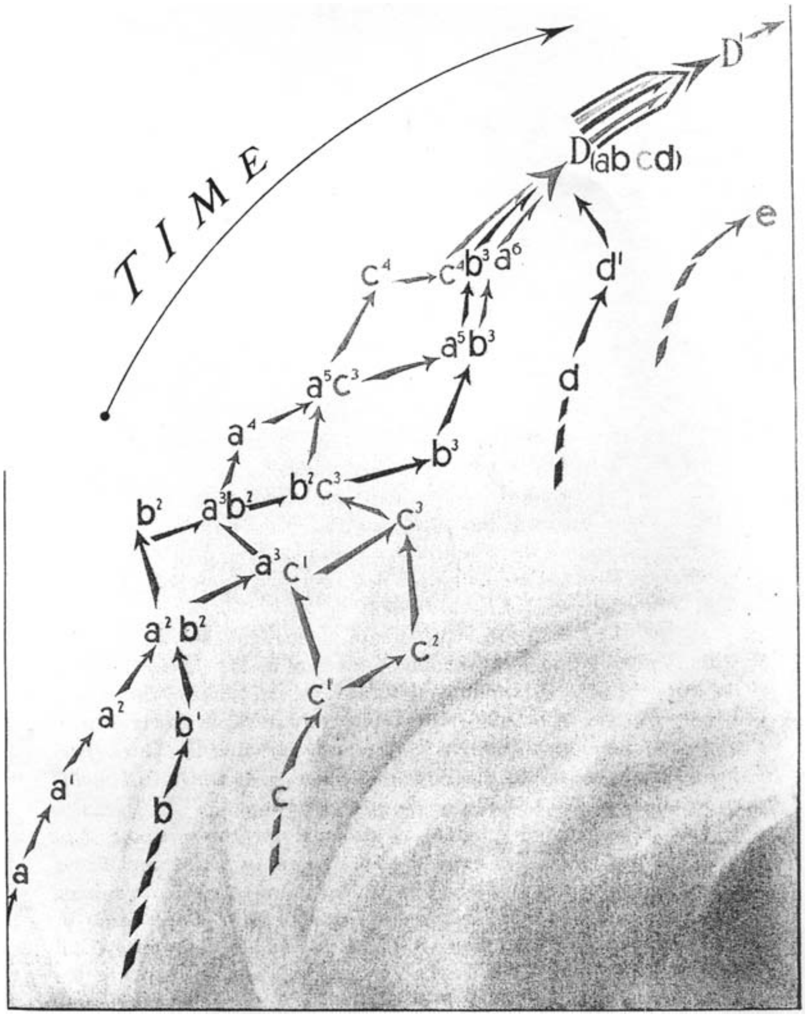

Figure 7. Gesell's depiction of the morphogenetic principles he proposed as giving rise to the formation of behavioral patterns and which he termed a 'time-space diagram' or 'dynamic map.' The shaded area refers to the 'corpus of behavior', which consists of potential and achieved expressions of the developing action system. The lower-case letters a, b, c, and d stand for traits or their parts, which over time merge into a developed complex of traits (D). The numbers associated with these letters represent the enhancement or elaboration of a trait, either of itself or through its integration with a related one. The broken lines denote latent traits that still have to be expressed in behavior, while the solid lines indicate dominant ones, with the former serving as replacements for the latter should that be required (e.g., as a consequence of focal brain damage). The behaviors at the edge of the shaded area (b^2, a^4, etc.) are those that are overtly manifest. In particular, this map illustrates the principle of reciprocal interweaving. From A. Gesell and C. S. Amatruda, 1945. *The Embryology of Behavior: The Beginnings of the Human Mind*. New York: Harper.

On developmental testing

Gesell was not only a psychologist, but also a pediatrician by training. The fusion of these two professions in his academic career led him inexorably to what has become his defining contribution to developmental psychology: the derivation of normative, age-based, criteria for use in developmental diagnosis, which culminated in his battery of tests referred to as the Gesell Developmental Schedules.

As pointed out by others, there is curious tension between Gesell the theoretician and Gesell the tester. On the one hand, he had articulated a complex and subtle theory designed to capture the development of the *whole* child. On the other hand, his schedules appear to bear little relationship to his theory, with the 'typical' child's development being disassembled into one of several functional domains that have been incorporated into subsequent scales of infant development. His test battery, which covered ten ages, was intended to serve two main purposes. Firstly, to identify signs of deviant development as early as possible, despite the fact that the norms for each item were appropriated from testing children from middle-class families of North European ancestry. Secondly, and resting on the embryological concept of competence, to provide an indication of 'readiness for schooling.' In pursuit of that purpose, it was never really made clear by Gesell whether it also implied a 'readiness for learning.'

A maturationist?

