INTRODUCTION

Study of child development: an interdisciplinary enterprise

BRIAN HOPKINS

Introduction

A short distance from London's Piccadilly Circus is Albermarle Street. Walk along the street, and you will come face to face with an elegant colonnaded building that since 1815 has housed the Royal Institution (RI) of Great Britain (founded in 1799). On February 27, 1874, it played host to the weekly evening meeting chaired on this occasion by George Busk, treasurer and vice-president of the RI, and former naval surgeon and zoologist of some repute. Sporting an impressive 'chinstrap' (the hipster facial attire of the day), he introduced the speaker with an equally striking set of 'sideburns' (we will have reason to return to the topic of beards later). The speaker? One Francis Galton (1822–1911), an archetypal Victorian polymath, who had celebrated his birthday two weeks previously.

On that winter's evening, Darwin's half-cousin delivered a talk entitled "On men of science, their nature and their nurture." With a telling adjectival addition, it formed the basis of his book *English men of science: Their nature and nurture* (1874). Together, the talk and the widely read book constituted the first scientific articulation of the nature–nurture issue, a catchphrase or 'convenient jingle' that then proceeded to swing like a wrecking ball through the study of human development for decades to come. This persistent but misguided dichotomy gave birth to an unending debate that still resonates today, especially but not only in sections of the popular press. Thus, we are confronted with media hype about 'the gene for' creativity or some complex developmental or psychiatric disorder, and even 'free will.' Its vacuity was perhaps best captured by Donald Hebb (1904–1985) in his curt reply to a journalist who asked what contributed more to personality, nature or nurture? His response: "Which contributes more to the area of a rectangle, its length or its width?"

So how do we escape the dead hand of the nature–nurture debate? According to some, escape is through embracing the notion of epigenetics. In short, there are two cardinal features of an epigenetic view of development. First, genes influence virtually all behavior, but virtually no behavior is determined by them. Second, the environment is instructive and the genotype permissive. In some quarters, this view has been referred to as 'epigenetic interactionism,' which has some similarities with what Gilbert Gottlieb (1929–2002) called 'probabilistic epigenesis.' The term 'epigenetics' has assumed an almost iconic status in contemporary attempts to capture the essence of development. As a consequence, it has been become a bit of an unquestioned buzzword such that its meaning has become open to misinterpretation.

In what follows, we will delve further into present-day rendering of what constitutes ontogenetic development and what it means to pursue an interdisciplinary endeavor. But first, the tale of the chess-playing Turk, a tale that could help to promote our understanding of development through raising a couple of obdurate problems that refuse to go away.

The Turk

In 1770, Wolfgang Farkas von Kempelen (1734–1804) wheeled a wooden cabinet on brass casters into the stateroom of the Habsburg court at the Schöbrunn palace in Vienna. Commissioned by Empress Maria Theresa, it was a chess-playing automaton consisting of a life-sized black-bearded head with a turban, a torso clad in robes, and seated behind a chessboard. The Turk defeated the Empress in chess, and for the next 80 or so years toured Europe and the USA, where it successfully beat the likes of Catherine the Great, Fredrick the Great, Napoleon Bonaparte, Benjamin Franklin and Edgar Alan Poe, as well as Charles Babbage (reputedly inspiring him to invent the first computer), until it was destroyed by fire in Philadelphia in 1854. During his lifetime, von Kempelen never revealed how his automaton worked. Convincing attempts have been made to reconstruct the mechanisms that enabled The Turk to become such a proficient chess player (see Figure 1).

