2016-09-13

Heterokairy: a significant form of developmental plasticity?

Rundle, Simon

http://hdl.handle.net/10026.1/6616

Heterokairy: a significant form of developmental plasticity?

Rundle, S.D.[1,2] & Spicer, J.I.[1]

[1] Marine Biology and Ecology Research Centre, Plymouth University

[2] Corresponding author (srundle@plymouth.ac.uk)

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-

25], there seems ample reason to include heterokairy, a potential driver of heterochrony, within this research agenda.

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 investigatethe 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

56 for such heterochronic shifts has been shown for spadefoot toads. Species associated with a

57 New World clade occupied ephemeral habitats and had shorter larval periods than those in

58 an Old World clade (sequence heterochrony) and there was also a positive correlation

59 between larval period and morphology (snout and leg length) (allometric heterochrony) [29].

60 These heterochronies were mirrored by intra-specific plastic responses to temperature; high

61 temperatures decreased larval periods (sequence heterokairy), snout and leg lengths

62 (allometric heterokairy). The reduced larval period in New World species inhabiting more

63 ephemeral sites was suggested to be driven by genetic accommodation from ancestral

64 plasticity. There is also evidence for a potential developmental heterochrony for such life

65 history shifts in anurans in the form of earlier notochord development relative to the time of

66 blastopore closure in fast, compared with slow, developing species [30].

67

68 A similar, correlative approach to explore the link between heterokairy and heterochrony has

69 been made with reference to the link between provisioning and life history strategies in

70 marine invertebrates. The evolution of lecithotrophic echinoderm larvae has been suggested

71 to have its origins in developmental plasticity of feeding structures within species driven by

72 different levels of maternal provisioning. A test of this hypothesis using the sea urchin,

73 *Paracentrotus lividus* showed that under high levels of food there was advanced

74 development of juvenile structures, which mirrored the heterochronic shift observed when

75 larvae received a high level of maternal provisioning [36]. Such plasticity has subsequently

76 been linked to increases in thyroid hormone, as a result of consuming algae that increases

77 development rate [37] and has also been shown in the filter feeding structures of planktonic

78 marine gastropod larvae [38].

79

80 Polyphenisms are an extreme form of phenotypic plasticity associated with evolutionary

81 diversification [23,25,39]. Under some circumstances, intraspecific variation in maternal

82 provisioning leads to polyphenisms within larvae. This form of heterokairy, termed

83 poecilogony, has been shown to occur relatively frequently in polychaetes and

4

84   opisthobranch molluscs [40,41]. The spionid polychaete *Boccardia proboscidea*, for example,

85   exhibited sequence heterokairy depending on whether or not they received provisioning [40].

86   Those, larvae that fed on nurse eggs (adelophagy) had advanced development of juvenile

87   (i.e. post larval) features compared with larvae that received no provisioning. There was also

88   another, more subtle, form of altered timing within larvae that had received provisioning.

89   Some of these larvae hatched as benthic juveniles, whereas the others, despite having

90   exhibited early development of some juvenile features hatched at an earlier developmental

91   stage as smaller planktotrophic larvae that were similar (but not identical) in form to the

92   planktotrophic larvae. Hence, as for spadefoot toads, this shows a combination of sequence

93   (hatching time, metamorphosis) and allometric heterokairy.

94

95   These examples provide evidence for potential links between heterokairy and heterochrony,

96   and together with the techniques now available for analysing sequence heterochronies

97   within phylogenies [6] pave the way for a more rigorous phylogenetic approach. The best

98   models for such research will be those where heterochronies occur in traits that are likely to

99   have adaptive significance and where experimental investigation of heterokairy early in

100   development is tractable [42,43].

101

102   **3. Heterokairy within a reaction norm context**

103   Whilst it is possible to use existing phylogenies onto which heterochronies have been

104   mapped as a starting point for exploring the link between heterokairy and heterochrony, this

105   approach is not without difficulties. For example, inferred adaptations for extinct species may

106   be spurious as selective pressures are likely to change through evolutionary time and a

107   restricted focus on macroevolutionary patterns (i.e. between lineages) may miss important

108   change at lower taxonomic levels. An alternative is to explore the adaptive potential of

109   heterokairy using the approaches currently employed to investigate the micro-evolutionary

110   potential of phenotypic plasticity.

