Historical and philosophical perspectives on the study of developmental bias

Short running title: Philosophical perspectives on developmental bias

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Abstract

Throughout the recent history of research at the intersection of evolution and development, notions such as developmental constraint, evolutionary novelty, and evolvability have been prominent, but the term 'developmental bias' has scarcely been used. And one may even doubt whether a unique and principled definition of bias is possible. I argue that the concept of developmental bias can still play a vital scientific role by means of setting an explanatory agenda that motivates investigation and guides the formulation of integrative explanatory frameworks. Less crucial is a definition that would classify patterns of phenotypic variation and unify variational patterns involving different traits and taxa as all being 'bias.' Instead, what we should want is a concept that generates intellectual identity across various researchers, and that unites the diverse fields and approaches relevant to the study of developmental bias, from paleontology to behavioral biology. I point to some advantages of conducting research specifically under the label of 'developmental bias,' compared to employing other, more common terms such as 'evolvability.'

Keywords: developmental bias, developmental constraint, evolvability, evolutionary novelty, explanatory agendas, disciplinary identity

Research highlights

- It may not be possible to arrive at a definition of developmental bias that classifies patterns of phenotypic variation involving different traits and taxa as all exhibiting 'bias.' But such a classificatory definition is not needed.
- The concept of developmental bias can play a vital role by setting an explanatory agenda that motivates research, provides intellectual identity across diverse fields and approaches investigating developmental bias, and coordinates the formation of integrative explanatory frameworks.
- Although there are other, more widely used notions pertaining to the generation of phenotypic variation, such as 'evolvability,' there are reasons for conducting research specifically under the label of 'developmental bias.'

1 Introduction

Various research efforts at the intersection of evolution, development, and other domains are dedicated to how development and related organismal processes generate phenotypic variation. The phenomenon of developmental bias is one instance of this. How the covariation among different characters of one species is biased (e.g., the variation of one or more characters exhibiting a certain directionality while other characters vary in an open fashion) or how the variation of a character across different taxa is biased (e.g., resulting in developmentally driven convergence) is in need of explanation, and calls for an integrative approach to evolution that includes development. At the same time, it is not clear which patterns of and propensities for phenotypic variation actually count as bias and how to define developmental bias. Moreover, one may question why research should be specifically devoted to the issue of 'developmental bias,' as opposed to other prominent explanatory agendas related to the generation of phenotypic variation, such as evolvability and the origin of novelty. Indeed, one may even wonder what phenomena would count as 'bias' or be skeptical of the very idea, on the grounds that it is unclear what the alternative scenario of unbiased development would look like, as has previously been argued for the analogous idea of constraint and constrained development (Salazar-Ciudad, 2006).

My historical and philosophical perspective is not primarily about the phenomenon of developmental bias, but specifically focuses on the *study* of developmental bias. The reason is that I am discussing why—despite all the complexities and the potential futility of defining 'bias'—it may well be fruitful for ongoing and future research to engage in an agenda under the heading of 'developmental bias.' In other words, I set out to explore how the *concept* of developmental bias can play a fruitful role for investigations at the intersection of evolution, development, and other domains.

I start out with a look at the history, which reveals that while even research during the 1980s under the label of 'constraint' had bias in view, the term of 'developmental bias' has been rarely used (with other notions having been much more prominent). The first part of my philosophical discussion (Section 3) argues that having an agreed upon definition of 'developmental bias' is less important, and that the concept of developmental bias can still play a very useful function for scientific practice by setting a joint explanatory agenda, so as to coordinate ongoing and motivate future research. A core insight of this is that there are other functions of scientific concepts apart from defining or classifying phenomena (which might also reconfigure prior criticisms of the definition of constraint; Salazar-Ciudad, 2006). Then I suggest that a particularly important consequence of this is that the concept of developmental bias may generate disciplinary identity—or more precisely, intellectual identity—across the diverse fields and approaches that matter for the investigation of bias. Finally, Section 5 assesses why a focus specifically on 'developmental bias' beyond traditional research in terms of evolvability or novelty may be advantageous.

2 Developmental bias in the history of evolutionary developmental biology

Let us begin with a historical look at research agendas at the intersection of evolution and development during the last four decades—traditions that can be seen as forerunners of evo-devo, but not yet operating under this modern label and including various domains such as paleontology and cell biology. My question is whether a biological phenomenon was a focal issue under investigation by means of a term such as 'developmental bias' having been widely used, or to which extent the phenomenon was still in view despite the absence of the currently preferred label.