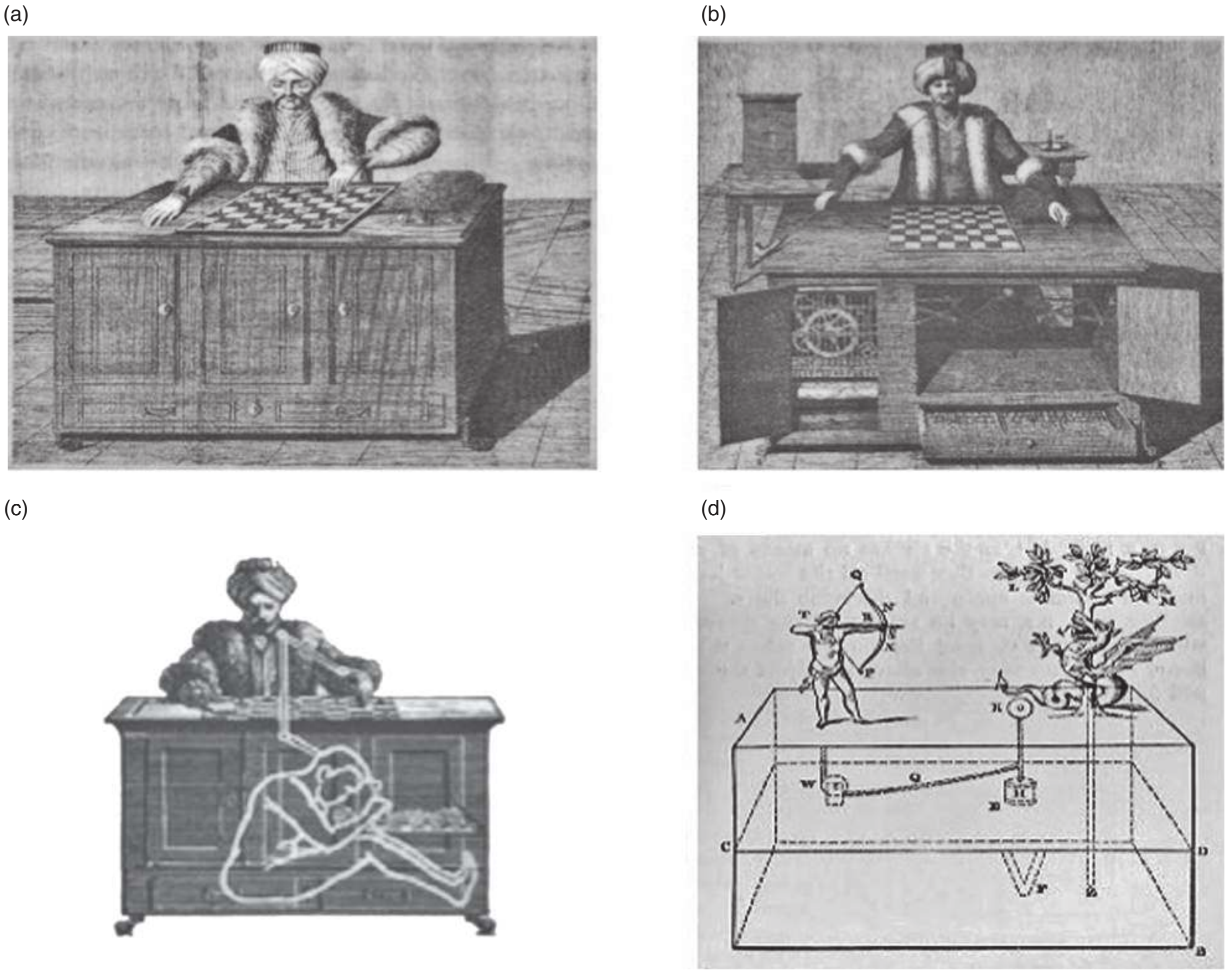


Figure 1. The Turk: chess player extraordinaire. a. A copper engraving of von Kempelen's chess-playing machine dating from 1784. b. Cabinet drawers opened to reveal the 'inner workings' of the machine that had no function other than to mislead onlookers. Drawers contained the chess pieces. c. A reconstruction of the machine's operator positioned on a seat that slid back to ensure concealment. As shown, when moved forward, the operator could grasp the pantogram in order to manipulate the reach-and-grasp movements of The Turk. A functioning model is on display in the Heinz Nixdorf Computer Museum in Paderborn in Germany. Originally, it was speculated that the operator was a legless Polish officer called Warousky, but as the Padeborn reconstruction reveals, the machine could accommodate a fully-grown adult. d. Predecessors and descendants of The Turk. Prior to von Kempelen, there were various attempts to construct automatons. Shown is one such example: hydraulically operated statue of Hercules shooting a dragon designed and built by Heron of Alexandria (10–70 AD). He had a sophisticated understanding of hydraulics, but as with other Greeks of the time, he did not take the step of relating hydraulics to human behavior. It was René Descartes (1596–1650) who took this step, and it was continued centuries later by Freud with his hydraulic model of the nervous system. During the eighteenth century, a craze for mechanical automatons like The Turk swept through Europe being mainly built for the entertainment of the wealthy. With the rise of artificial intelligence (AI) in the twentieth century, chess-playing computers became the vehicle for modeling the higher-level functions of the human mind. A major boost for the then flagging AI enterprise was when Deeper Blue defeated Gary Kasparov in 1997. More recently, a computer operated by the program AlphaGo defeated both the European and world champions of the Chinese board game of strategy named Go. It was a staggering achievement given the claim that the game has more potential moves than there are atoms in the universe. While it is another major breakthrough for AI, or what is now referred to as artificial general intelligence, the degrees-of-freedom problem has only been alluded to (or ignored), but not resolved, by such so-called intelligent agents when applied to the movements of robots.

Problem 1: degrees-of-freedom (not ones you learnt about in statistics)

What then are the 'telling tales' about The Turk and its predecessors and descendants that can be passed onto developmentalists? First, there is the degrees-of-freedom problem, a problem that AI and applications in robotics have yet to resolve satisfactorily in mimicking the fluency of human movements. To appreciate its connection with The Turk, mention needs to be made of the pantogram, an instrument used for scaling an image from a smaller to a larger one (Figure 2). According to

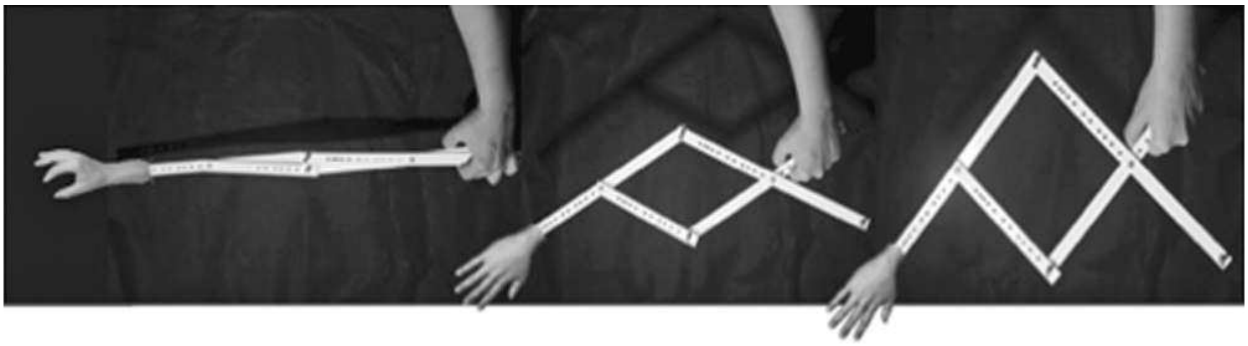
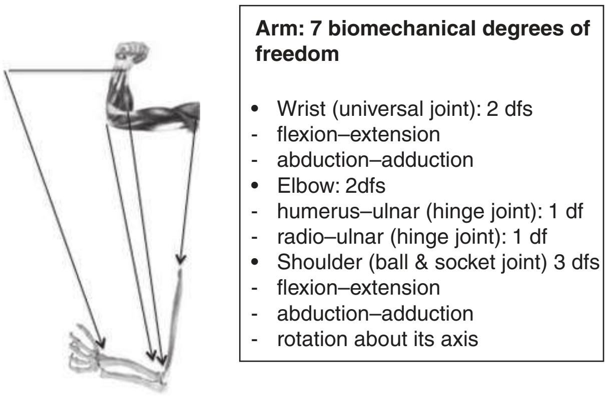