111

112   Reaction norms are central to the study of the evolutionary potential of phenotypic and

113   developmental plasticity and allow for formal tests of the relative importance of the genotype,

114   environment and genotype-environment interaction for the expression of the phenotype [44-

115   47]. Such tests can be used to establish the relative importance of local adaptation and

116   plasticity and, hence, the importance of processes such as genetic accommodation and

117   genetic assimilation in natural populations [23,48], or laboratory selection trials [49]. There

118   has been no explicit use of reaction norms in exploring heterokairy, but the importance of

119   considering developmental time within a plasticity context has attracted some attention. An

120   early approach was to use developmental or ontogenetic reaction norms (ORNs) by adding

121   an additional time axis to the traditional reaction norm approach to detect significant

122   genotype*environment*time interactions [44, 50]. For example, response to nutrients in the

123   plant, *Lobelia siphilitica* varied through development and was population dependent [51]. For

124   the grass, *Ampibromus scabrivalvis*, the degree of plasticity and the genetic variation for

125   plasticity in ramet number to nutrient levels increased through ontogeny [52]. The ORN

126   approach has been extended to assess the plastic expression of different ecomorphs of fish

127   [53-55] and larval dragonflies [56].

128

129   Whilst ORNs enabled some investigation of the importance of variation in plasticity through

130   developmental time they have focused on growth heterochrony and changes in size and

131   shape through ontogeny. A focus on environment-driven changes in the timing of

132   developmental events aligned with the sequence heterochrony approach, would allow more

133   integrative studies of the role of developmental plasticity in evolution. This approach could

134   be extended to include links between sequence and allometric heterochrony.

135

136   **5. Heterokairy: future directions**

137   One of the key questions within the study of plasticity for which heterokairy could be

138   particularly pertinent is whether adaptive or non-adaptive plasticity (or both) are likely to

139   promote evolution [57]. It has been proposed that if adaptive plasticity produces a phenotype

140 that is close to the optimal for that habitat, it will be subject to stabilizing rather than

141 directional selection and so is unlikely to evolve. However, if the phenotype produced falls

142 short of the optimum for the new habitat, but the new phenotype survives, then it is likely to

143 be subject to directional selection and evolution is more likely [58], particularly if there are

144 costs associated with the plasticity [59]. Whilst adaptive plasticity could give rise to

145 evolutionary change, empirical evidence is also accumulating to suggest that non-adaptive

146 plasticity may also play a role in evolution, with recent evidence that it may be more likely to

147 give rise to evolutionary change than adaptive plasticity [60]. When a species population

148 experiences a stressful new environment (e.g. with a higher level of predation) the plastic

149 response it shows is, in many cases, likely to lead to a maladaptive phenotype that does not

150 persist in the new environment. However, if the response includes an increase in the

151 variation of phenotypes expressed revealed through cryptic genetic variation [61], some of

152 the phenotypic variants may be close to the optimum for the new environment and so may

153 be subject to selection [57] (see Box 2).

154

155 Some examples of heterokairy sit comfortably within the context of non-adaptive plasticity as

156 they have been observed as physiological stress responses in species exposed to altered

157 environmental conditions and have been shown to have associated costs [9]. For example,

158 the brine shrimp *Artemia franciscana* responded to hypoxia by bringing forward in

159 chronological and developmental time the adult ability to maintain aerobic metabolism over a

160 wide range of external oxygen tensions but this heterokairy was associated with reduced

161 reproductive output [62]. A recent study also showed that those individuals of the intertidal

162 gastropod, *Littorina obtusata* that survived under chronic hypoxia had an early time of onset

163 of their adult heart beat [63]. This example falls within the category of non-adaptive plasticity

164 that could have evolutionary potential (Box 2). Examples of where stress increases

165 phenotypic variance and where clear measures of fitness can be made could offer useful

166 models for exploring the role of non-adaptive plasticity in the form of heterokairy.

