Chapter 4
Is Heterochrony Still an Effective Paradigm for Contemporary Studies of Evo-devo?

James Hanken

4.1 Introduction

If there is one topic that can be most closely associated with the tremendous resurgence of interest in the relation between evolution and development that characterized biology in the late 1970s and 1980s, then surely it is *heterochrony*. The role of change in the relative timing of developmental events has been emphasized again and again since before the term heterochrony was coined by Ernst Haeckel in the mid-nineteenth century. But this interest virtually exploded when Evo-devo was reborn in the late twentieth century following the publication of several seminal books and papers (e.g., Gould 1977; Raff and Kaufman 1983), the convening of timely workshops and symposia (Bonner 1982; Goodwin et al. 1983; Raff and Raff 1987), and the founding of new journals. These events reflected the growing recognition that a greater appreciation and consideration of the role of developmental patterns and their underlying mechanisms was needed to achieve a more comprehensive understanding of the evolution of organismal form and phyletic diversification than was offered by the prevailing Modern Synthesis (Hamburger 1980; Roth and Wake 1985). Thus, the 1981 Dahlem conference (Bonner 1982) straddled a key period in the history of evolutionary biology and provides a convenient and valuable vantage point from which to observe the history of these and related ideas.

The heterochrony literature is enormous, and it is not my goal here to present a comprehensive assessment of this exciting and much-debated topic. Readers interested in such compilations are encouraged to consult any of several lengthy reviews (Hall 1990; McKinney 1988; McKinney and McNamara 1991; Raff 1996). Rather, I present a more personal assessment of how views of heterochrony and its

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J. Hanken (✉)
Department of Organismic and Evolutionary Biology and Museum of Comparative Zoology,
Harvard University, 26 Oxford St, Cambridge, MA 02138, USA
e-mail: hanken@oeb.harvard.edu

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importance have changed over the last 30–40 years, from the standpoint of one who came of age in the late 1970s and early 1980s (academically speaking) and who has continued to work in Evo-devo, in one capacity or another, ever since. My treatment emphasizes the shorter interval that bracketed the 1981 Dahlem conference, but also benefits from the important perspective that has emerged over the last few years as a result of the tremendous increase in knowledge and understanding of the molecular-genetic mechanisms of development and of how these mechanisms are perturbed in the evolution of morphological diversity.

4.2 History of Heterochrony up to 1981 Dahlem

The recognition that changes in developmental timing may underlie evolutionary changes in juvenile and adult morphology has a long and complicated history. Ernst Haeckel, the sensational nineteenth century German naturalist, embryologist, evolutionist and philosopher, both popularized the concept—he literally coined the term "heterochrony"—and embedded it within an explicitly phylogenetic paradigm (Haeckel 1866). But Haeckel was far from the first scientist to call attention to the fact that embryos differ in the relative timing of developmental events or that such changes are related to differences in form that are manifest later in ontogeny (Gould 1977). Haeckel's views, however, and especially his "biogenetic law"—ontogeny recapitulates phylogeny—embraced the recapitulation doctrine, which by the early twentieth century was untenable to many leading embryologists. In 1930, Gavin de Beer presented a classification of evolutionary patterns that included several different types of heterochronic phenomena. This classification, which abandoned most of the claims and assumptions of recapitulation and rejected the causal connection between ontogeny and phylogeny that is implied in the biogenetic law, was published again a decade later and illustrated then for the first time (de Beer 1940; Fig. 4.1). de Beer's ideas had lasting impact. Indeed, they "formed the basis for most discussion, in the English literature at least" for much of the remainder of the twentieth century (Gould 1982, 334). At nearly the same time, in 1932, Julian Huxley's *Problems of Relative Growth* explored the implications of changes in developmental timing in an evolutionary context. Huxley implicated "rate-genes" as possible regulators of differential growth and, hence, morphological diversification (Fig. 4.2), a theme that he would later elaborate (Huxley 1942), along with Richard Goldschmidt (1940). Interestingly, while largely coincident in time, the ideas of Huxley and de Beer differed in important ways, reflecting these two Oxford-trained scientists' contrasting views regarding the appropriateness of seeing causal connections between ontogeny and phylogeny (Churchill 1980).

