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Heterokairy: a significant form of developmental plasticity?

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Abstract

There is a current surge of research interest in the potential role of developmental plasticity in adaptation and evolution. Here we make a case that some of this research effort should explore the adaptive significance of heterokairy, a specific type of plasticity that describes environmentally-driven, altered timing of development within a species. This emphasis seems warranted given the pervasive occurrence of heterochrony, altered developmental timing between species, in evolution. We briefly review studies investigating heterochrony within an adaptive context across animal taxa, including examples that explore links between heterokairy and heterochrony. We then outline how sequence heterokairy could be included within the research agenda for developmental plasticity. We suggest that the study of heterokairy may be particularly pertinent in: i) determining the importance of non-adaptive plasticity; and ii) embedding concepts from comparative embryology such as developmental modularity and disassociation within a developmental plasticity framework.
1. Introduction

How common is evolution by heterochrony? We can be certain…its effects have been
catalogued thousands of times and it is the dominant mode of evolution in many important
lineages”[1].

Heterochrony, the altered timing of development between ancestral and descendent taxa,
has been proposed to be one of the major drivers of evolution. Two main approaches have
been used to investigate heterochrony: growth heterochrony, focuses on shifts in growth
allometry, i.e. changes in the size and shape of organisms [1,2]; sequence heterochrony is a
more general measure of the time of onset and sequence of developmental events [3,4]
(Box 1). Growth heterochrony has contributed the majority of examples of heterochrony, but
its focus is somewhat restricted to morphological events late in ontogeny and, because of its
paleontological background [5], uses size as a surrogate for time. Sequence heterochrony
on the other hand, has been investigated more within an early (i.e. embryological)
developmental context and, most recently, uses computational approaches to map the
timing of developmental events onto phylogenies [6-8]. It can be applied in a more
integrative approach that allows the simultaneous investigation of morphological,
physiological and behavioural traits [9,10].

Despite this well documented occurrence of heterochrony as an evolutionary pattern,
exploring its mechanistic basis has not kept pace [but see 11]. The evolutionary potential of
intra-specific variation in the timing of key traits late in development has been discussed
peripherally within more general reviews of the evolutionary importance of heterochrony [1,
12, 13]. More recently, the term heterokairy has been proposed as an explicit descriptor for
the environmentally-sensitive, intra-specific variation in developmental event timing [14] (Box
1), but as yet, has only been applied as such by physiologists [9,15,16] and behavioural
ecologists [17] or within the context of hatching and diapause plasticity [18-20]. Given the
growing emphasis on phenotypic plasticity as a potential driver of evolutionary change [21-
28. there seems ample reason to include heterokairy, a potential driver of heterochrony, within this research agenda.

31. Here we build a case for heterokairy as a key research focus within the field of developmental plasticity and, in particular, the role that such plasticity during early development may play in evolution. We first present the evolutionary context using key examples where heterochrony and heterokairy have been attributed an explicit adaptive basis. We then outline, with examples, how the adaptive significance of heterokairy could be explored using a reaction norm approach, focusing on where heterokairy could contribute to our understanding of the role of non-adaptive plasticity and the integration of concepts from comparative embryology, such as developmental trait modularity, within a developmental plasticity framework.

2. Heterochrony and heterokairy in an adaptive context

One approach to that has been taken to investigate the potential for plasticity to drive evolutionary change is to establish whether there are links between plasticity and evolutionary divergence. This approach could be used to address questions such as: i) does plasticity bias phenotypic diversification by providing alternative phenotypes? [26]; ii) is plasticity positively correlated with the degree of environmental variability experienced by species across known phylogenies? [27]; and iii) do trait plasticities, or trait means, correlate better with fitness optima in new habitats [28]? To date, however, despite several examples where heterochrony has been attributed an adaptive basis [3, 10, 29-34] (see Table 1), there have been few attempts at a correlative approach to linking heterokairy and heterochrony.

There are several examples of adaptive heterochrony in response to habitat shifts (Table 1). In amphibians these shifts are associated with the exploitation of ephemeral habitats where predation risk and competition are reduced; here altered developmental timing occurs through selective pressures to reduce the larval period and hatch early. A phylogenetic basis
for such heterochronic shifts has been shown for spadefoot toads. Species associated with a New World clade occupied ephemeral habitats and had shorter larval periods than those in an Old World clade (sequence heterochrony) and there was also a positive correlation between larval period and morphology (snout and leg length) (allometric heterochrony) [29]. These heterochronies were mirrored by intra-specific plastic responses to temperature; high temperatures decreased larval periods (sequence heterokairy), snout and leg lengths (allometric heterokairy). The reduced larval period in New World species inhabiting more ephemeral sites was suggested to be driven by genetic accommodation from ancestral plasticity. There is also evidence for a potential developmental heterochrony for such life history shifts in anurans in the form of earlier notochord development relative to the time of blastopore closure in fast, compared with slow, developing species [30].