167

168 The study of heterokairy could provide an exciting opportunity to test theory from

169 comparative embryology within the developmental plasticity framework. For example, the

170 exploration of plasticity in timing of multiple traits in response to different environmental

171 stressors could be used to test for developmental modules (i.e., groups of traits that show

172 similar relative timing in different environments) and levels of dissociation in different

173 environments (i.e., environment-dependent shifts in timing of developmental modules) [64,

174 65]. Indeed, recent studies of sequence heterokairy in the pond snail, *Radix balthica* showed

175 that, under predation stress, both mantle muscle flexing and crawling had altered timing [42]

176 suggesting that these two developmental events might be part of the same developmental

177 module; under salinity stress, however, there was altered timing in different developmental

178 events, showing that the sensitivity of different developmental modules may be context-

179 dependent in this species. Selection pressures might also drive the dissociation of traits that

180 are part of the same developmental module if the optimum timing for each differed in a novel

181 environment (see Box 2). It would also be important to test how costs of plasticity [59] vary

182 through development and for trade-offs between traits with different timing. For example, it

183 might be predicted that the earlier expression of a 'costly' trait could affect traits occurring

184 later in development [66] with implications life history strategies. Here, the use of inbred lines

185 for developmental events that have been shown to be heritable [67] would be an effective

186 resource, as would species for which heterochronic genes have been identified [68]. Finally,

187 the approach of factoring sequence heterochrony into the study of developmental plasticity

188 could also be extended to include tests of quantitative genetic models for evolutionary

189 change during, including the potential role of epigenetic effects [69].

190

191 **6. Conclusions**

192 There is clear evidence that plasticity in the timing of development occurs, including in terms

193 of the sequence of developmental events – this evidence sits within a context of

194 heterochrony as a potential, key evolutionary pattern. In this brief review, we have proposed

195 that a specific strand of phenotypic plasticity research that focuses explicitly on heterokairy

196   could provide significant evidence in support of the idea of a role of plasticity in evolution.

197   This contribution would not only come from the fact that there is good reason to hypothesise

198   that a mechanism responsible for heterochrony should be an important evolutionary

199   mechanism, but also because the study of sequence heterokairy should also inform other

200   emerging ideas within the plasticity research agenda. This proposition will be extended in a

201   forthcoming, more substantial book chapter.

202

203   A key to adopting a sequence based approach to the study of heterokairy is having the

204   ability to measure, with high temporal resolution, the plasticity of events early during

205   development *in vivo*. Whilst this approach may be difficult for groups such as mammals

206   whose embryos undergo protected development, there are good models to be found

207   amongst other groups such as invertebrates and some fish whose embryonic development

208   occurs in external, transparent eggs. Recent technological developments have also allowed

209   the high resolution video imaging of such embryos that makes the measurement of

210   physiological events tractable [67].

References

1. Gould SJ. 1977 *Ontogeny and Phylogeny*. Harvard University Press, Cambridge, M.A., US.

2. Alberch PSJ, Gould SJ, Oster G & Wake D. 1979 Size and shape in ontogeny and phylogeny. *Paleobiol.* **5**, 296-317.

3. Smith KK. 2001 Heterochrony revisited: the evolution of developmental sequences. *Biol. J. Linn. Soc.* **73**, 169-186.

4. Bininda-Emonds OR, Jeffery JE, Richardson MK. 2003. Is sequence heterochrony an important evolutionary mechanism in mammals? *J. Mamm. Evol.* **10**, 335-361.

5. McKinney ML. 1988 *Heterochrony in Evolution: A Multidisciplinary Approach*. Plenum Press, New York..

6. Jeffery JE, Bininda-Emons ORP, Coates MI, Richardson MK., 2005. A new technique for identifying sequence heterochrony. *Syst. Biol.* **54**, 230-240.

7. Colbert MW, Rowe T. 2008 Ontogenetic sequence analysis: using parsimony to characterize developmental sequences and sequence polymorphism. *J. Exp. Zool.* **310**, 398-416.

8. Laurin M, Germain D. 2011 Developmental characters in phylogenetic inference and their absolute timing information. Syst. Biol. **5**, 630-644.

9. Spicer JI, Rundle SD. 2007 Plasticity in the timing of physiological development: physiological heterokairy--what is it, how frequent is it, and does it matter? *Comp. Biochem. Physiol. A* **148**, 712-719.

10. Smirthwaite JJ, Rundle SD, Bininda-Emonds ORP, Spicer JI 2007 An integrative approach identifies developmental sequence heterochronies in freshwater basommatophoran snails. *Evol. Dev.* **9**,122-130.

11. Raff RA, Wray GA. 1989 Heterochrony: developmental mechanisms and evolutionary results. *J. Evol. Biol.* **2**, 409-434.