Gould (1977) provided a lengthy historical review of heterochrony as a concept and how its definition in and application to evolutionary theory changed from the mid-1800s through the first three quarters of the twentieth century. Disappointed that previous definitions, applications, and graphical depictions of heterochrony lacked sufficient clarity to offer meaningful insights into underlying developmental

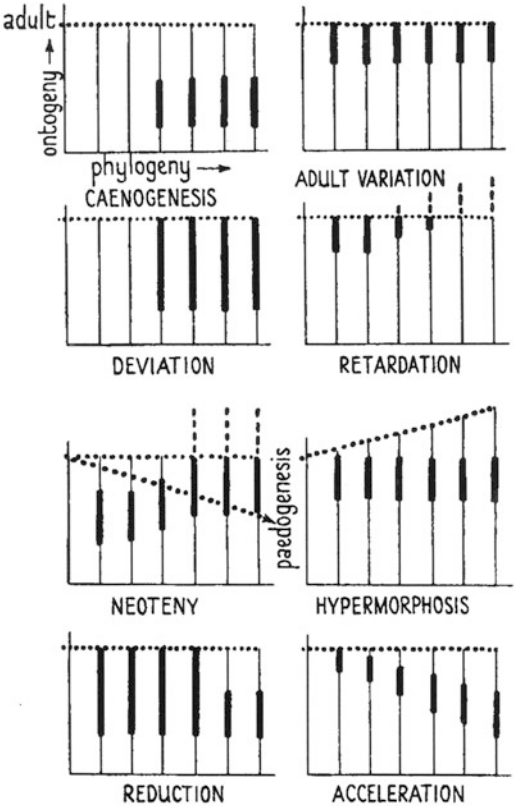


Fig. 4.1 de Beer's eight categories of heterochrony (1940, Fig. 2). Each graph depicts an ancestor-descendant sequence (from *left* to *right*) and an individual ontogeny (from *bottom* to *top*). The *thick black lines* denote "evolutionary novelty." The distinct pattern of evolutionary change depicted in each graph is regarded as a separate category, and each receives its own name (e.g., caenogenesis, retardation). As noted by Gould (1977), only some of de Beer's categories are actually modes of heterochrony (neoteny/paedogenesis, retardation and acceleration), and these "reduce to" discrete manifestations of two underlying processes, acceleration and retardation

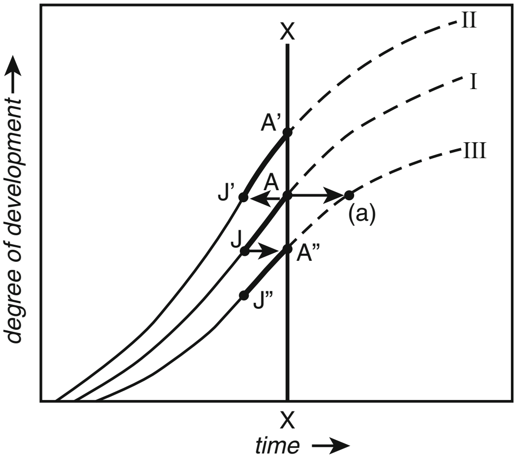


Fig. 4.2 Huxley's depiction of the possible alternative effects of mutations in "rate-factors" (or "rate-genes") on the developmental rate of a given character (1932, Fig. 104). Rate acceleration allows a derived ontogeny (line II) to exceed the degree of development attained in the ancestor (I). With rate deceleration (III), the derived ontogeny terminates before it reaches the degree of development attained by the ancestor. These two contrasting outcomes correspond to two of de Beer's (1930, 1940) eight categories of heterochrony, *acceleration* and *retardation*, respectively. Vertical line (X—X) denotes the time during ontogeny when differentiation ends