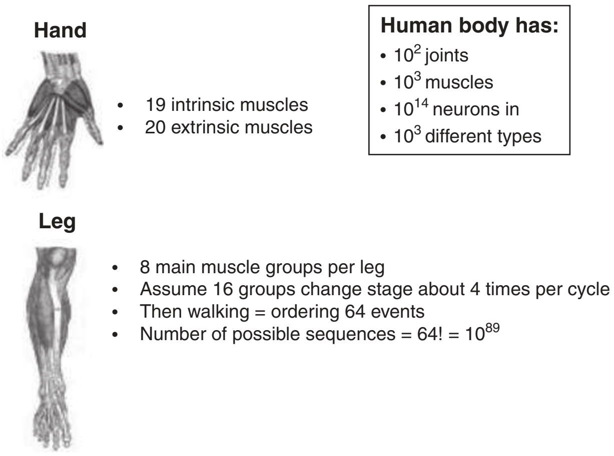
Figure 2. A simple pantogram. Assuming it is stabilized, one arm is grasped by an operator (right) and moved upward, the outcome of which resembles limb extension as in a reaching movement. Given the mechanical linkages between joints of the arm, only one needs to be activated to ensure an extension movement. In a rudimentary way, it depicts a way of resolving the degrees-of-freedom problem with couplings between joints functioning as a joint synergy. It is assumed that von Kempelen designed and used a more complex pantogram for the hidden operator to move the arm of the automaton. Photograph by Dave Gaskell.



Arm: 7 biomechanical degrees of freedom

- Wrist (universal joint): 2 dfs
- flexion–extension
- abduction–adduction
- Elbow: 2dfs
- humerus–ulnar (hinge joint): 1 df
- radio–ulnar (hinge joint): 1 df
- Shoulder (ball & socket joint) 3 dfs
- flexion–extension
- abduction–adduction
- rotation about its axis

Figure 3. Degrees-of-freedom problem applied to the joints of the arm. The problem, first raised by Bernstein (1967) with reference to the human musculoskeletal system (MSS), concerns how movements of joints that are free to vary are constrained in order to achieve the outcome of specific action (i.e., end state) in a variety of ways (i.e., motor equivalence). His solution was to propose that what the brain controls are functional, task-specific groupings of muscles spanning a number of joints (i.e., coordinative structures). It is estimated that the human adult MSS, with 148 movable bones connected by a variety of different types of joints, has 244 degrees-of-freedom.



Hand

- 19 intrinsic muscles
- 20 extrinsic muscles

Human body has:

- 10^2 joints
- 10^3 muscles
- 10^{14} neurons in
- 10^3 different types

Leg

- 8 main muscle groups per leg
- Assume 16 groups change stage about 4 times per cycle
- Then walking = ordering 64 events
- Number of possible sequences = $64! = 10^{89}$

Figure 4. The complexity of the degrees-of-freedom problem applied to joints pales into insignificance when one takes into account the musculature of effectors such as those of hands and legs, where there are more muscles than joints, and beyond joints and muscles to neurons.

reconstructions of von Kempelen's automaton, a more sophisticated version than depicted ensured that the human operator hidden in the cabinet could perform the reach-and-grasp movements required for picking and repositioning the chess pieces. It is a problem that straddles levels of organization from joints to muscles, and explodes at the neural level (Figures 3 & 4). It seems reasonable to assume that von Kempelen had in a sense found a resolution to the biomechanical degrees-of-freedom problem through the grace of a very competent chess-playing operator controlling the arm movements with a pantogram.

From a developmental standpoint, the problem is exacerbated by morphological changes, especially during early infancy. Such changes involve not only modifications in body proportions (biologically induced 'shape shifting') but also successive task-based reorganizations of the musculoskeletal system (e.g., with the change from standing to walking). It is interesting to note that the problem of dealing with an excess of biomechanical degrees-of-freedom is in part aided by the fact that humans are born with more than 300 bones, which during growth become selectively fused to form about 200 bones. All told, the degrees-of-freedom problem has been largely ignored in mainstream developmental psychology. A concerted effort to tackle it will enable us to gain valuable insights into how morphological constraints and overcoming them fashion changes in exploratory behavior, and thereby the

CAMBRIDGE
Cambridge University Press
978-1-107-10341-2 — The Cambridge Encyclopedia of Child Development
Edited by Brian Hopkins , Elena Geangu , Sally Linkenauger
Excerpt
More Information

acquisition of new abilities emerging from the increasing nexus between perception and action.

Problem 2: who or what controls what?

The next problem that von Kempelen's automaton with its hidden operator gives rise to is a deep-seated and long-standing philosophical issue: the homunculus problem and the associated problem of infinite regress (jokingly labeled "turtles all the way down," possibly by Bertrand Russell (1872–1970) among others). Mention of it can sometimes induce a state of boredom bordering on sleepwalking among some empirically focused psychologists (despite an implicit acceptance of aspects of a homunculus when assuming the brain is composed of psychological functions that are simply manifested when and where appropriate).

This particular conundrum has undergone an interminable voyage of invention and discovery in (neuro-) psychology that has unearthed a veritable treasure trove of candidate homunculi such as schemata, representations, motor programs, and central pattern generators. The problem is endemic to the information-processing approaches that derive from an a priori prescriptive formal automata theory, as well as to cognitivist theories (e.g., theories of vision allied to the notion of indirect perception such as those of Marr (2010) and Fodor (1983) on mental architecture). In a nutshell, the problem is who or what controls the controller, and who or what decides what information to use (often without according any clear meaning to information)? Ultimately, the source of control and decision-making regresses back into yet another one, *ad infinitum*.