12. West-Eberhard MJ. 2003. Developmental Plasticity and Evolution. Oxford University Press, New York.

13. McKinney M, McNamara, KJ. 1991 Heterochrony: the Evolution of Ontogeny. Springer, New York.

14. Spicer JI, Burggren WW. 2003 Development of physiological regulatory systems: altering the timing of crucial events *Zoology* **106**, 91-99.

15. Spicer JI, Rundle SD, Tills O. 2011 Studying the altered timing of physiological events during development: it's about time…or is it? *Resp. Physiol. Neurobiol.* **178**, 3-12.

16. Burggren WW, Reyna KS. 2011 Developmental trajectories, critical windows and phenotypic alteration during cardio-respiratory development. *Resp. Physiol. Neurobiol.* **178**, 13-21.

17. Muratori FB 2010 Heterokairy as an anti-predator strategy for parasitic species. *Comm. Int. Biol.* **3**, 309-312.

18. Gomez-Mestre I, Wiens JJ, Warkentin KM. 2008 Evolution of adaptive plasticity: risk-sensitive hatching in Neotropical leaf-breeding treefrogs. *Ecol. Monogr.* **78**, 205-224.

19. Touchon J, McCoy MW, Vonesh JR, Warkentin KM. 2013 Effects of plastic hatching timing carry over through metamorphosis in red-eye treefrogs. *Ecology* **94**, 850-860.

20. Varela-Lasheras I, Van Dooren JM. 2014 Desiccation plasticity in the embryonic life histories of non-annual rivulid species. *EvoDevo.* **5**, 16

21. West-Eberhard MJ. 2005 Developmental plasticity and the origin of species differences. *Proc Nat. Acad. Sci.USA* **102**, 6543-6549.

22. Laland KN, Uller, T, Feldman, MW, Sterelny K, Müller GB, Moczek A, Jablonka, E, Odling-Smee J. 2015 The extended evolutionary synthesis: its structure, assumptions and predictions. *Proc. Roy. Soc. Lond. B* **282**, 20151019

23. Wund MA, Baker JA, Clancy B, Golub JL, Fosterk SA. 2008 A test of the "flexible stem" model of evolution: ancestral plasticity, genetic accommodation and morphological divergence in the three-spine stickleback radiation *Am. Nat.* **172**, 449-462.

24. Moczek AP, Sultan S, Foster S, Ledón-Rettig, Dworkin I, Nijhout HF, Abouheif E, Pfenning DW. 2011 The role of developmental plasticity in evolutionary innovation. *Proc. Roy. Soc. Lond. B* **278**, 2705-2713.

25. Pfenning DW, Wund MA, Snell-Rood EC, Cruikshank T, Schlichting CD, Moczek AP. 2010 Phenotypic plasticity's impacts on diversification and speciation. *Trends Ecol. Evol.* **25**, 459-467.

26. Wund MA. 2012 Assessing the impacts of phenotypic plasticity on evolution. *Integr. Comp. Biol.* **52**, 5-15.

27. Van Buskirk J., 2002 A comparative test of the adaptive plasticity hypothesis: relationships between habitat and phenotype in anuran larvae. *Am. Nat.* **160**, 87-102.

28. Godoy O, Valladares F, Castro-Díez 2012 The relative importance for plant invasiveness of trait means, and their plasticity and integration in a multivariate framework. *New Phytol.* **195**, 912-922.

29. Gomez-Mestre I & Buchholz DR. 2006 Developmental plasticity mirrors differences among taxa in spadefoot toads linking plasticity and diversity. *Proc. Nat. Acad. Sci. USA* **103**, 19021-19026.

30. Sáenz-Ponce N, Mitgutsch C, del Pino EM. 2012 Variation in the schedules of somite and neural development in frogs. *Proc. Nat. Acad. Sci. USA* **109,** 20503-20507.

31. Wake DB. 1966 Comparaive osteology and evolution of the lungless salamanders, family Plethodontidae. *Mem. South. Calif. Acad. Sci.* **4**, 1-117.

32. Fišer C, Bininda-Emonds ORP, Blejec A, Sket B. 2008 Can heterochrony help explain the high morphological diversity within the genus *Niphargus* (Crustacea: Amphipoda)? *Org. Div. Evol.* **8**, 146-162.

33. Gibson GD. 2003 Larval development and metamorphosis in *Pleurobrancaea maculate*, with a review of development in the Notospidea. *Biol. Bull.* **205**, 121-132.