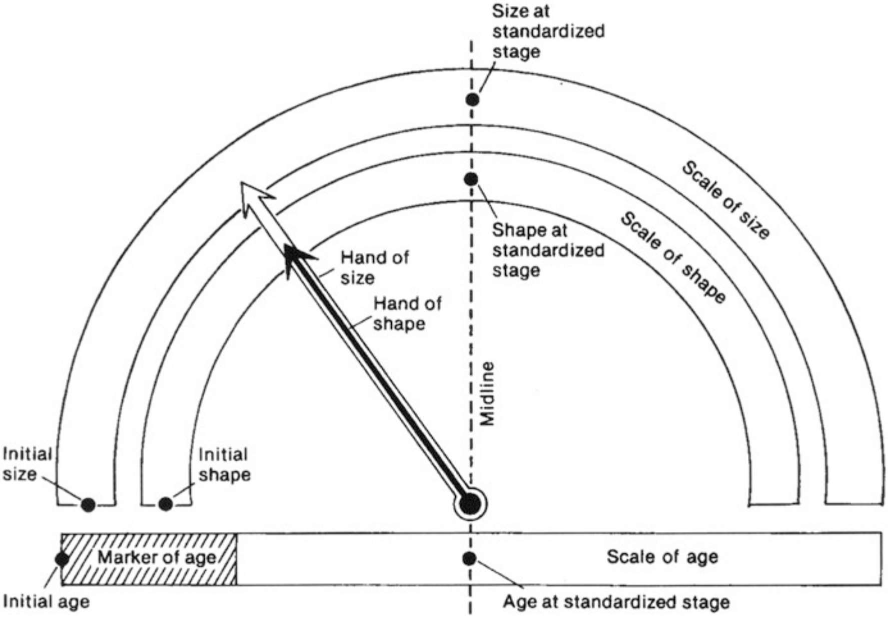


Fig. 4.3 Gould's "clock model" was offered as a means of graphically depicting correlations among organismal size, shape, and age during ontogeny, as well as dissociations among these three parameters that might occur during evolution (1977, Fig. 33)

mechanisms, Gould proposed a "clock model" to explicitly represent—independently and in combination—the effects of change in age, shape, and size (Fig. 4.3). In doing so, he hoped to achieve a synthesis of "the two great literatures on size and shape: the quantitative measurement of allometry … and the study of heterochrony, a subject that has doggedly maintained a purely quantitative and descriptive approach" (246).

Gould's (1977) book spurred widespread interest in the relation between evolution and development in general, and in heterochrony in particular. Arguably the most significant response was a paper published only 2 years later by Alberch et al. (1979), with Gould as one of the four co-authors. Building on the intention to more explicitly identify underlying developmental processes and mechanisms that led Gould (1977) to devise the clock model, this paper offered a more quantitative method for describing how heterochronic changes in ontogeny might mediate morphological evolution and explain phyletic trends. It defined a finite number of "heterochronic processes" (e.g., progenesis) and the corresponding "controlling parameters" (e.g., timing of the offset of development), as well as the morphological and phylogenetic results obtained when those parameters change during evolution (Fig. 4.4). Gould himself would later concede that his clock model "was incomplete and insufficiently quantified to rank as an adequate formalism for heterochrony [but that] Alberch et al. … have devised a complete and operational system" (Gould 1982, 334).

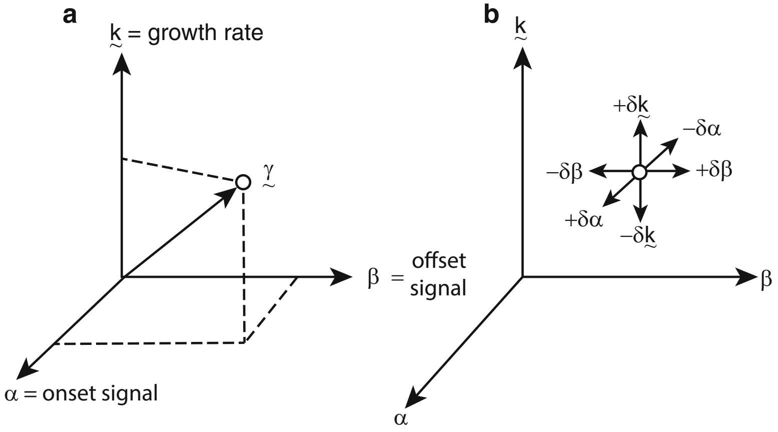


Fig. 4.4 As an improvement on Gould's (1977) two-dimensional clock model, Alberch et al. (1979, Fig. 14) conceptualized ontogeny as occupying a three-dimensional "age-size-shape" space. (**a**) Heterochronic changes within that space comprise positive and negative perturbations in any of four growth parameters: onset age (or signal), offset signal (age or organ size), growth rate (size or shape), and initial size at the commencement of growth. (**b**) Possible perturbations to three of the four growth parameters (changes in initial size are not included in either panel)