2.1 Historical background: developmental constraint

Before getting to our focal notion of developmental bias, I will provide some background by investigating related and historically important concepts. The basic trend has been that whereas the notion of *developmental constraint* was very prominent in the 1980s—in fact providing the main link between evolution and development at this time (as the notion of heterochrony may have done in earlier decades)—subsequently the concept of constraint moved more to the background, and the terms *evolvability* and *novelty* became prominent. A simplistic historical account of this shift assumes that 'developmental constraint' was a negative notion and primarily used as a criticism of neo-Darwinism, in contrast to later notions. Yet a more thorough look at the history will show that constraint has always been part of a positive explanatory agenda (for a more detailed discussion, see Brigandt, 2015).

There is a motivation for the simplistic history. The idea of developmental constraint became widely known throughout overall evolutionary biology among other things in virtue of Gould and Lewontin's (1979) famous critique of adaptationism (the 'spandrels' paper).[1] And neo-Darwinian biologists certainly reacted to the perceived opposition that wielded the concept of constraint (Charlesworth et al., 1982). Such neo-Darwinists problematically construed selection and constraint as two *opposing* forces, where a significant amount of constraint would stamp out natural selection as a force shaping the direction of evolution and resulting in adaptations (Amundson, 1994). Consequently, a major response was to acknowledge that developmental constraint may exist, but that it had only a minor role, so as to provide no challenge to selection (e.g., Charlesworth et al., 1982). If this is all there was to the concept of constraint, then an immediate problem would be that a criticism of the neo-Darwinian (mutation and selection centered) explanatory framework—no matter how convincing a criticism—would not provide any *alternative explanatory framework*. From this perspective, the later shift toward evolvability and evolutionary novelty did provide the necessary positive agenda. Evolvability as understood in evo-devo concerns the generation of morphological variation (Hendrikse, Parsons,

[1] Gould was also the driving force behind using the notion of constraint to explain evolutionary stasis in the punctuated equilibrium model, and to frame this model as an expulsion of neo-Darwinian gradualism (Charlesworth, Lande, & Slatkin, 1982; Eldredge & Gould, 1972).

& Hallgrímsson, 2007; Kirschner & Gerhart, 1998). How variation is generated is in need of explanation—so that the concept of evolvability sets up an active research agenda.

A closer look at history reveals that discussions surrounding developmental constraint in the 1980s did pursue a positive explanatory agenda, and were after more than development restricting the production of possible phenotypes. Moreover, those who coined and actively employed the concept of constraint did *not* view constraint as a force operating on the same level than selection, while pulling in the opposite direction. A well-known article by Oster and Alberch (1982) clearly illustrates this. One diagram of theirs is reproduced here as Figure 1, and it shows that they envision a two-step process. First, development accounts for how genetic changes lead to possible phenotypic transitions—the stage where constraints operate—and subsequently selection determines how some of these phenotypes show up as the realized ones. Thus, constraint and selection are not opposing forces, but orthogonal and complementary processes. Oster and Alberch's vision is that development restricts as well as generates phenotypic variation in the first place—the latter nowadays going under the name of 'evolvability.'

For this historical period, a look at the 1981 Dahlem workshop on 'Evolution and Development' is revealing, as it captures the range of approaches and core scientific concerns that were present at the intersection of evolution and development. Even though the term 'evolvability' was not on the landscape yet (there had only been a few incidental uses of it before the 1980s), similar notions were quite prominent at the Dahlem workshop, as witnessed by the proceeding's detailed reports (Bonner, 1982). There was talk about evolutionary 'opportunity,' evolutionary 'potential,' the 'facilitation' of macroevolutionary transformation and novelty, and evolutionary 'adaptability' (Brigandt, 2015). These are obviously related to evolvability and the evolution of novelty, so that what is now called evolvability and novelty was already on the scientific agenda of the 1980s. Even though back then the focus was on constraint, constraint was seen as connected to evolvability and novelty (Brigandt, 2015). First, in line with what we have seen in Oster and Alberch (1982), development was understood to yield constraints on phenotypic variation as well as novel phenotypic variation (see also Gould, 1989). Second, the release of ancestral constraints was seen as resulting in evolutionary opportunity (i.e., novelty). Third, while these first two ideas create a link between constraint and novelty—yet still viewing them as different phenomena—already at the Dahlem workshop there were also statements

indicating that constraints entail or even *are* opportunities for the generation of novelty: "constraints as such and as evolutionary opportunities" (Horn et al., 1982, p. 218), the theme "of constraint (what novelties are possible and also—the positive side—what novelties are facilitated)" (Maderson et al., 1982, p. 308).[2]