34. Lindberg DR, Guralnick RP. 2003 Phyletic patterns of early development in gastropod molluscs. *Evol. Dev.* **5**, 494-507.

35. Snoke Smith M, Zigler KS, Raff RA. 2007 Evolution of direct-developing larvae: selection vs loss. *BioEssays* **29**, 566-571.

36. Strathmann RR, Fenaux L, Strathman MF. 1992 Heterochronic developmental plasticity in larval sea urchins and its implications for evolution of nonfeeding larvae. *Evolution* **46**, 972-986.

37. Heyland A, Hodin J. 2004 Heterochronic developmental shift caused by thyroid hormone in larval sand dollars and its implications for phenotypic plasticity and the evolution of nonfeeding development. *Evolution* **58**, 524-538.

38. Strathmann RR, Fenaux L, Sewell AT, Strathmann MF. 1993 Abundance of food affects relative size of larval and postlarval structures of a molluscan veliger. *Biol. Bull.* **185**, 232-239.

39. Pfenning DW, McGee M. (2010) Resource polyphenism increases species richness: a test of the hypothesis. *Phil. Trans Roy. Soc.Lond.* **365**, 577-591.

40. Gibson GD, Gibson AJF. 2004 Heterochrony and the evolution of poecilogony: generating larval diversity *Evolution* **58**, 2704-2717.

41. Ellington RA, Krug PJ. 2006 Evolution of poecilogony from planktotrophy: cryptic speciation, phylogeography, and larval development in the gastropod genus *Aldeira*. *Evolution* **60**, 2293-2310.

42. Rundle SD, Smirthwaite JJ, Colbert MW, Spicer JI. 2010 Predator cues alter the timing of developmental events in gastropod embryos *Biol. Lett.* **7**, 285-287.

43. Tills O, Spicer JI, Rundle SD. 2010 Salinity induced heterokairy in an upper estuarine population of the snail *Radix balthica* (Molusca: Pulmonata). *Aquat. Biol.* **9**, 95-105.

44. Schlichting CD, Pigliucci M. 1998 *Phenotypic Evolution: A Reaction Norm Perspective* Sinauer Associates, Inc.

45. DeWitt TJ, Scheiner, SM. 2004 *Phenotypic Plasticity: Functional and Conceptual Approaches.* Oxford University Press.

46. Dingemanse NJ, Kazem AJN, Réale D, Wright J. 2009 Behavioural reaction norms: animal personality meets individual plasticity. *Trends Ecol. Evol.* **25**, 81-89.

47. Murren CJ, Maclean HJ, Diamond SE, Steiner UK, Heskel MA, Handelsman CA, Ghalambor CK, Auld JR, Callahan HS, Pfenning DW, Relyea RA, Schlichting CD, & Kingsolver J. 2014 Evolutionary change in continuous reaction norms. *Am. Nat.* **183**, 453-467.

48. Scoville AG, Pfrender ME. 2010 Phenotypic plasticity facilitates recurrent rapid adaptation to introduced predators. *Proc. Nat. Acad. Sci. USA* **107**, 4260-4263.

49. Sikkink KL, Reynolds RM, Tuarte, CM, Cresko WA, Phillips C. 2014 Rapid evolution of phenotypic plasticity and shifting thresholds of genetic assimilation in the nematode *Caenorhabditis remanei*. *Genes, Genomes, Genetics* **4**, 1103-1112.

50. Pilgliucci M, Schlichting, CD, Jones CS, Schwenk K. 1996 Developmental reaction norms: the interactions among allometry, ontogeny and plasticity. *Plant Species Biol.* **11**, 69-85.

51. Pigliucci M, Schlichting CD. 1995 Ontogenetic reaction norms in *Lobelia siphilitica* (Lobeliaceae): response to shading. *Ecology* **76**, 2134-2144.

52. Cheplick GP. 1995 Genotypic variation and plasticity of clonal growth in relation to nutrient availability in *Amphibromus scabrivalvis J. Ecol.* **83**, 459-468.

53. Hjelm J, Svanbäck R, Byström P, Persson L, Wahlström E. 2001 Diet-dependent body morphology and ontogenetic reaction norms in Eurasian perch. *Oikos* **95**, 311-323.