A similar, correlative approach to explore the link between heterokairy and heterochrony has been made with reference to the link between provisioning and life history strategies in marine invertebrates. The evolution of lecithotrophic echinoderm larvae has been suggested to have its origins in developmental plasticity of feeding structures within species driven by different levels of maternal provisioning. A test of this hypothesis using the sea urchin, Paracentrotus lividus showed that under high levels of food there was advanced development of juvenile structures, which mirrored the heterochronic shift observed when larvae received a high level of maternal provisioning [36]. Such plasticity has subsequently been linked to increases in thyroid hormone, as a result of consuming algae that increases development rate [37] and has also been shown in the filter feeding structures of planktonic marine gastropod larvae [38].

Polyphenisms are an extreme form of phenotypic plasticity associated with evolutionary diversification [23,25,39]. Under some circumstances, intraspecific variation in maternal provisioning leads to polyphenisms within larvae. This form of heterokairy, termed poecilogony, has been shown to occur relatively frequently in polychaetes and
opisthobranch molluscs [40,41]. The spionid polychaete Boccardia proboscidea, for example, exhibited sequence heterokairy depending on whether or not they received provisioning [40]. Those, larvae that fed on nurse eggs (adelophagy) had advanced development of juvenile (i.e. post larval) features compared with larvae that received no provisioning. There was also another, more subtle, form of altered timing within larvae that had received provisioning. Some of these larvae hatched as benthic juveniles, whereas the others, despite having exhibited early development of some juvenile features hatched at an earlier developmental stage as smaller planktotrophic larvae that were similar (but not identical) in form to the planktotrophic larvae. Hence, as for spadefoot toads, this shows a combination of sequence (hatching time, metamorphosis) and allometric heterokairy.

These examples provide evidence for potential links between heterokairy and heterochrony, and together with the techniques now available for analysing sequence heterochronies within phylogenies [6] pave the way for a more rigorous phylogenetic approach. The best models for such research will be those where heterochronies occur in traits that are likely to have adaptive significance and where experimental investigation of heterokairy early in development is tractable [42,43].

3. Heterokairy within a reaction norm context

Whilst it is possible to use existing phylogenies onto which heterochronies have been mapped as a starting point for exploring the link between heterokairy and heterochrony, this approach is not without difficulties. For example, inferred adaptations for extinct species may be spurious as selective pressures are likely to change through evolutionary time and a restricted focus on macroevolutionary patterns (i.e. between lineages) may miss important change at lower taxonomic levels. An alternative is to explore the adaptive potential of heterokairy using the approaches currently employed to investigate the micro-evolutionary potential of phenotypic plasticity.
Reaction norms are central to the study of the evolutionary potential of phenotypic and developmental plasticity and allow for formal tests of the relative importance of the genotype, environment and genotype-environment interaction for the expression of the phenotype [44-47]. Such tests can be used to establish the relative importance of local adaptation and plasticity and, hence, the importance of processes such as genetic accommodation and genetic assimilation in natural populations [23,48], or laboratory selection trials [49]. There has been no explicit use of reaction norms in exploring heterokairy, but the importance of considering developmental time within a plasticity context has attracted some attention. An early approach was to use developmental or ontogenetic reaction norms (ORNs) by adding an additional time axis to the traditional reaction norm approach to detect significant genotype*environment*time interactions [44, 50]. For example, response to nutrients in the plant, *Lobelia siphilitica* varied through development and was population dependent [51]. For the grass, *Ampibromus scabralvis*, the degree of plasticity and the genetic variation for plasticity in ramet number to nutrient levels increased through ontogeny [52]. The ORN approach has been extended to assess the plastic expression of different ecomorphs of fish [53-55] and larval dragonflies [56].

Whilst ORNs enabled some investigation of the importance of variation in plasticity through developmental time they have focused on growth heterochrony and changes in size and shape through ontogeny. A focus on environment-driven changes in the timing of developmental events aligned with the sequence heterochrony approach, would allow more integrative studies of the role of developmental plasticity in evolution. This approach could be extended to include links between sequence and allometric heterochrony.