The truncated overview of Gesell's prodigious and diverse publications does not entirely justify his continuing categorization as a 'maturationist' who simply rendered an account of ontogenetic development within the restrictive confines of neural determinism. A careful reading of his more theoretically oriented publications (e.g., Gesell & Amatruda, 1945) should dispel the commonplace supposition that he held such a 'one-cause' theory of development. Gesell was a pioneering student of child development who had many 'firsts' to his name: the first to employ the co-twin method, the first to use one-way observation mirrors together with cinematography in recording infant and child behavior, and the first to employ these and other techniques to study systematically the development of sleep and wakefulness (and the transitions between them) in both preterm and fullterm infants. He was, however, not an experimenter (except perhaps within the context of his co-twin study) and thus left an incomplete theory of how brain and behavior co-develop. McGraw, in contrast, can be said to have gone further than Gesell in these respects.

McGraw the theoretician and experimenter

Reflexology and the cortical inhibition hypothesis

In a paper published in 1985, McGraw contends that she had never worked out her own theory of development (McGraw in Dalton & Bergenn, 1995a, pp. 57–64). If she did not have her own theory, then she certainly took guidance from those of Dewey and Coghill, and at least one of the tenets of reflexology, in formulating the theoretical underpinnings of her broadly based program of research.

While the doctrine of reflexology was evident in how she interpreted her findings, McGraw was selective in her use of it. She never accepted that newborn behavior amounted to just a bundle of reflexes (or a 'mid-brain preparation') that were somehow activated and chained together by the grace of external stimulation. Rather, it was predicated in the first instance on a spontaneously active brain.

What she did extract from reflexology was the cortical inhibition hypothesis. In the Introduction to the 1962 edition of McGraw (1943), she expressed regret at having given prominence to this hypothesis as providing an explanation for what she saw as a change from sub-cortical to cortical mediation of behavior occurring around 2–3 months after birth. It is recognized, also in her time, that cortical activity is both inhibitory and excitatory. Moreover, the hypothesis has been refuted by both animal and human developmental studies and in particular by the fact that movements in near-term anencephalic fetuses are qualitatively different from those of their healthy counterparts. Nevertheless, it still lingers on as an explanatory construct in some quarters of developmental psychology.

A reductionist?

Some recent evaluations of McGraw's published work have led to the assertion that it bears the badge of a reductionist in the sense that she claimed that behavioral development was prescribed by changes in the brain. In the same breath, she is portrayed as being more of a 'maturationist' than Gesell. Her writings speak firmly against such an adumbration. Take, for example, the following conclusion about the nature of development in McGraw (1946): ". . . it probably is the interrelationship of a multitude of factors which determines the course of behavior development at any one time" (p. 369). As another example, consider this comment from her *Psychological Review* paper published in 1940:

> In studying the development of reaching-prehensile behavior of the infant, for example, the object in the field of vision is just as much an integral part in the organization of the behavior as are the arms, fingers and eyes of the baby . . . One manipulates arms and fingers quite differently when picking up a bowl a water from the way one does when trying to catch a fly. In that the object determines the configuration of neuromuscular movements, and as such might be considered an "organizer" of behavior.
>
> (McGraw in Dalton & Bergenn, 1995a, p. 218)

Does this sound familiar? It should do as it conveys the essence of organism-environment mutualism that is the foundation of J. J. Gibson's affordance concept.

Structure and function

On the issue of structure-function relationships during development, McGraw was more explicit than Gesell. For example, in McGraw (1946), she writes:

> It seems fairly evident that certain structural changes take place prior to the onset of overt function; it seems equally evident that cessation of neurostructural development does not coincide with the onset of function. There is every reason to believe that when conditions are favorable function makes some contribution to further advancement in the structural development of the nervous system . . . Obviously, rigid demarcation between structure and function as two distinct processes of development is not possible. The two are interrelated, and at one time one aspect may have greater weight than the other.
>
> (p. 369)

Similar commitments to a bidirectional model of development are dispersed throughout both her books (McGraw, 1935; 1943).

Based on her studies concerned with the development of locomotion, McGraw (1943) went beyond Gesell in acknowledging that structure-function relationships emerged from ongoing interactions between the central nervous system (CNS) and the energy-converting musculoskeletal system (MSS). In McGraw's case, the MSS was the interface between the CNS and the infant's external environment (Fig. 8), an insight commonly accredited to Nikolai A. Bernstein (1896–1966).

Just motor development?