For some, the homunculus problem is not insurmountable. Take, for example, the working memory model of Baddeley (1998), in which he identifies the homunculus as being the central executive. His solution is to gradually fractionate the central executive into subsystems and then explain and take away their functions. When the 'pulling apart' process has been fully achieved, the homunculus can be retired. How you achieve this and what is left following retirement is left unclear. Dennett (1991), for his part, proposes a similar scenario: Start with specialist homunculi (think mental modules) and gradually break them down into increasingly simpler functional units, or what he calls 'stupid functionaries,' things so simple you could replace each one with a neuron. In this way, a finite regress is achieved, but how an executive 'committee' of stupid functionaries can manufacture and control complex functions remains something of an enigma. A more thoroughgoing criticism of Dennett's solution can be found in Tallis (2011), who extends it to other 'neuromaniacs' and in particular to those who embrace the theoretical underpinnings of mirror neurons, which he contends fall victim to the fractionated homunculi exposition offered by Baddeley (1998).

How then do we dispel homunculi, these 'ghosts in the machine' and the associated problem of infinite regress? One alternative prospect put forward is the dynamical systems perspective, an assembly of closely related theoretical vistas based on first (i.e., physical) principles applied to pattern formation in complex open systems. The conceptual 'glue' that holds them together is self-organization: a process occurring in systems with many degrees-of-freedom in which new spatial and temporal patterns emerge as a consequence of some form of internal reorganization in response to changes in external conditions that do not prescribe what should be changed. We shall return to this perspective in the next section when considering a contemporary interpretation of epigenetics (viz., theory of neuronal group selection).

To round off the homunculus problem, it is germane to note that it brings to the surface a key but often-neglected corollary relevant to the study of development: the origin problem, a problem that has pervaded the history of embryology at least since the time of Nicolaas Hartzoeker (1656–1725), a leading preformationist of his time (Needham, 1959). It refers to events that predispose or prepare a developing organism to achieve a particular developmental outcome (e.g., ability to emit paralinguistic sounds such as babbling). Accordingly, each event is a necessary, but not sufficient, condition for the emergence of a new ability with a readily ascribable function (i.e., when that ability emerges, the fetus or infant can perform functions that were previously not possible). For example, the human fetus begins to display breathing movements at the gestational age of 10 weeks (de Vries, Visser, & Prechtl, 1982). Such movements do not become functional in the sense of gas exchange in and out of the lungs until after birth. Breathing movements before birth constitute, then, a necessary exercise preparing the fetus to achieve the act of taking in and expelling air from the lungs for the transition to the extrauterine environment.

We turn next to the two topics highlighted in the title of this entry. First, the meanings accorded to ontogenetic development. Second, its setting in an interdisciplinary landscape. Both were covered in the first edition (2005) of this book, so they will be addressed with somewhat different accentuations.

What is this thing we call development?

Like the New York Yankees from 1965 to 1975, Charles Darwin (1809–1882) had his 'lean' years following the completion of his five-year round-the-world voyage as the naturalist on HMS *Beagle* in 1836. Bedeviled by illness and settling into family life in Down House in 1846, he began finally formulating his theory of

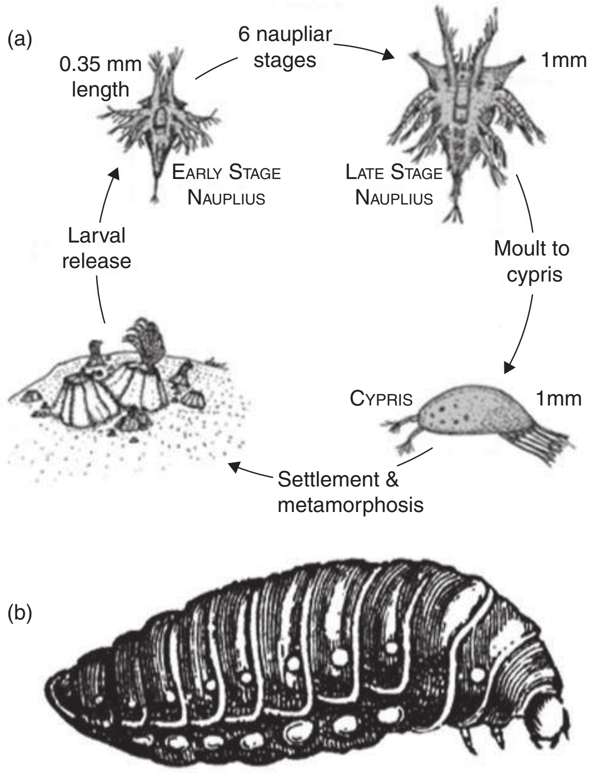


Figure 5. Barnacle and beetle extensively studied by Darwin. (a) Metamorphic life cycle of acorn barnacle, most common of more than 1200 species, and one of many studied by Darwin. It starts out as a motile larva, eventually becoming an immobile adult. When the larvae are released, they go through nektonic (free-swimming or naupliar) phases. After attaching to a hard surface, it molts, sheds its exoskeleton, and turns its body to expose a cone-shaped wall of plates to become a sessile cyprid. (b) Sitaris beetle larva commented on by Darwin due to its fascinating metamorphic life cycle. Once in the nest of bees, they feed on the eggs. After pupation, they change into distinctive orange and black beetles feeding on honey. Figure 5a from Pechenik, J.A., Wendt, D.E., & Jaffetl, J.N. (1998). Metamorphosis is not a new beginning. *Bioscience*, 48, 901–910. Published with permission of Oxford University Press.

evolution. Critical in this endeavor was his abiding interest in invertebrate zoology stemming from his time as a medical student in Edinburgh. Two invertebrates received special attention (see Figure 5): barnacles (cirripedes) and a rather nasty beetle (sitaris), a close cousin of the blister fly.