It is hard to overestimate the combined impact of Gould (1977) and Alberch et al. (1979) on comparative biology for the following decade. The combination of a more explicit and operational terminology for use in describing heterochronic phenomena, a simple yet effective way to graphically depict differences between ancestral and descendant ontogenies, and the general acceptance that heterochrony might underlie and at least in part explain many of the most important morphological and phyletic trends in evolution, motivated the undertaking of large numbers of empirical analyses of heterochrony in groups as disparate as flowering plants, Mexican salamanders, and primates, including humans (Guerrant 1982; Hanken 1984; Shea 1983). This surge of interest in heterochrony is conveniently and simply illustrated by an analysis of the annual number of scientific publications that include "heterochrony" in their title or abstract, as tracked by several of the largest bibliographic databases (Fig. 4.5). Even though the word was first coined by Haeckel in the latter half of the nineteenth century, its use increases beginning in the late 1970s and early 1980s and has remained high to this day.

This is the environment and general attitude regarding heterochrony that prevailed among many comparative biologists at the time of the 1981 Dahlem conference. Gould's concurrent assessment of most prior work on heterochrony is stark and merciless: "the previous lack of a rigorous framework has spawned 200 years of squabble and incomprehension and has led to the common impression among evolutionists that this subject is both arcane and unprofitable" (1982, 334). Yet, he continues, "the subject of change in developmental timing still exerts its major fascination through the claim that small inputs might lead to large and

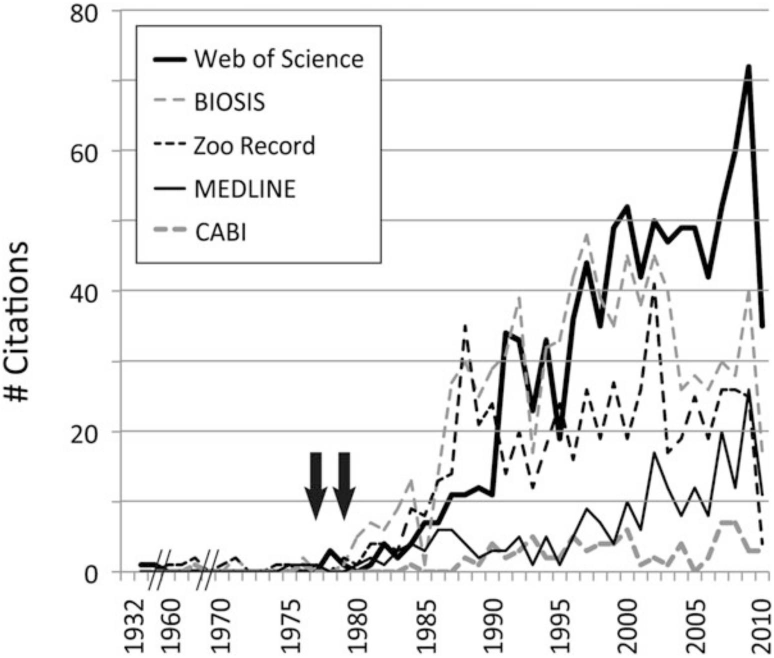


Fig. 4.5 Number of times per year that a scientific paper was published that has the word heterochrony in its title or abstract, as indexed in five bibliographic databases: Science Citation Index Expanded [=Web of Science®], *BIOSIS* Previews and Zoological Record (Thomson Reuters, Philadelphia, PA); MEDLINE (National Library of Medicine, Bethesda MD); and CAB Abstracts (CABI, Wallingford, England). "Heterochrony" first appears in 1932 and continues to be used rarely until the mid-1970s, when its use increases dramatically. That increase continues, in at least two databases, to the present day. The two *black arrows* indicate the years of publication of Gould (1977) and Alberch et al. (1979). Each database tracks a different set of journals, although several of them track many of the same titles. Zoological Record, Science Citation Index Expanded, and CAB Abstracts track citations beginning in 1864, 1899 and 1910, respectively. Citations in MEDLINE and *BIOSIS* Previews begin much later, in 1966 and 1970, respectively. Results depicted here were obtained in July 2010

surprising outputs" (Gould 1982, 338). Subsequent analyses would continue to emphasize and explore the role of heterochrony in mediating morphological evolution and accounting for phyletic trends, such as the origin of complex novelty, homoplasy, and developmental constraint (e.g., Alberch 1983; Bininda-Emonds et al. 2003; Richardson 1999; Wake and Larson 1987).