Beyond Bernstein, connections to Piaget's theory of development are also to be found in her publications. McGraw (1935), in her co-twin study, regarded the attainment of dynamical balance not only as a necessary condition for persistent bipedal locomotion to be achieved, but also as contributing to the development of problem-solving abilities and thereby to the promotion of consciousness. This was another example of McGraw putting Dewey's theory of development to the test. To do so, her famous twins Johnny (with practice) and Jimmy (without practice) Woods had to resolve balance problems in, for example, roller skating before they could walk habitually, climbing up inclines at various angles, and demounting from pedestals of different heights. Her ingenuity in devising such age-appropriate manipulations matches that of Piaget. Both still stand as exemplars in their attempts to link theory with apposite methods in studying development through presenting infants with challenges on the cusp of their current abilities. Allowing them to discover their own solutions when challenged in this way complies with Piaget's assertion that the resolution of conflict is a motivating force in generating development.

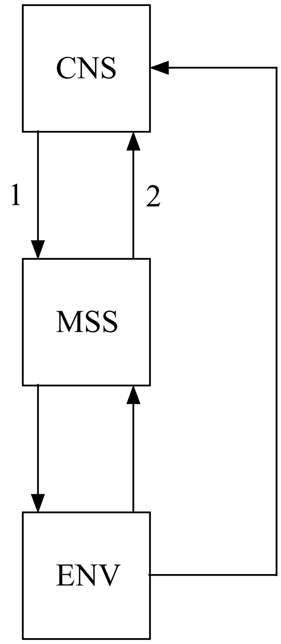

Figure 8. The central nervous system (CNS) interacts with the musculoskeletal system (MSS) throughout development. Moreover, the latter functions as the interface with the external environment (ENV), with which it also interacts. In a very simplified way, this figure illustrates some of the features of Bernstein's (1967) approach to resolving issues about motor control and coordination which he applied to the development of upright walking in infants. McGraw (1943) also treated motor development, and specifically locomotion, as consisting of bidirectional influences between the CNS and the MSS, and between the MSS and the ENV. The arrow labeled (1) signifies the common interpretation imposed on neuromaturational theories (structure → function), which therefore can be seen as omitting the many interactions between intrinsic and extrinsic factors considered by McGraw. The one labeled (2) refers to an interesting proposal by Bernstein (1967) that has implications for understanding (motor) development, which he communicates as follows: ". . . the reorganization of the movement begins with its biomechanics . . . ; this biomechanical reorganization sets up new problems for the central nervous system, to which it gradually adapts" (pp. 87–89). Thus, according to this rather radical viewpoint, developmental transformations occur not just because the brain changes, but rather the opposite, namely, there are changes in the biomechanical properties of the body segments (i.e., the MSS) to which the developing brain adjusts.

Gesell and McGraw: similarities and differences

There are similarities, but even more so differences, between Gesell and McGraw in terms of the theoretical assumptions and associated methods they assimilated into their research programs. Some similarities have been mentioned previously. Others that stand out are:

1. Reciprocal interweaving: McGraw, like Gesell, envisaged development to consist of alternating and overlapping phases, which resulted in both progression and regression. It seems to be the case

that McGraw (1935) used weaving as a metaphor to capture the non-linearity of development some four years before Gesell introduced into the literature his related principles of reciprocal interweaving and spiral reincorporation (Dalton in Dalton & Bergenn, 1995a, pp. 134–135).

2. The role of movement: for both Gesell and McGraw, movement was a 'final common pathway' for the enhancement of all aspects of development (e.g., cognitive, social, emotional, etc.). While Gesell (& Thompson, 1934) alluded to movement as an essential ingredient in the development of exploration (or what he considered to be movement-generated 'sensory experience'), he also included posture in this context. He went so far as to say that "Posture is behavior," by which he meant ". . . the position of the body as a whole or by its members, in order to execute a movement or to maintain an attitude" (Gesell & Amatruda, 1945, p. 46). In Gesell's view, the asymmetrical tonic neck (ATN) posture, or what he termed "This new visual postural visual-manual-prehensory pattern" (Gesell & Amatruda, 1945, p. 458), exerted a formative influence on the development of handedness. This conjecture brings us to the first of the differences between Gesell and McGraw.