54. Parsons KJ, Sheets HD, Skúlason S, Ferguson MM. 2011 Pheotypic plasticity, heterochrony and ontogenetic repatterning during juvenile development of divergent Arctic charr (*Salvelinus alpinus*) *J. Evol. Biol.* **24**, 1640-1652.

55. Corse E, Neve G, Sinama M, Pech N, Costedoat C, Chappaz R, Gilles A. 2012 Plasticity of ontogenetic trajectories in cyprinids: a source of evolutionary novelties. *Biol. J. Linn. Soc.* **106**, 342-355.

56. Arnqvist G, Johansson F. 1998 Ontogenetic reaction norms of predator-induced defensive morphology in dragonfly larvae. *Ecology* **79**, 1847-1858.

57. Ghalambor CK, McKay JK, Carroll SP, Reznick DN. 2007 Adaptive versus non-adaptive phenotypic plasticity and the potential for contemporary adaptation in new environments. *Funct. Ecol.* **21**, 394-407.

58. Price TC, Qvarnström A, Irwin DE. 2003 The role of phenotypic plasticity in driving genetic evolution *Proc Roy. Soc. Lond. B* **270**, 1433-1440.

59. Murren CJ, Auld JR, Callahan H, Ghalambor CK, Handelsman CA, Heskel MA, Kingsolver JG, Maclean HJ, Masel J, Maughan H *et al.* 2015 Constraints on the evolution of phenotypic plasticity: limits and costs of phenotype and plasticity. *Heredity* **115**, 293-301.

60. Ghalambor CK, Hoke KL., Ruell EW, Fischer EK, Reznick DN, Hughes KA. 2015 Non-adaptive plasticity potentiates rapid adaptive evolution of gene expression in nature. *Nature doi: 10.1038/15256.*

61. Le Rouzic A, Carlborg Ö. 2007 Evolutionary potential of hidden genetic variation *Trends Ecol. Evol.* **23**, 33-37.

62. Spicer JI, El-Gamal MM. 1999 Hypoxia accelerates the development of respiratory regulation in brine shrimp – but at a cost. *J. Exp. Biol.* **202**, 3637-3646.

63. Rudin-Bitterli TS, Spicer JI, Rundle SD. 2016 Differences in the timing of cardio-respiratory development determine whether larval marine gastropods survive or die in hypoxia. *J Exp. Biol.* **219**, 1076-1085.

64. Poe S. 2004 A test for patterns of modularity in sequences of developmental events. *Evolution* **58**, 1852-1855.

65. Raff EC, Raff RA 2000 Dissociability, modularity, evolvability. *Evol. Dev.* **2**, 235-237.

66. Monaghan P, Haussmann MF. 2015 The positive and negative consequences of stressors during early life. *Early Hum. Dev.* **91**, 643-647.

67. Tills O, Rundle SD, Spicer JI. 2013b. Parent-offspring similarity in the timing of developmental events: a potential link between ontogeny and phylogeny. *Proc. Roy. Soc. Lond. B* **280**, 20131479.

68. Faunes F, Larraín J 2016 Conservation in the involvement of heterochronic genes and hormones during developmental transitions. *Dev. Biol.* **416**, 3-17.

69. Atchley WR, Xu S, Vogl C. 1994 Developmental quantitative genetic models of evolutionary change. *Dev. Genetics* **15**, 92-103.