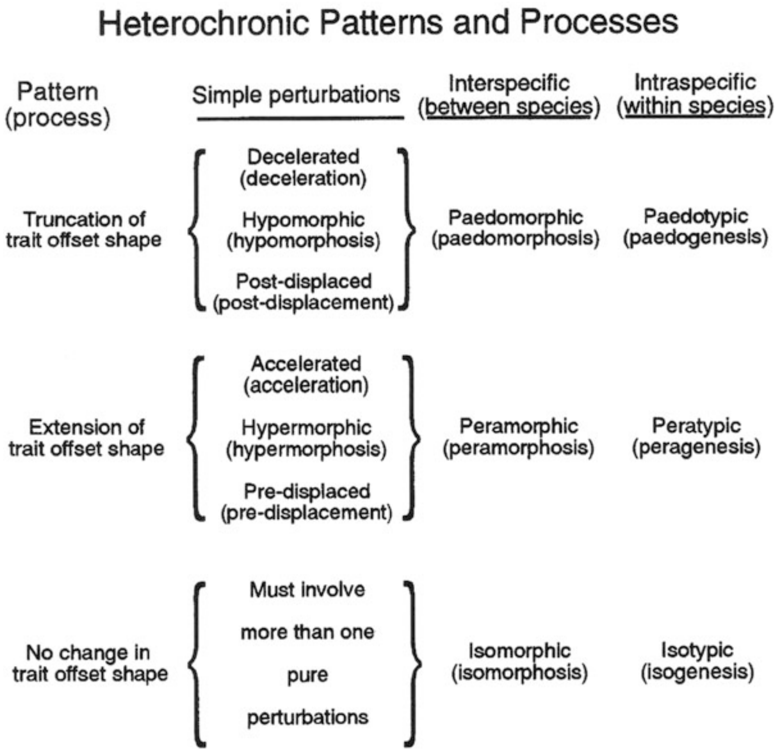
4.3 Heterochrony After 1981 Dahlem

Interest in heterochrony continued to swell in the years following the 1981 Dahlem conference. Viewed from today's perspective, nearly 35 years on, these studies can be seen to represent two divergent intellectual paths. One direction comprises a large number of mostly empirical studies of morphological variation in particular taxonomic groups, which demonstrate the valuable insights into evolutionary pattern and process offered by formal heterochronic analysis. A second path, however, is defined by researchers who highlight the limitations of heterochronic analysis. These researchers assert that other developmental processes, distinct from heterochrony, must be considered to effectively and adequately represent the evolutionary patterns involved in morphological diversification, let alone the underlying developmental mechanisms. Examples of the two contrasting approaches, and their basic conclusions, are described here.

4.3.1 Heterochronic Analysis is Indispensable

Most analyses of heterochrony in the years following the 1981 Dahlem conference comprise empirical studies that analyze ontogenetic and phylogenetic data in particular clades. For the most part, these studies attempted to resolve observed trends in terms of the heterochronic processes and possible outcomes that were defined as part of Gould's (1977) original clock model, but especially as represented in the subsequent formalism provided by Alberch et al. (1979). Several authors, however, sought further modification of the formal representation and nomenclature of heterochrony. These modifications were intended to correct perceived deficiencies or limitations in the model of Alberch et al. (1979), which ranged from incorrect or confusing terminology (McNamara 1986) to a principal if not exclusive focus on interspecific comparisons (Reilly et al. 1997). Shea (1983), for example, proclaimed the need to distinguish between time- and rate-dependent processes that may yield identical morphological patterns. Thus, in place of Alberch et al.'s *paedomorphosis* and *peramorphosis*, Shea offered four new terms, *time hypo-* and *hypermorphosis* and *rate hypo-* and *hypermorphosis*. McKinney and McNamara (1991) added new terminology and further extended the heterochrony paradigm to the developmental and cellular processes that underlie patterns of morphological variation, particular those that mediate cell-cell interactions and resulting histodifferentiation early in ontogeny. McKinney and McNamara distinguished these *differentiative heterochronies* from *growth heterochronies* of late ontogeny, and argued that the latter were the focus of most prior studies of heterochrony. Differentiative heterochronies were identified as comprising two categories of phenomena, *global* and *local,* and the local differentiative category was further subdivided into two distinct types, *size differentiative* and *novel differentiative*. Befitting a discussion among systematic biologists who are frequently called upon to formally describe, differentiate, and name species, one author even offered a "key to heterochronic processes," which provided "diagnostic characters of each process" (McNamara 1986, 11).