1. Antecedent-consequence relationships: a consistent theme in Gesell's writings is that mature expressions of behavior can be observed in incomplete forms earlier in development, with both being part of the same developmental sequence. His Developmental Schedules reflect this point of view. McGraw did not share such an ontogenetic scenario. This is exemplified in her interpretation of the ATN posture: it was not an antecedent condition for the acquisition of a hand preference, but instead forms part of an age-appropriate righting response that later becomes incorporated into prone locomotion (Dalton in Dalton & Bergenn, 1995a, p. 144). While neither of them referred to ontogenetic adaptations as such, it is clear McGraw envisaged development as being more of a discontinuous process than Gesell.
2. Heterochrony: during development, there are differential rates in the timing with which new structures and functions appear (i.e., the accelerated development of particular brain areas and behaviors relative to others). While Gesell and McGraw depicted development as essentially heterochronic in nature, they differed in this regard on one important aspect based on the findings of their respective co-twin studies. According to McGraw, but not Gesell, early experiences could affect heterochronicity between functions in the sense of accelerating slower developing components (or what she labelled as 'ontogenetic skills' as opposed to 'phylogenetic skills').
3. Intra-individual differences: inter-individual differences in intra-individual change, to use a somewhat clumsy formulation, should be the overriding concern in studying ontogenetic development. Only possible to address with a longitudinal design, it tends to be neglected in research on child development. Such was not the case with McGraw and her attention to tracking change within individual infants is considered to have been a key feature of her research (Touwen in Dalton & Bergenn, 1995a, pp. 271–283). Together with her co-workers, she devised a number of analytical techniques for detecting differences in developmental trajectories between infants (McGraw, 1943). Gesell, on the other hand, gave little regard to intra-individual change and at most considered it to be an indication of deviant development (i.e., 'deviant' in not complying with the sequential age-related norms in his Development Schedules). Drawing on the distinction between population and typological thinking, McGraw was representative of the former and Gesell of the latter.
4. Chronological age: in keeping with Baldwin and Piaget, McGraw was not particularly concerned with mapping the development of various abilities as a function of chronological age (McGraw in Dalton & Bergenn, 1995a, p. 60). Instead, she was more interested in the 'how' and 'why' rather than the 'when' of developmental achievements. To say that Gesell did not address all three questions would be to do him a disservice. As Gesell the theoretician, he did so, but as his program of research progressed the questions of 'how' and 'why' tended to become subordinated by Gesell the tester to a focus on the modal chronological ages at which particular abilities were attained. Unfortunately, that is what he is chiefly remembered for in the developmental literature despite the fact he distinguished astronomical (i.e., chronological) time from biological (i.e., developmental) time in the following way: "Astronomical time is rigid, neutral, two-way, reversible. Biological time is elastic, cyclical, one-way, irreversible" (Gesell & Amatruda, 1945, p. 16). His observations on preterm infants, never studied by McGraw, reveal an attempt to reconcile these two time scales, and he was one of the first to assert the importance of using corrected age when evaluating their postterm development. In his more popular writings aimed chiefly at parents, Gesell the tester really comes to the fore. Here, parents are confronted with age-encapsulated caricatures of children (e.g., the assentive and conforming three-year-old as

against the assertive, lively four-year-old). Such an example of typological thinking was completely absent from McGraw's publications.

There are many other points of departure that can be discerned when comparing the published work of Gesell and McGraw (e.g., McGraw's attempts to apply mathematical modeling to her data as outlined in Fig. 4 for one of her studies). However, it should be clear that their approaches to the study of ontogenetic development were so divergent as to leave us wondering why they are still lumped together under the rubric 'neuromaturational theories.'

Conclusions

If unbridled genetic determinism defines the essence of neuromaturational theories of development and Gesell and McGraw are taken to be their standard-bearers, then we continue to labor under false pretences. Neither of them held to such a reductionistic and monocausal view of development. Their theoretical formulations were much more subtle than this and still bear insights that resonate with current dynamical systems approaches to development. Recognition that development is a self-organizing phenomenon, and intimations that there is a circular causality between perception and action, are readily apparent in both their writings. If the label 'neuromaturationist' does in any way seem to be appropriate, then perhaps it is more applicable to Gesell when defending his theory against attacks from the radical behaviorists. Outside this context, both he and McGraw strove to find the middle ground in the maturation versus learning debate of the time.

With the foundation of experimental embryology in the late 19th century by Wilhelm Roux (1850–1924), the bidirectionality of the relationship between structure and function during development became an undisputed maxim (at least among the embryologists). In drawing theoretical inspiration from such a source, both Gesell and McGraw transported this dictum into the realm of postnatal behavioral development. All of this suggests that at least by the end of the 19th century, there was no such thing any more that complied with a radical neuromaturational theory. The irony is that now in fact we have such theoretical radicalism as contained, for example, in theories of innate knowledge and language acquisition as well as those addressing the role of the prefrontal cortex in the development of executive functions. At the same time, Gesell and McGraw continue to be castigated as representatives of an overly simplistic maturational stance on the mechanism of development.

In conclusion, it is long overdue that Gesell and McGraw should no longer be classified as 'neuromaturationists.' More germane would be something like 'developmental psychobiologists,' while at the same time acknowledging important differences between them in how they endeavored to describe and explain ontogenetic development. The last word is perhaps best given to Myrtle McGraw, the consummate developmentalist:

> In the present state of knowledge a more profitable approach lies in the systematic determination of the changing interrelationships between the various aspects of a growing phenomenon. It has been suggested that relative rates of growth may afford a common symbolic means by which the underlying principles of development may be formulated. Once the laws of development have been determined the maturation concept may fade into insignificance.
>
> (McGraw, 1946, p. 369)

If only . . .