Darwin on metamorphosis

Darwin's conclusions from his observations on barnacles in the often-neglected penultimate chapter of *The Origin* on 'Development and embryology' are captured in the following excerpt even though he is referring to insects here:

> We can see how by changes of structure in the young and conformity with changed habits of life, together with inheritance at corresponding ages, animals might come to pass through stages of development, perfectly distinct from the primordial condition of their adult progenitors. (p. 344)

He then goes on to write about the larvae of the beetle sitaris that eat the eggs of bees stored on the honey, after which their eyes disappear and their legs and antennae become rudimentary, but are sufficiently functional for them to feed on honey.

What Darwin was observing and reporting was the process of metamorphosis or indirect development: the hormonally driven transition from a larval stage to an adult in which a significant proportion of an organism's structure changes such that the larval and adult stages are not recognizable as the same individual.

Concept of ontogenetic adaptation

Metamorphosis was originally re-categorized from indirect to direct development (monogenesis or development without morphogenesis) by Delage and Goldsmith (1913) as a means of bringing to the fore their vision of ontogenetic[1] development as undergoing a stage-like process. Subsequently, it assumed relatively commonplace usage in post-Darwinian biology and psychology in the late nineteenth and early twentieth centuries. Why it waned in popularity is unclear. Its use was restored to theorizing about development by the neuroembryologist Ron Oppenheim in a series of papers starting in the 1980s (e.g., Oppenheim, 1981) that proffered it as a metamorphic metaphor for non-metamorphic development. Table 1 provides a summarizing definition of the concept, together with a couple of qualifications.

The natural world is replete with ontogenetic adaptations. Some salient examples are illustrated in Figure 6.

The depiction and examples should serve to emphasize that development *is* adaptation. Put another way, it is a concatenation of adaptive changes in tandem with a sequence of developmental niches.

And what of human development? Are there instances that qualify as ontogenetic adaptations? The transition from prenatal to postnatal life provides clear-cut examples such as the placenta and the fibrous skull sutures that permit movements of the bony plates during passage through the birth canal. The placenta is dispensed with after birth having supplied the developing fetus with oxygen and nutrients from maternal circulation, while the skull plates begin the lengthy process of fusing about 2 to 3 months later. Another example is the brown fat that is unique to newborns who, lacking fur, have poor

---

[1] 'Ontogenetic' stems from the Greek word *onto*, which means a being or individual. It thus refers to individual development rather than development more generically (e.g., development of cities), as well disassociating it from the notion of evolution.

Table 1. Defining and refining the concept of ontogenetic adaptation.

An anatomical, physiological or behavioral characteristic that serves a transient, age-specific, biological function during development, and which may occur relatively independently of experience. It may be appropriate for survival during one phase of development (e.g., during prenatal life), but unnecessary or even incompatible with adaptations required for later phases. As a consequence, they must be eliminated, suppressed or reorganized in the course of further normal development.

Qualifications:

1. It does not exclude the influence of antecedent events in development. Thus:
2. It does not imply that development is only a discontinuous stage-like process, but also acknowledges that there can be continuities between earlier and later outcomes.
3. It does imply that the process of re-organization can involve both quantitative regressions (e.g., reduction in number of neurons and synapses, leading to elimination of polysynaptic connections to postsynaptic targets inappropriate for subsequent development) and qualitative regressions (e.g., disappearance or removal of transient structures and functions, with sometimes replacement by others leading to adaptation to a development niche such as feeding niches that change from suckling to sucking to chewing). Ontogenetic adaptation and the provision of an age-appropriate niche together form a mutually related developmental process.

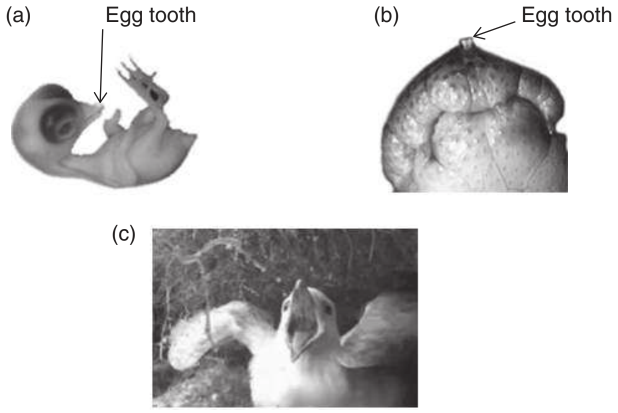


Figure 6. Egg tooth (or carbuncle), and fulmar chick. The egg tooth evident in the chick embryo (a) and the newborn crocodile (b). It is a hard tooth-like projection on the top of the beak of embryonic birds or from the upper jaw of pre-hatchling crocodiles (as well as tortoises and turtles) that is used to cut the egg membrane and break open the shell so that the animal can hatch. There is a specialized hatching muscle at the back of the neck as well as stereotyped movements of the head and the legs that also assist in release from the egg. Once hatching is complete, the egg tooth drops off, the movements disappear and the neck muscle begins to shrink. Both are examples of ontogenetic adaptations, with the loss of egg tooth and disappearance of the hatching movements constituting qualitative regressions, and atrophying neck muscle perhaps being an example of a quantitative regression in development. The fulmar chick (c) represents an interesting example, with an intriguing weapon of survival. They have the rather disgusting habit of vomiting a bright orange, irritating oil from their stomachs rather indiscriminately, which not only smells bad but also clings to the predator's feathers (or fur). The oil makes the feathers of predatory birds become matted, thus losing their insulating properties, and the predator may die of exposure or drown if waterlogged. It appears, however, that the parents are immune to this effect. This makes fulmar chicks not only unappetizing, but actually very dangerous to potential predators. The oil is also an energy-rich food source for chicks and for adults during their long flights. Fulmar chicks are left on their own from about 2 weeks of age, when they no longer need brooding, while parents travel to get food. The rapidly fattening chick can by this time defend itself by oil spitting. Interestingly, although adult fulmars can spit oil too, chicks have much better aim, and can shoot repeatedly. They can spit practically since the moment they are born, and some have been reported as spitting even before hatching completely from their egg. This particular example highlights the problem of identifying an ontogenetic adaptation that is strictly age-restricted, as adults continue with this anti-predator behavioral adaptation. Figure 6c published with permission of Si Wagen, Director of Photography, Eyefish Ltd., Bristol, UK.