Perhaps the most comprehensive criticism and revision of the model of Alberch et al. (1979) was offered by Reilly et al. (1997). They conceded that the model had come to be "accepted by nearly all workers in the field" (120), but identified a series



Heterochronic Patterns and Processes

Pattern (process)	Simple perturbations	Interspecific (between species)	Intraspecific (within species)
Truncation of trait offset shape	Decelerated (deceleration) Hypomorphic (hypomorphosis) Post-displaced (post-displacement)	Paedomorphic (paedomorphosis)	Paedotypic (paedogenesis)
Extension of trait offset shape	Accelerated (acceleration) Hypermorphic (hypermorphosis) Pre-displaced (pre-displacement)	Peramorphic (peramorphosis)	Peratypic (peragenesis)
No change in trait offset shape	Must involve more than one pure perturbations	Isomorphic (isomorphosis)	Isotypic (isogenesis)

Fig. 4.6 Revised classification of heterochronic patterns and processes. Reilly et al. (1997, Fig. 7) offered this "integrated terminology to describe intra- and interspecific heterochronic phenomena" to correct perceived errors in the model of Alberch et al. (1979), including its restriction to phylogenetic patterns (interspecific variation). The terminology recommended here is more extensive than that offered by Alberch et al.; for example, nearly all terms in the rightmost column are new, as is its explicit application to intraspecific phenomena. Parentheses denote "process names," each associated with a corresponding "pattern name"

of minor problems with the recommended terminology for describing heterochrony and one fundamental objection to the model: whereas it was intended to be used to evaluate phylogenetic patterns (i.e., interspecific comparisons), it was frequently applied to intraspecific comparisons. They found the model to be "confusing and incomplete," and that this had "led to varying degrees of misunderstanding about heterochrony among evolutionary biologists" (120). To address these problems, Reilly et al. (1997) revised the terminology of Alberch et al. (1979) as it pertains to interspecific heterochrony, but they also provided new, additional nomenclature for heterochrony that specifically applies to intraspecific phenomena (Fig. 4.6).

In evaluating the above studies of heterochrony, it is important to remember that those who were critical of the terminology, scope, and other aspects of specific models (e.g., Alberch et al. 1979) also, for the most part, accepted the basic premise that heterochronic analysis is indispensible to a meaningful understanding and explanation of morphological diversification. Reilly et al. (1997) prominently asserted that “heterochrony may underlie all morphological variation and possibly is *the* developmental phenomenon producing all morphological change” (120).

4.3.2 Heterochronic Analysis is not Enough

At the same time that numerous empirical studies of morphological variation in particular taxonomic groups were demonstrating the valuable insights into evolutionary pattern and process that could be achieved by formal heterochronic analysis, a second path was beginning to be laid down by other researchers who highlighted the limitations of just such an approach. These authors argued that other developmental phenomena, distinct from heterochrony, must be considered to effectively and adequately discover many of the developmental mechanisms that underlie observed patterns of morphological diversification, or even to appropriately represent the patterns themselves. Although these authors do not deny an important role for heterochrony at some level, or that heterochronic analysis can provide valuable insights, they do assert that heterochrony does not tell the whole story. Indeed, in some instances heterochrony may not even tell the most significant part of the story.