See also:
The concept of development: historical perspectives; Understanding ontogenetic development: debates about the nature of the epigenetic process; Learning theories; Dynamical systems approaches; Developmental testing; Cross-sectional and longitudinal designs; Twin and adoption studies; Conceptions and misconceptions about embryonic development; Motor development; Brain and behavioral development (I): sub-cortical; Brain and behavioral development (II): cortical; Executive functions; Handedness; Locomotion; Prehension; Sleep and wakefulness; Prematurity and low birthweight; Behavioral embryology; Cognitive neuroscience; Developmental genetics; Pediatrics; James Mark Baldwin; George E. Coghill; Viktor Hamburger; Jean Piaget; Milestones of motor development and indicators of biological maturity

Further reading

Ames, L. B. (1989). *Arnold Gesell: Themes of his Work*. New York: Human Sciences Library.
Dalton, T. C. and Bergenn, V. W. (eds.) (1995). *Reconsidering Myrtle McGraw's Contribution to Developmental Psychology*. Special Issue *Developmental Review*, 18, 472–503.
Thelen, E. and Adolph, K. E. (1992). Arnold L. Gesell: The paradox of nature and nurture. *Developmental Psychology*, 28, 368–380.

Constructivist theories

MICHAEL F. MASCOLO AND KURT W. FISCHER

Introduction

Constructivism is the philosophical and scientific position that knowledge arises through a process of active construction. From this view, knowledge structures are neither innate properties of the mind nor are they passively transmitted to individuals by experience. In this entry, we outline recent advances in constructivist models of cognitive development, beginning by analyzing the origins of constructivist developmental theory in the seminal writings of Piaget. We then examine the ways in which theoretical and empirical challenges to his theory have resulted in the elaboration of a more powerful constructivism in the form of neo-Piagetian and systems models of human development.

Piagetian foundations of constructivist theory

Piaget's theory of cognitive development is simultaneously a structuralist and constructivist theory. For Piaget, psychological structures are constructed in development. The basic unit of cognitive analysis is the psychological structure, which is an organized system of action or thought. All psychological activities are organized, whether they consist of a 6-month-old's reach for a rattle, an 8-year-old's logical solution to a conservation problem, or a 15-year-old's systematic manipulation of variables in a science experiment.

Psychological structures, or schemes, operate through the dual processes of assimilation and accommodation. Piaget appropriated these notions from the prior work of James Mark Baldwin. Drawn from the biological metaphor of digestion, assimilation refers to the process by which objects are broken down and incorporated into existing structures, while accommodation reflects complementary processes of modifying or adapting an existing structure to accept or incorporate an object. Any psychological act requires the assimilation of an object into an existing structure and the simultaneous accommodation of that structure to the incorporated object. For example, to perform the sensorimotor act of grasping a rattle, an infant incorporates (assimilates) the rattle into her grasping scheme. However, to grasp the rattle, the infant must modify her scheme to the particular contours of the incorporated object.

Piaget maintained that psychological structures undergo successive transformations over time in a series of four stages. Within his theory, stages exhibit several important properties. Firstly, each stage corresponds to a particular type or quality of thinking or psychological organization. From this view, infants are not simply small adults – they think in fundamentally different ways from older children and adults. Secondly, the stages form a hierarchical progression with later stages building upon earlier ones. Thirdly, the stages form a single, universal, and unidirectional sequence. Regardless of the culture in which a child resides, thinking develops in stages toward the common endpoint of formal operations. Fourthly, Piagetian stages form *structures d'ensemble* (i.e., 'structures of the whole'). Piaget's position on the organization of thinking within stages was complex. On the one hand, the concept of stage implies homogeneity of organization. Within a given stage, Piaget held that schemes are general and have wide application to broad ranges of cognitive tasks. On the other hand, he also invoked the concept of *décalage* – the idea that cognitive abilities within a stage develop at different times. Despite such *décalage*, Piaget held that as children resolve the conflicts that exist between cognitive sub-systems, psychological structures develop into increasingly broad and integrated wholes.

According to Piaget, for the first two years of life, infant schemes function within the sensorimotor stage of development. Sensorimotor schemes consist of organized systems of action on objects. Piaget held that infants cannot form representations (images) of events in the absence of direct sensory input. As such, sensorimotor schemes reflect integrations of the sensory and motor aspects of action. Thinking emerges between 18 and 24 months of age with the onset of the semiotic function during the pre-operational stage of development. During this stage, children are capable of forming representations of events (e.g., words, images), but are incapable of manipulating these images in logical or systematic ways. Pre-operational intelligence is marked by the emergence of symbolic play, deferred imitation, and the use of words to refer to present and absent objects. During the concrete operational stage, thinking becomes systematic and logical. Children are able to operate logically on concrete representations of events. The capacity for concrete operations underlies a child's ability to perform various logical tasks, including conservation, class inclusion, seriation, transitivity judgments, etc. It is not until the formal operational stage (adolescence onward) that individuals are able to free their logical thinking from concrete content. In formal operations, adolescents become capable of operating using abstract forms. In so doing, thinking becomes abstract, and adolescents and adults can conceptualize hypothetical and systematic solutions to logical, mathematical, and scientific problems.