thermoregulation: When heat loss occurs, receptors in the skin are triggered that result in oxidizing (burning) brown fat to generate heat and shivering (muscle twitching that generates heat). Developmental changes in the gut, sometimes referred as the 'second brain,' is also an interesting source of pertinent examples. Take, for instance, what happens during and after weaning: The infant's intestine is adapted to digesting and absorbing breast milk, but following weaning, the gut epithelium undergoes structural and histological changes in preparation for a wider range of nutrients (Drozdowski, Clandinin, & Thomson, 2010).

In terms of behavior, the case of fetal breathing movements to postnatal respiratory movements has already been given. In fact, fetal movements in general are both a prenatal adaptation and necessary precursor for their subsequent expression in a decidedly different environment after birth. They provide an eloquent fit with what Bowlby (1969) termed the 'environment of evolutionary adaptedness' (viz., the body of the mother). Thus, the claim can be made that a movement repertoire adapted to life *within* the mother can, with little modification, be used for living *on* the mother. The point made in Table 1 about development being a melding of both discontinuous and continuous processes is brought into relief with these examples.

Beyond birth, candidate ontogenetic adaptations are less obvious to identify, and care is needed in labeling them as such. Take, for example, suckling, in which movements of the jaw and tongue are quite different from those for sucking. They have a strong stripping action, which facilitates the release of colostrum (the 'first milk') that contains antibodies serving to bolster the newborn's immune system, thus protecting against infections and diseases during a particularly vulnerable period immediately after birth via changes in the intestinal mucosa. Another, albeit controversial, example could be neonatal imitation of facial expressions (Bjorkland, 1987): It appears to be qualitatively different and unrelated to imitation later in infancy, and by about 2 months all but disappears from the infant's repertoire. A case can also be made for play, but perhaps less so in humans (termed *Homo ludens* in the past) compared to other primate species in which it does seem to have more distinct age-specific functions (e.g., honing hunting skills), after which it is much less evident.

In the context of current theories of cognitive development, ontogenetic adaptation perhaps comes across as a radical idea. Historically, it is by no means a novel one, but has become something of a forgotten concept, possibly due to a lack of appreciation of the relevance of evolutionary theory for the study of ontogenetic development. It stands as a challenge to depictions of human development typically found in contemporary textbooks on the topic.

Depictions of developmental change

Thelen and Smith (1994) make a relevant distinction between depicting development in terms of a 'view-from-above' versus a 'view-from-below.' Let us refer to them as the macro- and micro-view of development, respectively. From the macro-view, common in textbooks on typical development, ontogeny appears to be an orderly, linear process displaying regularity (e.g., milestones, stages) and progressing inexorably toward some end state, rather like physical growth. It is not only directional but also an irreversible process that is in some way rule-governed. It manifests increasing complexity only in the sense of quantitative increases in the number of parts and functions.

Contrast that model of orderliness with the micro-view. Now development is characterized as being 'messy,' fluid, and context-sensitive. Any illusions of linearity, regularity, and irreversibility evaporate from the diorama. Regressions are now evident, behavior being highly variable, both within and between individuals, and noticeably task-dependent. At the neural level, 'messiness' pervades and is reflected in a 'grunge-like' model at the functional level. Initially, there is an overabundant harvest of neurons (neural proliferation), followed by a veritable battlefield of death and destruction (apoptosis [cell death], axonal retraction necessitating 'garbage collectors' [macrophages or white blood cells]). Set against this language of *Sturm und Drang*, there are amazing feats of navigating to far-away destinations (axons led by growth cones), and overlain with bouts of transient chemically addicted attachments (e.g., neuromuscular junctions between axons and muscle fibers) that are clasped together by a 'match-maker' (synapse).

The micro-view, reflected at both neural and functional levels, is more biologically plausible (and a reason for trying to understand how brain and behavior co-develop). For a better understanding of development, however, there needs to be a theoretical blend between the macro and the micro in order to bring out the broader canvas together with the 'messy' details. Such blending would be particularly beneficial in designing and implementing studies on developmental intervention and communicating their efficacy in the public arena where a 'bigger picture' story is required. How can this be achieved without succumbing to the homunculus problem? The answer, according to advocates of the dynamical systems approach, is the concept of self-organization.

Self-organization: order from disorder

Here, we refer to a process by which new and task-specific spatial and temporal patterns emerge in open systems without any specification from internal or external factors. Thus, there is no executive agent prescribing change. Rather, self-organization is a property 'owned' by open systems with many degrees-of-freedom such as the brain or musculoskeletal system that respond to a non-specific perturbation at the micro-level (e.g., a surge in testosterone) with state change at the macro-level (e.g., display of aggression) when manifesting disorder in far-from-equilibrium (e.g., during a developmental transition). A good introduction to these ideas and their applications to a range of developmental phenomena can be found in Thelen and Smith (1994).