**5. Heterokairy: future directions**

One of the key questions within the study of plasticity for which heterokairy could be particularly pertinent is whether adaptive or non-adaptive plasticity (or both) are likely to promote evolution [57]. It has been proposed that if adaptive plasticity produces a phenotype
that is close to the optimal for that habitat, it will be subject to stabilizing rather than directional selection and so is unlikely to evolve. However, if the phenotype produced falls short of the optimum for the new habitat, but the new phenotype survives, then it is likely to be subject to directional selection and evolution is more likely [58], particularly if there are costs associated with the plasticity [59]. Whilst adaptive plasticity could give rise to evolutionary change, empirical evidence is also accumulating to suggest that non-adaptive plasticity may also play a role in evolution, with recent evidence that it may be more likely to give rise to evolutionary change than adaptive plasticity [60]. When a species population experiences a stressful new environment (e.g. with a higher level of predation) the plastic response it shows is, in many cases, likely to lead to a maladaptive phenotype that does not persist in the new environment. However, if the response includes an increase in the variation of phenotypes expressed revealed through cryptic genetic variation [61], some of the phenotypic variants may be close to the optimum for the new environment and so may be subject to selection [57] (see Box 2).

Some examples of heterokairy sit comfortably within the context of non-adaptive plasticity as they have been observed as physiological stress responses in species exposed to altered environmental conditions and have been shown to have associated costs [9]. For example, the brine shrimp *Artemia franciscana* responded to hypoxia by bringing forward in chronological and developmental time the adult ability to maintain aerobic metabolism over a wide range of external oxygen tensions but this heterokairy was associated with reduced reproductive output [62]. A recent study also showed that those individuals of the intertidal gastropod, *Littorina obtusata* that survived under chronic hypoxia had an early time of onset of their adult heart beat [63]. This example falls within the category of non-adaptive plasticity that could have evolutionary potential (Box 2). Examples of where stress increases phenotypic variance and where clear measures of fitness can be made could offer useful models for exploring the role of non-adaptive plasticity in the form of heterokairy.
The study of heterokairy could provide an exciting opportunity to test theory from comparative embryology within the developmental plasticity framework. For example, the exploration of plasticity in timing of multiple traits in response to different environmental stressors could be used to test for developmental modules (i.e., groups of traits that show similar relative timing in different environments) and levels of dissociation in different environments (i.e., environment-dependent shifts in timing of developmental modules) [64, 65]. Indeed, recent studies of sequence heterokairy in the pond snail, *Radix balthica* showed that, under predation stress, both mantle muscle flexing and crawling had altered timing [42] suggesting that these two developmental events might be part of the same developmental module; under salinity stress, however, there was altered timing in different developmental events, showing that the sensitivity of different developmental modules may be context-dependent in this species. Selection pressures might also drive the dissociation of traits that are part of the same developmental module if the optimum timing for each differed in a novel environment (see Box 2). It would also be important to test how costs of plasticity [59] vary through development and for trade-offs between traits with different timing. For example, it might be predicted that the earlier expression of a ‘costly’ trait could affect traits occurring later in development [66] with implications life history strategies. Here, the use of inbred lines for developmental events that have been shown to be heritable [67] would be an effective resource, as would species for which heterochronic genes have been identified [68]. Finally, the approach of factoring sequence heterochrony into the study of developmental plasticity could also be extended to include tests of quantitative genetic models for evolutionary change during, including the potential role of epigenetic effects [69].

### 6. Conclusions

There is clear evidence that plasticity in the timing of development occurs, including in terms of the sequence of developmental events – this evidence sits within a context of heterochrony as a potential, key evolutionary pattern. In this brief review, we have proposed that a specific strand of phenotypic plasticity research that focuses explicitly on heterokairy
could provide significant evidence in support of the idea of a role of plasticity in evolution. This contribution would not only come from the fact that there is good reason to hypothesise that a mechanism responsible for heterochrony should be an important evolutionary mechanism, but also because the study of sequence heterokairy should also inform other emerging ideas within the plasticity research agenda. This proposition will be extended in a forthcoming, more substantial book chapter.