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.
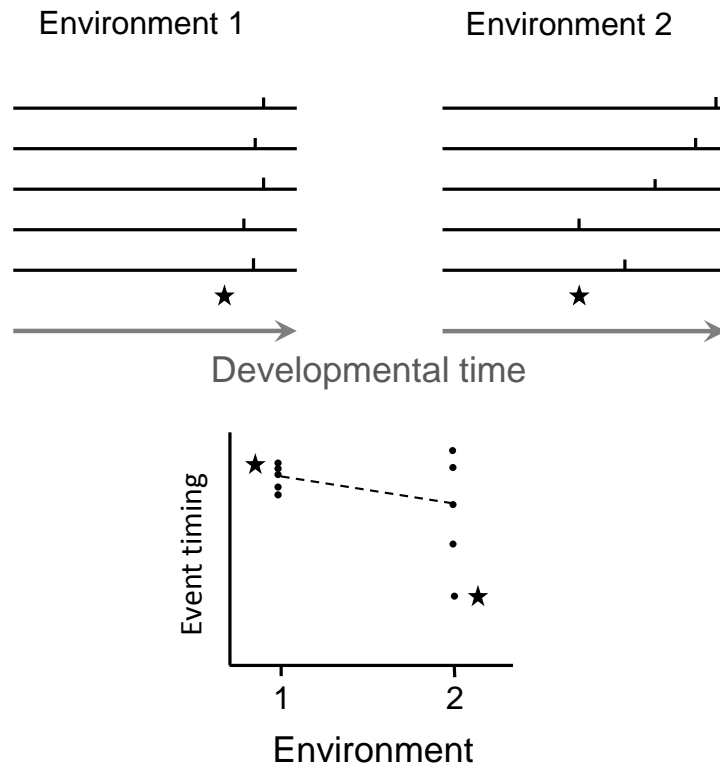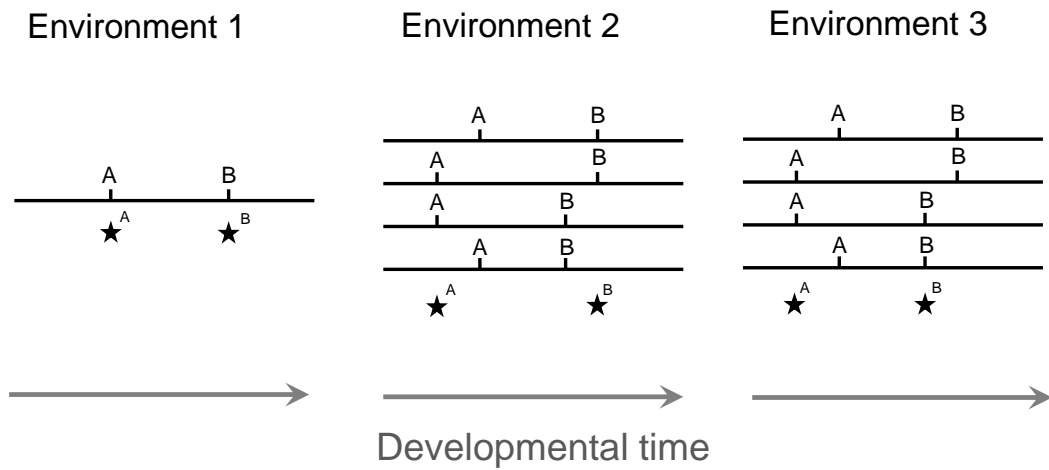
Box 1

A)

B)

Box 2

A)

Environment 1   Environment 2

Developmental time

B)