When undergoing a process of self-organization, the system marshals the available degrees-of-freedom into a controllable dynamical unit. The essence of this project is

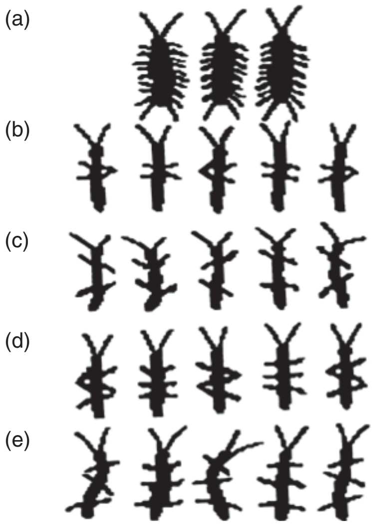


Figure 7. Erich von Holst's self-organizing centipede. a. Intact centipede (*Lithobius*) does not have 100 legs, but rather about 15 (typically one pair per body segment) that move in a wave-like motion along the whole body. b & c. von Holst removed all legs except two pairs: walks like a quadruped. d & e. Retaining three pairs of legs: locomotes with a tripod pattern like a six-legged insect. Conclusions: an aspecific change in constraints (boundary conditions) through reducing the number of degrees-of-freedom (viz., legs) gives rise to system-wide reorganization and change to a new state of locomotion. Only complex, non-linear systems display this form of behavioral self-organization. From Martin, R. (Ed. & Trans). (1973). *The behavioral physiology animals and men: The collected papers of Erich von Holst*, Vol 1. Coral Gables, FL: University of Miami Press.

dramatically captured in an experiment by Erich von Holst (1908–1962) on locomotion in the centipede (Figure 7).

It is important to recognize that self-organization takes place across different timescales. These extend from moment-to-moment experiences occurring over seconds and minutes, to those embracing hours and days that constitute a learning scale, to developmental changes apparent over weeks and months, to a geological timescale delivering changes in evolution. A continuing source of neglect in studying development is the lack of attention paid to the interdependence among these time-bound scales (see Sheya & Smith, this volume). Theory building aimed at addressing this disregard will make it unnecessary to treat learning, development and evolution as distinct processes. The interdisciplinary enterprise of evolutionary developmental biology (evo-devo) is a step in this direction, at least across two of the timescales.

Is there a well-articulated developmental theory that incorporates self-organization as part of its framework? The foremost claimant to this mantle is the theory of neuronal group selection (TNGS) originally outlined by Gerard Edelman (1924–2014) arising from his Nobel Prize-awarded work on immunology.

Edelman's theory

In short, TNGS (or Neural Darwinism), avowedly anti-computational in its fundamentals, is based on self-organization due to selection processes operating over learning, developmental and evolutionary time. In terms of ontogeny, it acknowledges that the development of brain and behavior is, above all, activity-dependent (in the sense of the Hebbian rule "cells that fire together, wire together"). The selection acting on development is twofold. The first, developmental selection, involves Darwinian competition among populations of neurons constrained in part by the genes. The second, experiential selection, facilitates a learning process uncomplicated by a faster, less permanent process that temporally strengthens or weakens neuronal connections. Due to both selection processes, as well as those arising from self-organization at many levels of the nervous system, behavior emerges in ways that cannot be predicted by environmental instructionism or by knowledge of brain evolution.

Another constraint woven into the fabric of TNGS concerns value systems. These are depicted as evolutionary-endowed preferences that react to inclusive forms of sensations. These involve, for example, preferences for warmth rather than cold, soft versus hard objects, and sound within certain frequency ranges (at least in these respects revealing a kinship with the biphasic theory of approach–withdrawal advanced by Schneirla, 1965, but ignored by Edelman). Value systems address the origin problem in that they form the neural bedrock of brain development. As such, they kick-start development of the brain–behavior nexus. These foundations consist of aminergic (e.g., epinephrine) and cholinergic (viz., acetylcholine) systems that 'fan out' to diffuse projections at all levels of the neuroaxis. Among the things they modulate are lasting changes in the likes of behavioral plasticity and long-term potentiation of synaptic strength, the latter regarded as the cellular basis of learning and memory.

Consequently, with its inclusion of value systems, it seems that TNGS has not escaped the homunculus trap after all. Although that may be the case, at least the notion is accorded a well-defined neural embodiment, unlike Dennett's legion of 'stupid' neurons. Perhaps the problem is inescapable, particularly when accounting for developmental origins. Edelman's theory does attempt to circumvent the associated problem of infinite regression: Evolutionary processes can select the 'valuable' neural functions in developmental time, but they do not select for mechanisms associated with neuronal selection.

Table 2. Comparative data in two 5-year periods from 1956 to 2000 for developmental psychology, social psychology, and experimental psychology covering changes in mean team sizes, mean fraction of work done in teams, and relative team impact (mean number of citations received by team).

			Mean team size			*Fraction$_{teams}$*			*Relative team impact*		
Field	*N_{papers}*	*Years$_{covered}$*	*1st 5y*	*last 5y*	*% change*	*1st 5y*	*last 5y*	*% change*	*1st 5y*	*last 5y*	*% change*
Dev psychol	43,788	1956–2000	1.65	2.96	79	0.43	0.79	86	1.74	1.90	9
Soc psychol	42,090	1956–2000	1.53	2.44	59	0.39	0.77	95	1.61	1.84	2
Exp psychol	67,729	1956–2000	1.35	2.56	90	0.26	0.78	198	2.02	1.66	–18
Multidis psychol	93,363	1956–2000	1.52	2.27	50	0.36	0.61	73	0.87	2.22	154

All three branches of psychology show considerable changes in team size and the proportion of individuals in a team contributing to publications, not surprisingly for experimental psychology in both instances. Perhaps just as surprisingly, experimental psychology shows a relative decline in team impact, suggesting that it has become increasingly diffused over other branches (e.g., experimental social psychology). With regard to multidisciplinary psychology (not specified), the impact on team citations has undergone a strikingly large increase in the second period. Data based on Wuchty, S., Jones, B.F., & Uzzi, B. (2007). The increasing dominance of teams in production of knowledge. *Science*, 316, 1036–1039.

Border crossing and trading zones

Two men take a New York yellow cab, early 1980s. One is Michael Gazziniga, the other George A. Miller (1920–2012), both with interests in relationships between brain and high-level cognitive functions. During that short journey, they come up with the name of a new multidisciplinary border-crossing endeavor: cognitive neuroscience. Inextricably linked with advances in brain imaging in order to maintain its momentum, its influence has permeated the many branches of psychology, propagating a raft of interdisciplinary enterprises including developmental cognitive neuroscience.