A key to adopting a sequence based approach to the study of heterokairy is having the ability to measure, with high temporal resolution, the plasticity of events early during development in vivo. Whilst this approach may be difficult for groups such as mammals whose embryos undergo protected development, there are good models to be found amongst other groups such as invertebrates and some fish whose embryonic development occurs in external, transparent eggs. Recent technological developments have also allowed the high resolution video imaging of such embryos that makes the measurement of physiological events tractable [67].
References


Box 1: Heterochrony and heterokairy

A) **Sequence heterochrony** is a change in developmental event timing between ancestral and descendent species. Unlike growth heterochrony, which tends to focus on differences in size and shape late in development, sequence heterochrony gives greater emphasis to the timing and sequence of developmental events during embryonic development and can be applied to morphological, physiological and behavioural traits. Here, the timing of event E occurs earlier in the developmental sequence in the descendent compared with the ancestral species.

B) **Heterokairy** is defined as environmentally sensitive differences in developmental event timing within a species – it is a form of developmental plasticity and differs from heterochrony in that it is an intra-specific phenomenon. Here, heterokairy is shown in the bottom plot, alongside heterochrony (top versus middle plot). In this case for simplicity, the time of onset of a single developmental event is shown for an individual ontogeny in each of two environments.

Box 2: Embedding Heterokairy within Developmental Plasticity

A) **Non-adaptive heterokairy.** The timing of a single developmental event is shown for ten individuals of a species, five in each of two different environments. These event timings are projected onto a reaction norm plot. The optimal timing for this event at each site is indicated by a black star – at site two, an earlier expression of the event is optimal. The reaction norm (dashed line), based on the mean event timing at each site, shows that the plasticity exhibited is non-adaptive as the mean falls short of the (earlier) optimal event timing value for site 2. However, the high phenotypic variation in site 2 means that one individual has an event timing that is close to the optimum. This could lead to directional selection in site 2.

B) **Heterokairy in multiple events.** This plot depicts the timing of two developmental events (A and B) in an ancestral (Environment 1) and two descendent (Environments 2 and 3) environments. Four possible scenarios for the relative timing of two traits are shown for each descendent environment, with the optimal event timing for each trait in each environment indicated by a star and superscript. In Environment 2 the optimal timing has shifted early for event A but not event B; in Environment 3 the optimal timing has shifted earlier for both events. Note that where the timing of trait B is associated with trait A (suggesting they might be part of the same developmental module), the timing of trait B is suboptimal in environment 2 but optimal in environment 3, whereas dissociation between events A & B leads to optimal timing of event B in environment 2 but suboptimal timing in environment 3.
A)

Ancestor

Descendent

Development

B)

Genotype A

Genotype B

Genotype C

Development

Environment

Event timing

Genotype B

Genotype C

Event timing

Event timing
Box 2

A)

Environment 1

Environment 2

Developmental time

Event timing

1 2

Environment

B)

Environment 1

Environment 2

Environment 3

Developmental time
Table 1: Key examples of heterochrony attributed an explicit adaptive context.

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Driver</th>
<th>Trait</th>
<th>Inferred adaptive basis</th>
</tr>
</thead>
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<tr>
<td>Spadefoot toads [29]</td>
<td>Habitat shift</td>
<td>Hatching</td>
<td>Early hatching in New World, species inhabiting more ephemeral water bodies than Old World species.</td>
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<td>Frogs [30]</td>
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<td>Notochord elongation</td>
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<td>Plethodontid salamanders [31]</td>
<td>Habitat shift</td>
<td>Timing of maturity</td>
<td>Paedomorphic loss of adult stage with animals becoming sexually mature as larvae – associated with the transition from running water to subterranean/terrestrial habitat.</td>
</tr>
<tr>
<td>Gastropods (opisthobranch) [33]</td>
<td>Predation</td>
<td>Mantle glands (chemical defence), ciliary tufts, shell growth.</td>
<td>Early development of adult traits suggested increased protection earlier during development.</td>
</tr>
<tr>
<td>Gastropods (pulmonate) [10]</td>
<td>Predation</td>
<td>Crawling within the egg capsule</td>
<td>Advanced timing of crawling in the family Physidae related to comparatively fast crawling and predator avoidance behaviour in hatched snails.</td>
</tr>
<tr>
<td>Gastropods [34]</td>
<td>Food resource</td>
<td>Timing of developmental stages</td>
<td>Shorter trochophore and lengthened veliger (i.e. feeding) stage during development, associated with an evolutionary increase in ocean productivity.</td>
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<td>Echinoderms [35]</td>
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