Environment 1   Environment 2   Environment 3

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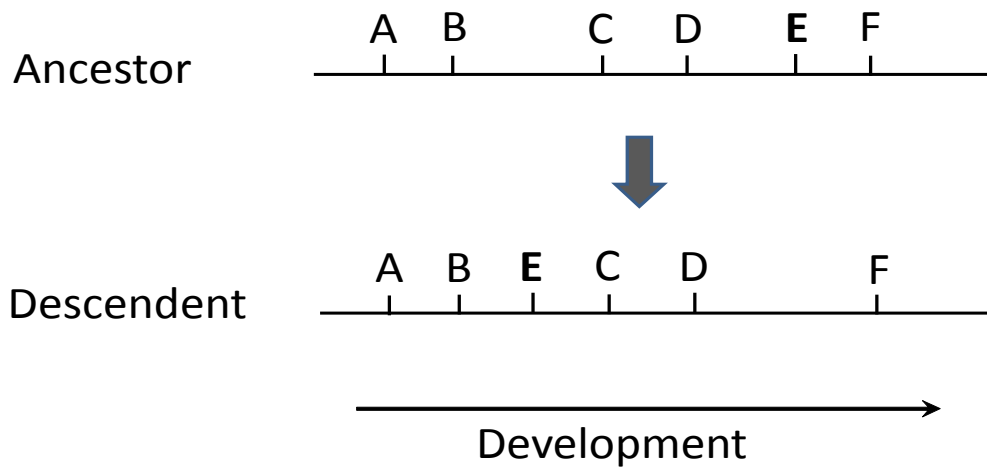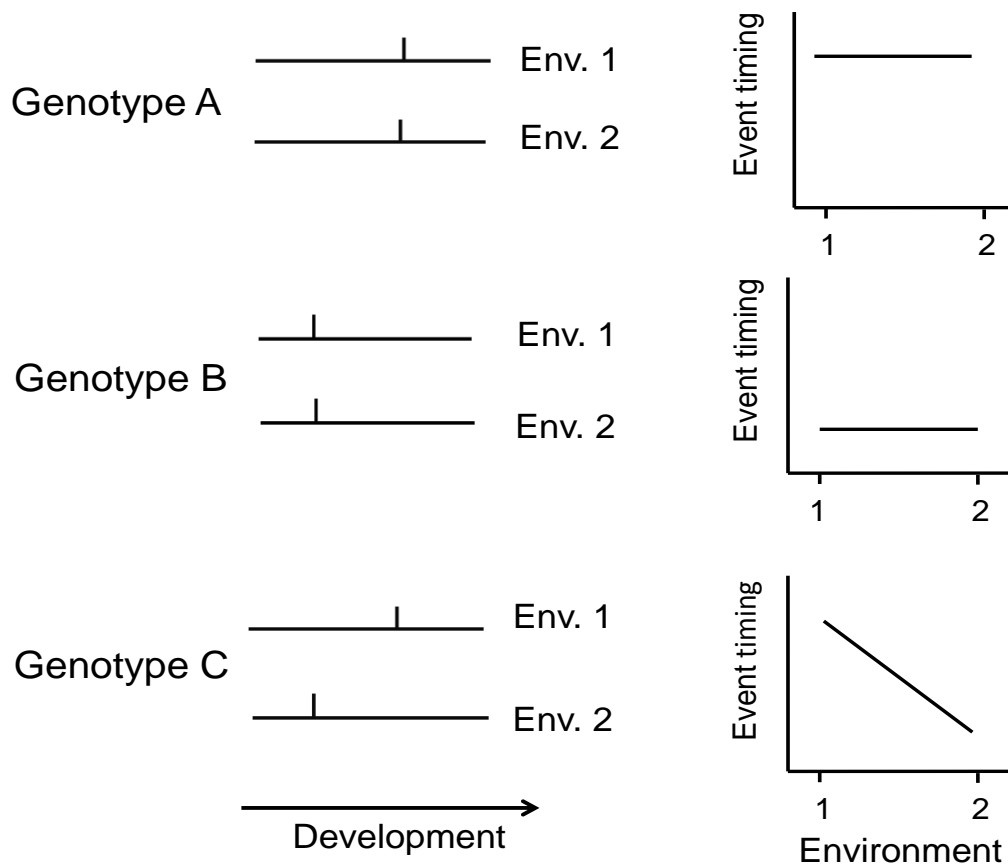
Table 1: Key examples of heterochrony attributed an explicit adaptive context.

Taxon	Driver	Trait	Inferred adaptive basis
Mammals [3]	Food resource	Cranofacial skeletal-muscular and central nervous system	Early development of skeletal-muscular facial features in marsupial comparative to placental mammals associated with feeding at an early stage.
Spadefoot toads [29]	Habitat shift	Hatching	Early hatching in New World, species inhabiting more ephemeral water bodies than Old World species.
Frogs [30]	Habitat shift	Notochord elongation	Early development of notochord in species with more rapid development.
Plethodontid salamanders [31]	Habitat shift	Timing of maturity	Paedomorphic loss of adult stage with animals becoming sexually mature as larvae – associated with the transition from running water to subterranean/terrestrial habitat.
Amphipod crustaceans (*Niphargus* spp.) [32]	Habitat shift	Antenna I and pereopod.	Increased size of 'troglomorphic' features through early onset/accelerated growth.
Gastropods (opisthobranch) [33]	Predation	Mantle glands (chemical defence), cilial tufts, shell growth.	Early development of adult traits suggested increased protection earlier during development.
Gastropods (pulmonate) [10]	Predation	Crawling within the egg capsule	Advanced timing of crawling in the family Physidae related to comparatively fast crawling and predator avoidance behaviour in hatched snails.
Gastropods [34]	Food resource	Timing of developmental stages	Shorter trochophore and lengthened veliger (ie. feeding) stage during development, associated with an evolutionary increase in ocean productivity.
Echinoderms [35]	Food resource	Left coelem development	Acceleration of left coelem development leads to reduced development time and the evolution of lecithotrophic development (i.e. greater dependence on maternal provisioning)