So what about psychology and interdisciplinary research (IDR)? Any quantitative data indicating degree of staffing investment over time? From the period of 1956 to 2000, developmental psychology displays an upward trend in the allocation of resources (Table 2). More recent data of a similar nature seem to be unavailable. A proxy, albeit a less than optimal one, is a comparative Google search (April 2016): There were 189,000 'hits' for the entry 'Developmental psychology and IDR' in 2005, rising to 317,000 in 2016. Undoubtedly, there is a lot of 'dross' in such a measure, but a survey from 2000 to 2016 comparable to the one published in 2007 would in all probability reveal a similar, even greater, ascending tendency.

And IDR? What is a meaningful, all-purpose interpretation? Table 3 houses a utilitarian definition compatible with one used in the 2007 survey.

It is one thing to talk about bulls, another to be in the bullring (Spanish saying)

Stifling recondite debates have revolved about whether IDR is different from cross-, multi-, or trans-disciplinary undertakings. A firm grasp of what of it means to enter the risky IDR bullring is best conveyed in contrasting it with multidisciplinary research (MDR), a distinction visually summarized in Figure 8.

Both involve border crossings between disciplines, but IDR aims to remove them, while participants in MDR ultimately return across the border to their own territories of expertise. When talking about borders, however, one should remember that they are arbitrary impositions, remnants of the history of how academic and social forces created discrete disciplines, especially during the twentieth century. The same admonition applies to the notion of levels of organization or explanation, an almost inescapable feature of IDR, which can sometimes lead to misleading characterizations about the relationships between biological and psychological events (e.g., brain mechanisms *underlying* emotional development when it would be more appropriate to say 'associated with').

Bearing in mind these caveats, there is a case for a rudimentary distinction to be made between restricted and unrestricted sciences (Pantin, 1968). Physics and chemistry are self-contained exemplars of the former in that investigators are not required "... to traverse all other sciences," and investigators in biology (by implication psychology) "... must be prepared to follow their problems into any science whatsoever" (Pantin, 1968, p. 24). Although a bit extreme, it does, however, suggest that psychology is best served by seeking out research partners in other disciplines. On the other hand, (developmental) psychology can have a foot on both sides of the divide: It can benefit from IDR, but as research on cognitive development continues to demonstrate, it can remain resolutely in the realm of monodisciplinarity (e.g., research on infant object permanence).

Table 3. General definition of IDR, together with its potential benefits and challenges. The latter are based on personal experience of IDR, rank-ordered from most positive benefits to most serious challenges.

Definition:

A mode of research involving teams or individuals engaged in a common cause of drawing together two or more traditionally bounded academic (sub-)disciplines with specialized knowledge as means of integrating their respective theories, data, and methods in order to advance fundamental understanding or to solve problems whose resolutions are beyond the purview of a single discipline.

Benefits:

1. Enables specific, intellectual, social, and practical problems to be addressed and resolved through:
   a. posing completely new questions or
   b. reframing old problems, particularly those shown to be intractable through the medium of a single discipline.
2. Serves a broader function of generating new areas of academic conjecture through the process of merging together different (sub-)disciplines to form interdisciplines.
3. If successful, it has the potential of leading to significant scientific innovations, influencing a range of disciplines, and engendering new scientific endeavors.
4. In crossing and breaking down borders between conventional disciplines, it also has the potential to play a role in defending and promoting academic freedom.

Challenges:

1. Being a group enterprise requiring cooperation among individuals rather than the sum of individual contributions increases the risk of failure relative to research conducted in single disciplines. An associated problem is 'groupthink' giving rise to a lack of innovative initiatives by individual members or disciplinary partners.
2. Maintaining knowledge across two (or more) fields is more demanding in terms of time and effort than the workload associated with single disciplines (e.g., reading a broader range of literature, attending meetings across different departments).
3. The traditional structure of university departments, organized around single disciplines, creates resistance to crossing borders, despite the fact it does not reflect contemporary scientific challenges.
4. Funding mechanisms and departmental resources are typically directed toward research in single disciplines that are favored by quantitative measures of scientific prestige.
5. Highly ranked journals can be narrowly focused, making it difficult to publish interdisciplinary findings.
6. Putting teams together and integrating disciplines take time, thereby making research more expensive.

Does IDR benefit theory building in the study of child development? The answer is not straightforward, and an attempt at doing so requires the distinction between process and mechanism in the context of the change problem in the first instance.

Process, mechanism and the change problem

Process and mechanism are two terms that tend to be interpreted and treated as being seemingly interchangeable in the literature. However, the distinction is fundamental to a proper understanding of development, as was the origin problem appraised previously. Process boils down to describing *how* a system changes its spatial or temporal organization or both over (developmental) time. In dynamical systems terminology, its description is referred to as an order parameter. With mechanism, however, we are dealing with the agent or agents *responsible* for creating change in a process. The causal agents are labeled control parameters, which when scaled up beyond some critical value can lead to a change in state (i.e., a change from one stable attractor or state to another). A more technical illustration of the distinction between order and control parameter is offered by Frank, Richardson, Lopresti-Goodman, and Turvey (2009).

Take, for example, the development of upright locomotion. We have extensive descriptions of how it changes, but they will vary depending on how frequently and with what resolution it is observed (cf., macro- vs. micro-approaches considered previously). Understanding mechanisms is more problematic because capturing them decisively requires experimental manipulations. According to dynamical systems thinking, it requires the search for and identification of age-specific control parameters, which, when scaled up beyond some critical value, no longer act as constraints but trigger changes in the organization of behavior at the macro-level (i.e., order parameter).

In terms of human development, an insightful comment by Bernstein (1967) has provided students of motor development with an entry point for the pursuit