The concept of equilibration provides the backbone of Piaget's constructivist theory of development. Equilibration refers to an inherent, self-regulating, compensatory process that balances assimilation and accommodation and prompts stage transition. Piaget elaborated upon several forms of equilibration. The first involves the detection of a conflict or discrepancy between an existing scheme and a novel object. He held that a state of equilibrium results when an object is successfully incorporated into a given scheme, and thus when assimilation and accommodation are in a state of balance. A state of disequilibrium results when there is a failure to incorporate an object into a given scheme. A child who only has schemes for cats and dogs will have little difficulty identifying common instances of these two classes, but his schemes would be in disequilibrium when first encountering a rabbit. Disequilibrium, in turn, motivates successive acts of accommodation that result in a significant modification of the existing schemes. A new scheme thus emerges from the failure of existing schemes. Where there were initially only schemes for cats and dogs, there are now schemes for cats, dogs, and bunnies.

Piaget discussed additional forms of equilibration, which involve the resolution of conflict between two competing cognitive schemes (e.g., when conservation of length and conservation of number come into conflict), and between individual schemes and the larger systems of which they are a part (e.g., integrating conservation of length, number, and mass into an abstract understanding of conservation). Piaget also acknowledged other processes that contribute to development. For example, in order for a stage transition to occur, there must be a requisite level of neurological maturation; a child must actively experience the world by acting on objects and people; a child must receive cultural knowledge in the form of socially transmitted and linguistically mediated rule systems (e.g., mathematics, science). Nonetheless, disequilibrium engendered by cognitive conflict provides the driving force of development.

Questions about Piaget's structuralism

Table 1 describes five basic problems and criticisms that emerged with regard to central principles in Piaget's theory of development. The first four critiques concern the Piagetian notion of cognitive structure or stage. Each critique is a variant on the idea that there exists more variability in children's cognitive functioning than would be predicted by a strong notion of stage. Research has indicated that the developmental level of even a single child's cognitive actions can change with variations in the level of contextual support provided to the child, the specific nature of the task, the conceptual domain in which the task occurs, and the child's emotional disposition. For example, Western European and North American children generally conserve number by 6–7 years of age, mass by 8 years, and weight by 10 years, but generally do not solve tasks about inclusion of sub-classes within classes until 9 or 10 years of age.

Research also suggests that providing training and contextual support for concrete operational tasks lowers the age at which children succeed in performing such tasks. For example, Peter Bryant and Thomas Trabasso demonstrated that providing young children with memory training (e.g., having them memorize which of each pair of adjacent sticks was larger or smaller) lowered the age at which they were able to perform a transitivity task, determining which stick in a pair is larger by inferring from comparisons of other pairs of sticks. Studies like these challenge the idea that children's thinking develops in broadly integrated and homogeneous structures (i.e., stages). Instead, they suggest that thinking is organized in terms of partially independent cognitive skills that develop along different pathways. Researchers have also criticized Piagetian concepts such as equilibration, assimilation, and accommodation as difficult to translate into clear and testable hypotheses. Finally, others have noted that Piaget did not pay enough attention to the ways in which social processes contribute to development. This last issue requires additional elaboration.

Table 1. Moving toward the new constructivism.

Piagetian construct	*Source of problem*	*Analysis of developing skills*
Structural principles		
I. Inner *competence* as property of individual child. Individual *cognitive structures* function as basic units of cognitive activity. Cognitive structures are seen as properties of individual children.	**Social context and affective state play a direct role in modulating level of functioning**. Evidence suggests that performance on similar tasks in the same children vary dramatically with changes in contextual support and affective state.	**Skill as property of individual in social context**. Skills reflect actions performed on physical and social objects in particular social contexts. Child and social context collaborate in the joint construction of skills.
II. Limited number of broad stages. Piaget postulated four broad stages of cognitive development with a series of sub-stages.	**Variability in performances as a result of task complexity**. Differences in the complexity of tasks used to test children's stage acquisition produce different assessments of operative ability.	**Precise developmental yardsticks**. Skill analyses allow both broad and fine-grained analysis of development across a total of thirteen *levels* with a large number of smaller *steps* between levels.
III. Stage as *structure d'ensemble*. Piaget held that cognitive structures entail broad abilities having wide application to multiple tasks.	***Décalage***. Uneveness in the development of skills is the rule rather than the exception in ontogenesis, even for abilities presumed to be at the same developmental level.	**Skills develop within particular tasks, domains, and social contexts**. Rejecting the notion of globally consistent stages, skill analyses assess skill development within particular conceptual domains, tasks, and social contexts.
IV. Development as unidirectional ladder. Piaget proposed a unidirectional model of stage progression in which cognitive capacities in all cultures follow the same abstract progression of stages.	**Varied sequences of development**. Evidence suggests variation in developmental sequence in different children, tasks, and cultures, as well as failures to observe predicted Piagetian sequences.	**Development as multidirectional web**. Different skills develop along different trajectories for different *tasks*, *domains*, *persons*, *contexts*, and *cultures*. As such, development proceeds as a web of trajectories rather than as a ladder of fixed or universal steps.
Process principles		
V. Individual action as primary source of developmental change. Piaget viewed cognitive *disequilibria* as the primary mover of development, suggesting a central role for the individual child as the main mover of development.	**Limited focus on social, cultural, biological, and emotional organizers of developmental change**. Evidence suggests that social interaction, language, culture, genetics, and emotion play important roles in the constitution of psychological structures.	**Developmental change occurs as a product of *relations between* biological, psychological, and sociocultural processes**. Biological, psychological, social, and cultural processes necessarily coact in the formation of novel psychological structures.

