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Review

Plasticity in the timing of physiological development: Physiological heterokairy — What is it, how frequent is it, and does it matter? ☆

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Abstract

The study of developmental sequences of physiological traits could be an important way of placing comparative developmental physiology (CDP) within the research agenda being forged by work on developmental plasticity. Here we focus on the concept of heterokairy defined by Spicer & Burggren in 2003 as changes in the timing of physiological development in an individual. The role of this concept in the future of the CDP is discussed. First we provide an historical perspective of the ideas that have led to the investigation of sequences in CDP. This is followed by a re-examination and clarification of the definition of physiological heterokairy before empirical case studies that (explicitly or implicitly) demonstrate physiological heterokairy are reviewed. We suggest that physiological heterokairy can be demonstrated through a wide range of invertebrate and vertebrate examples. However, care must be taken when inferring that heterokairy as a pattern is always the result of heterokairic processes as there is evidence that physiological heterokairy could result from the altered timing of both homologous or analogous physiological mechanisms. We conclude by discussing the potential link between heterokairy and heterochrony and suggest that the investigation of this link should be a major goal for workers in both CDP and developmental plasticity.

Keywords: Altered timing; Heterokairy; Heterochrony; Development; Phenotypic plasticity

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1. Introduction

The zoological literature is replete with the description of sequences of developmental events. Such events are required for the construction of viable adult phenotypes, or (more mundanely) for the identification of developmental stage of experimental

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organisms. With the advent of Evo-Devo this understanding now spans from molecular expression through to the phenotype (Hall, 1999) and even, in some cases, the evolutionary and ecological significance for populations of these phenotypes (e.g. Beldade and Brakefield, 2002; Brakefield, 2006). Few workers, however, have considered the degree of plasticity or latitude for variation in such sequences as a subject of serious study. That is not to say that environmentally-mediated changes in development as a whole have been ignored. On the contrary, developmental phenotypic plasticity, and phenotypic plasticity generally, have both been the subject of intense study over the past decade or so (Pigliucci, 1998, 2005; Pigliucci et al., 2006; West-Eberhard, 2003, 2005a, b). However, the plasticity is nearly always examined with respect to the generation of morphologically different adult phenotypes; the occurrence and significance of alterations in the developmental sequence of physiological function are rarely considered.

As with phenotypic plasticity, comparative developmental physiology (CDP) can be seen as a convergence of the studies of genetics, development, physiology and evolution that provides an integrative approach to systems biology (Burggren and Warburton, 2005; Warburton et al., 2006). Yet, it might be argued that, compared with plasticity, CDP is literally at an embryonic stage as a scientific approach. Progress in studying the ontogeny of many physiological systems is still at the first step of scientific investigation; the documentation of patterns. It is unsurprising, therefore, that little has been done to take a CDP approach to studying the developmental sequence of physiological events or stagemarks (Adolph, 1968), yet this approach relates closely to two key strands within CDP: between-species (Spicer and Gaston, 1999; Spicer, 2006; Spicer and Rundle, 2006), and within-individual comparisons (Spicer and Burggren, 2003). At the same time, studying variability (i.e. plasticity) in physiological developmental sequences would serve to link CDP with the current debate on the role of developmental phenotypic plasticity.

The importance of interspecific comparisons of developmental sequences has received some attention recently. Spicer (2006) and Spicer and Rundle (2006) discussed the ecological and evolutionary implications of altered developmental sequences (including physiological events) between ancestor and descendent species (i.e. heterochronies). Here we focus on the importance of potential changes in the timing of physiological events within individuals caused by environmental influences. The term heterokairy was proposed by Spicer and Burggren (2003) for describing such alterations to developmental sequences at the level of the individual.[1] One of the main aims of this paper is to examine the empirical evidence for this phenomenon. However, to provide a wider context and rationale for this review, we first examine the history of ideas and questions that have led to the current day construction and investigation of sequences in CDP. This is followed by a re-examination and clarification of the definition of heterokairy given by Spicer and Burggren (2003). We conclude by tackling the concept of heterochrony as a pattern and a process, including a discussion of the possible relationship between heterokairy and heterochrony.

2. Back to the future

Arguably the idea of fixed (i.e. unchanged and unchanging) sequences in development was originally articulated by Aristotle with its physiological corollary perhaps first expressed explicitly by William Harvey in his studies of the circulation of the blood. In his book *De Mortu Cordis*, Harvey (1651) states that, 'the heart is the first thing that lives and the last that dies, but its auricles (and in snakes, fish and suchlike creatures, the part which serves as an auricle) have life before the ventricles and die after them'. '… whence it is that that which in living creatures is made last fails first, and that which is first made fails last.' In passing it is interesting to note that, the 'view' that Harvey proffered hundreds of years ago (the immutability of the developmental sequence), actually makes a respectable null hypothesis for those who would study the development of an individual's physiology today.

However, in the case of Aristotle at least, there was no real biological rationale or unifying materialistic theory underlying the idea of fixed sequences in development. After the publication of Darwin's *Origin of Species* and the advent of natural selection as a major mechanism underlying evolutionary change, the notion that developmental sequences were not fixed and, indeed, that such alterations were fundamental to evolution was championed by Haeckel in his Biogenetic law (Haeckel, 1866). In Haeckel's view, development could be altered through the terminal "addition" of traits. These additions had a genetic basis. Ultimately, evolution occurred through the phylogenetic "recapitulation" of ontogenies. Hence, although the Biogenetic law suggested that developmental sequences were variable between species, its central tenet was that this variability was restricted to the later stages of development. Haeckel used the term heterochrony to describe 'exceptions' to the law, where evolutionary changes in the rate and/or timing of development occurred. Over the following century it became apparent that such exceptions were, in fact, widespread. Recognition of such exceptions resulted in heterochrony replacing recapitulation as the focus for those workers interested in the relationship between evolution and development (de Beer, 1958; Gould, 1977). However, the use of the term heterochrony, which has its roots as a descriptor of a between-species pattern has expanded over time. Despite explicit attempts to rectify the situation (e.g. Alberch et al., 1979; Gould, 2000), it has often been used to describe a between-species process and even a within-species pattern and/or process (e.g. Spicer and El-Gamal, 1999; Mabee et al., 2000).

The slippage in heterochronal terminology was one of the main prompts for Spicer and Burggren (2003) to re-visit the subject of how developmental sequences within individuals

[1] Heterokairy is constructed from two ancient Greek words 'hetero'- (meaning different or other) and kairos (κκαοίιτρός). Kairos, while difficult to translate, embodies the idea of the 'right time' or the 'opportune' moment, a time when something special happens: "a passing instant when an opening appears which must be driven through with force if success is to be achieved" (White, 1987). Kairos was important to New Testament theology in understanding the timing of events in the earthly ministry of Jesus, and the Sophist school of thought as they majored on rhetor's ability to adapt to and take advantage of changing, contingent circumstances (Scenters-Zapico, 1993).