Parichy (2001), for example, compared pigment pattern evolution and development among closely related species of salamanders (Fig. 4.7). He sought to test

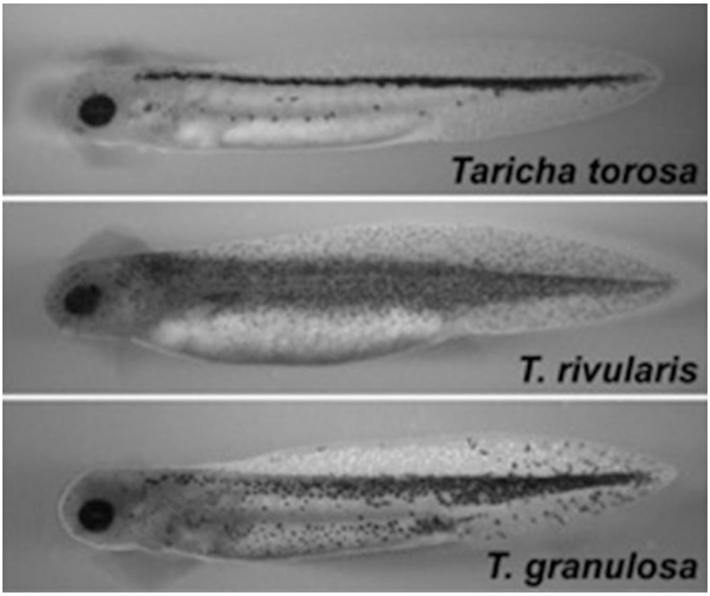


Fig. 4.7 Larval pigment patterns vary among species in the salamander genus *Taricha*, principally in the degree to which dark pigment cells (melanophores) form a discrete longitudinal stripe on each side of the body (Parichy 2001, Fig. 7.9)

whether “interspecific diversity is causally related to heterochronies at the cellular level,” or if, instead, differences among species “result from nonheterochronic changes in developmental mechanisms” (230). His conclusion was unequivocal. While conceding that “a heterochronic framework can be a useful heuristic device as it ensures consideration of various possibilities for rate and timing changes that otherwise might be overlooked,” he concluded that “it is unlikely that broad patterns of heterochrony will be identified as causally related to pigment pattern evolution” (258). Moreover, “a heterochronic framework is not essential for understand [*sic*] evolutionary changes in developmental mechanisms. In some instances, it can be positively misleading. . . .investigations directed solely toward testing for heterochronies may provide relatively little insight on their own” (259).

Comparable objections or qualifications regarding heterochrony as an explanatory tool are reflected in other studies that emphasize the importance of developmental processes that mediate *spatial* patterning instead of changes in developmental timing. Zelditch and Fink (1996), for example, championed *heterotopy*, evolutionary change in the spatial patterning of development, as having at least a complementary and in some cases a prominent role in morphological evolution, particularly in the origin of morphological novelty. Interestingly, the term heterotopy was also coined by Haeckel (1866) as a complement to heterochrony, but for various reasons it never achieved anything close to the amount of attention that has been showered on heterochrony (Hall 2001). Hall (1990, 1999) and Raff and Wray (1989) offer additional discussions of the limitations of heterochrony as a conceptual and explanatory tool.

De-emphasis on heterochrony as the primary if not exclusive determinant of morphological variation, or even as a satisfactory explanation, may be seen, at least in part, as a consequence of the ongoing explosion of knowledge regarding the molecular-genetic mechanisms that mediate the genesis of organic form and how these mechanisms may be perturbed to generate phenotypic diversity (Carroll et al. 2005; Gerhart and Kirschner 1997; Wilkins 2002). The ability to implicate the action of specific genes in the generation of novel morphologies in the context of increasingly well understood models of spatial pattern formation—even when the associated genetic changes are associated with changes in the timing of gene expression—provides to many investigators a fuller and more detailed understanding of the mechanisms of evolutionary diversification than does a purely phenomenological description of a heterochronic pattern. One excellent example is the recent comparative analysis of beak morphology in Galapagos finches by Abzhanov et al. (2004, 2006). Interspecific variation in beak size and shape, which can be explained at one level simply in terms of differences in temporal aspects of growth and other heterochronic parameters (Campàs et al. 2010), is revealed to reflect the action of a small number of specific genes, each of which mediates craniofacial patterning in particular ways, combined with differences in the intensity and location of gene expression among species (Fig. 4.8).