Sociocultural challenges to the primacy of individual action

Piagetian constructivism relies heavily, but not exclusively, on the notion that children's own actions are primary movers of development (equilibration). According to Piaget, thinking emerges in the pre-operational stage as children abbreviate and internalize sensorimotor actions to form mental images (inner abbreviated action). Constructing an image of one's mother involves the abbreviated and internal reconstruction of actions that one performs when one actually looks at one's mother. Thus, thinking becomes a matter of internally manipulating images that have their origins in the actions of individual children.

Sociocultural psychologists, especially those inspired by Vygotsky, noted that Piaget's constructivism neglected the role of social interaction, language, and culture in development. From a Vygotskian perspective, children are not solitary actors. They work with adults and peers in the creation of any higher-order developmental process. In social interaction, partners direct each other's actions and thoughts using language and signs. Signs function as important vehicles of enculturation. Unlike symbol systems, such as mental images or pictures, signs are used to represent relatively arbitrary meanings that are shared within a linguistic community. For example, understanding the meaning of words such as 'good' or 'democracy' involves learning a relatively arbitrary cultural meaning that is shared and understood among individuals who comprehend a certain language, such as English. Vygotsky maintained that all higher-order psychological processes are mediated by signs. Development of higher-order mental functions occurs as children internalize the results of sign-mediated interactions that they have with others. As children come to use signs to mediate their thinking, they think in culturally not merely personally organized ways.

In his explanation of the social origins of higher-order functions, Vygotsky (1978) invoked his general genetic law of cultural development: "Any function in children's cultural development occurs twice, or on two planes. First, it appears on the social plane and then on the psychological plane. First it appears between people as an interpsychological category and then within the individual child as an intrapsychological category" (p. 57). The concept of internalization explains how sign-mediated activity that initially occurs between people comes to be produced within individuals in development. For example, to help his 6-year-old remember where she put her soccer ball, a father may ask, "Where did you last play with it?" In so doing, the father and daughter use signs to regulate the mental retracing of the girl's actions. As the girl internalizes these sign-mediated interactions, she acquires a higher-order memory strategy – 'retracing one's steps.'

This vignette illustrates the Vygotskian principle of the zone of proximal development (ZPD). The ZPD refers to the distance between a child's level of functioning when working alone and her developmental level working with a more accomplished individual. In the above example, the father's questions raise his child's remembering to a level beyond that which she can sustain alone. The child's remembering strategy is formed as she internalizes the verbal strategy that originated in joint action. In this way, the research spawned by sociocultural theory challenges the primacy of children's individual actions as main movers of development.

Reinventing constructivist theory: trajectories of skill development

In what follows, we will elaborate the major tenets of dynamic skill theory, a neo-Piagetian constructivist theory of psychological development. We describe how skill development can explain cognitive development and address key challenges to Piaget's theory elaborated in Table 1. Rather than speaking of broad logico-mathematical competences, according to dynamic skill theory the main unit of acting and thinking is the developing skill.

The concept of skill

The concept of skill provides a useful way to think about psychological structures. A skill refers to an individual's capacity to control her behavior, thinking, and feeling within specified contexts and within particular task domains. As such, a skill is a type of control structure. It refers to the organization of action that an individual can bring under her own control within a given context. The concept of skill differs from the Piagetian notion of scheme or cognitive structure in several important ways. To begin with, a skill is not simply an attribute of an individual; instead, it is a property of an individual-in-a-context. The production of any instance of skilled action is a joint product of person and context (physical and social). As such, a change in the context in which a given act is performed can result in changes in the form and developmental level of the skill in question. In this way, context plays a direct role in the construction of skilled activity.

Contexts differ in the extent to which they support an individual's attempt to produce skilled activity. Contexts involving high support provide assistance that supports an individual's actions (e.g., modeling desired behavior; providing cues, prompts, or questions that prompt key components to help structure children's actions). Contexts involving low support provide no such assistance. Level of contextual support contributes directly to the level of performance a person is able to sustain in deploying a given skill. A person's optimal level refers to the highest level of performance one is capable of achieving, usually in contexts offering high support. A person's functional level consists of his or her everyday level of functioning in low support contexts. In general, a person's optimal level of performance under conditions of high support is several steps higher than his functional level in low support contexts.

Figure 1 depicts developmental variation in a child's story telling in a variety of high and low support conditions. In the context of elicited imitation, a child is asked to imitate a complex story modeled by an adult. In elicited imitation, the child's story functions at a level that is several steps higher than when he or she tells stories in free play, or is asked to tell his or her best story – both conditions of low support. Minutes later, when an adult prompts the child by stating the key components of the story, the child again functions at optimal level. Then after a few more minutes low support conditions result in reduction of the child's performance to functional level again. These fluctuations in skill level occur in the same child on the

Step	Performance Level	Social Support
1		
2		
3	Functional level	None
4		
5		
6	Optimal level	Priming through modeling, etc.
7		
8	Scaffolded level	Direct participation by adult
9		

Figure 1. Variation in skill level for stories as a function of social-contextual support. In the high-support assessments, the interviewer either modeled a story to a child (elicited imitation) or described the gist of a story and provided cues (prompt); the child then acted out the story. In low support assessments, the interviewer provided no such support but either asked for the child's best story or simply observed story telling in free play.

same task across varying conditions of contextual support separated by mere minutes.

Contexts involving high and low support differ from contexts involving scaffolded support. In contexts involving high or low support, the child alone is responsible for coordinating the elements of a given skill. For example, an adult may model a complex story for a child who then produces the story without further assistance. In scaffolded contexts, an adult assists the child by performing part of the task or otherwise structures the child's actions during the course of skill deployment. Scaffolding allows adult-child dyads to function at levels that surpass a child's optimal level. When a mother helps her 6-year-old tell a story by intermittently providing story parts and asking the child leading questions, the dyad can produce a more complex story than the child could tell alone, even with high support. As a result of contextual support and scaffolding, children do not function at a single developmental level in any given skilled activity. Instead, they function within a developmental range of possible skill levels.

A second way in which the concept of skill departs from Piagetian theory is that skills are not general structures. There are no general, de-contextualized, or all-purpose skills. Skills are tied to specific tasks and task domains. Skills in different conceptual domains (e.g., conservation, classification, reading words, social interaction, etc.) develop relatively independently of each other at different rates and toward different developmental endpoints. Assessments of the developmental level of one skill in one conceptual domain (e.g., conservation) will not necessarily predict the developmental level of skills in a different domain (e.g., classification), or even in conceptually similar tasks (conservation of number versus conservation of volume). One can chart developmental sequences only for skills within a given domain and within particular social contexts and assessment conditions.

Levels of skill development

Skills develop through the hierarchical coordination of lower level action systems into higher-order structures. Table 2 presents the levels of hierarchical organization of a developing skill based on Fischer's dynamic skill theory (Fischer, 1980; Fischer & Bidell, 1998). In this model, skills develop through four broad tiers: reflexes refer to innate action elements (e.g., sucking; closing fingers around an object placed in the hand); sensorimotor actions refer to smoothly controlled actions on objects (e.g., reaching for an object); representations consist of symbolic meanings about concrete aspects of objects, events, and persons (e.g., "Mommy eat candy"); abstractions consist of higher-order representations about intangible and generalized aspects of objects and events (e.g., "Conservation refers to no change in the quantity of something despite a change in its appearance"). Within each broad tier, skills develop through four levels. A single set refers to a single organized reflex, action, representation or abstraction. Mappings refer to coordinations between two or more single sets, whereas systems consist of coordinations of two or more mappings. A system of systems reflects the intercoordination of at least two systems and constitutes the first level of the next broad tier of skills. For example, a *system* of sensorimotor systems constitutes a single representational set.

In this way, dynamic skill theory specifies four broad qualitatively distinct tiers of development comprising a total of thirteen specific levels. It also provides a set of tools for identifying a variable number of steps between any two developmental levels. These levels have been documented in scores of studies in a variety of different developmental domains. In the following sub-sections, we illustrate dynamics of skill development through an analysis of how sample skills move through the levels and tiers specified in Table 2.

Development in infancy

Here, we examine the development of visually guided reaching as an example of skill development. Like all skills, reaching does not emerge at any single point in time. Instead, like all skills, it develops gradually over the course of infancy and takes a series of different forms over time. In addition, at any given point in development, an infant's capacity to reach for seen objects varies dramatically depending upon the task at hand, the