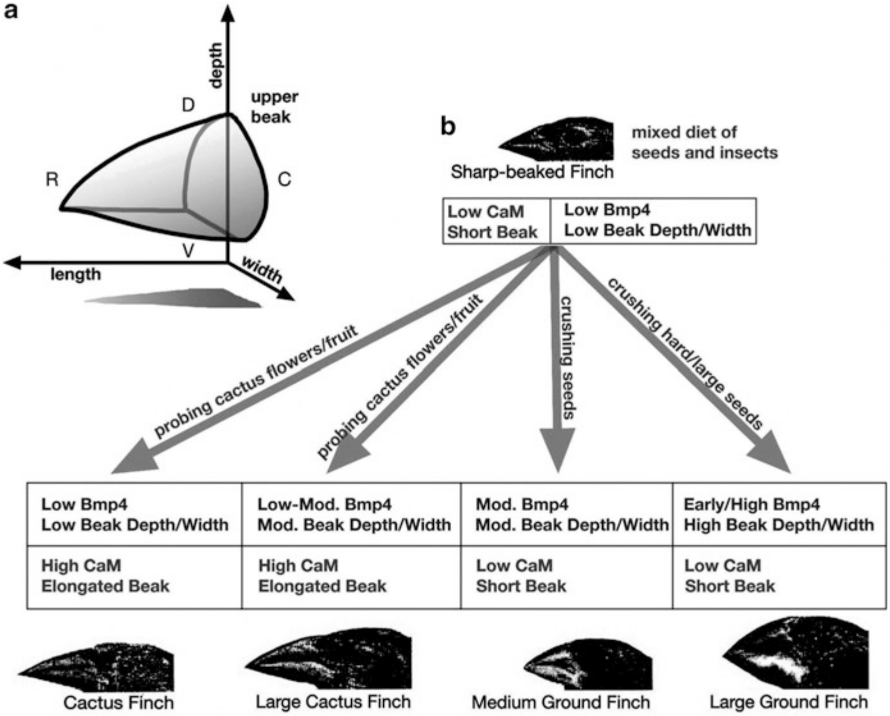


Fig. 4.8 Levels of bone morphogenetic protein (Bmp) and calmodulin (CaM) expressed during embryonic development mediate beak growth along different axes, facilitating the evolution of distinct beak morphologies among species of Darwin's finches (Abzhanov et al. 2006, Fig. 4). The sharp-beaked finch displays a basal beak morphology from which elongated and deep/wide beaks evolved in the more derived species. Abbreviations: *C* caudal, *D* dorsal, *R* rostral, *V* ventral

4.4 Heterochrony in the Future: Is It an Effective Paradigm?

Evolutionists borrowed "an old word in a new context" when, beginning with de Beer (1930) and continuing for much of the twentieth century, they embraced heterochrony as "the general phenomenon of change in the timing of development" (Gould 1982, 334). In the extreme, heterochrony was represented as an all-encompassing phenomenon that is central to understanding virtually any and all aspects of phenotypic diversification. Even when underlying processes were considered, there was a conviction that these phenomena too are most effectively characterized or described in the language of heterochrony.

Increasingly, however, there has been a recognition, particularly among developmental biologists but also among comparative biologists (e.g., Thomson 1988), that the underlying molecular and developmental mechanisms may be more effectively understood in terms of processes other than heterochrony. Although heterochrony is an effective descriptor of many patterns of morphological variation among related taxa and provides valuable insights into changes in development that effect morphological transitions during evolution, including in some instances the origin of morphological novelty, an exclusive focus on heterochrony is unwarranted except in isolated cases (Ambros and Horvitz 1984; Raff et al. 1984) This more nuanced view of heterochrony—as an important paradigm, but not the sole paradigm—provides a more comprehensive depiction and understanding of the developmental basis of evolutionary change.

At least superficially, this more nuanced paradigm is faithful to earlier theories. Haeckel required two distinct categories of ontogenetic change—heterochrony and heterotopy—to explain the evolutionary patterns he saw, and the duality of ontogenetic processes and their underlying mechanisms has been recognized again and again in the study of evolutionary morphology (Brylski and Hall 1988a, b; Radinsky 1983; Zelditch et al. 2000). Heterochrony still has an important role to play in contemporary studies of Evo-devo, but it is not an all-encompassing and exclusive role. Rather, heterochrony is one of several analytical tools needed to achieve a complete understanding of the developmental basis of evolutionary change.

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