2.2 Developmental bias since the 1980s

It is now time to take a historical look at *developmental bias*. The point that I have made is that although the term 'evolvability' has become much more prominent than the previously favored term 'developmental constraint,' precursor traditions of modern evolutionary developmental biology did have the generation of morphological variation and thus the idea of evolvability in view (albeit using different terms for it). Something similar holds for the idea of developmental bias. Regardless of whether this very term was actively used, discussions in the 1980s around developmental constraint clearly assumed that constraints are not absolute, but bias the generation of morphological variation in certain directions, as this famous definition illustrates:

> A developmental constraint is a bias on the production of variant phenotypes or a limitation on phenotypic variability caused by the structure, character, composition, or dynamics of the developmental system. … By biasing the likelihood of entering onto one pathway rather than another, a developmental constraint can affect the evolutionary outcome even when it does not strictly preclude an alternative outcome. (Maynard Smith et al., 1985, pp. 266 & 269)

The famous paper by Oster and Alberch (1982) mentioned above also contained the tenet that "the dynamics inherent in the process of development itself imposes constraints and biases on morphological evolution that cannot be comprehended from a genetic or a population perspective alone" (p. 454), and their diagram reproduced here as Figure 1 clearly indicated that phenotypic transitions are "non-random." Likewise, Roth and Wake (1989, p. 19) advocated the approach of studying organisms as structurally and functionally coupled systems where such "a

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[2] Likewise, whereas in the 1980s sometimes universal (e.g., physical) constraints were emphasized as something that could not be under genetic control (so as to have an argument against neo-Darwinists), non-universal developmental constraints, such as constraints resulting from cell-cell interactions were already in view (Gerhart et al., 1982). Such constraints are not only subject to evolutionary change, but were seen as providing opportunities for evolutionary innovation (Gerhart et al., 1982, pp. 90-91).

multidimensional approach is to determine why biases occur in evolution and why some kinds of changes are more likely than others" (actually viewing within-system coupling as an alternative perspective to the hitherto focus on constraint).

Beyond noting that the noun 'bias' or more commonly the verb 'to bias' was in play, it is instructive to consider whether and how the overall term 'developmental bias' was used, as this is indicative of terminological trends and preferences, and can reveal whether the focus of research was more on the constraining or the biasing aspect of development. Indeed, whereas in the 1980s the overall term 'developmental constraint' was widely used, I am aware of only one instance where forerunners of current evo-devo used the term 'developmental bias.' It is in the Oster and Alberch paper that I have repeatedly mentioned:

> "developmental program" has perhaps a more deterministic connotation than we intend here. … however, at the cellular level events proceed in a more stochastic fashion … Thus a better term than "developmental program" might be "developmental bias." (Oster & Alberch, 1982, pp. 444-445)

In the 1990s and 2000s, the basic situation persisted that despite some talk about 'bias' the overall term 'developmental bias' has not been very popular. In contrast, the notion of 'evolutionary novelty' prominently made it onto the scientific agenda. And Hendrikse et al. (2007) boldly consider 'evolvability' to be *the* core issue defining evolutionary developmental biology:

> investigating the concepts and phenomena of developmental constraint and bias (modularity, canalization, heterochrony, allometry, and integration) is how evo-devo sheds light on the evolutionary process. … We argue that there are two major ways in which the generation of variation by development is relevant to evolutionary biology: (i) Bias in the direction of variation generated. (ii) Modulation of the amount of variation generated. (Hendrikse et al., 2007, pp. 394 & 396)

Although there is an obvious connection to bias and their phrase "developmental constraint and bias" actually contains the term 'developmental bias,' they do not seem to view it as an independent research agenda and instead subsume it under their evolvability project. Similarly, the recent discussion by Moczek et al. (2015) repeatedly mentions 'bias' and the biasing of variation, but the term 'developmental bias' is used only once, and not until the last page of their extensive discussion.

A notable counterexample, i.e., someone repeatedly using the very term 'developmental

bias' and championing this notion, has been Wallace Arthur—take especially a look at Arthur (2004) in *Evolution & Development*. He connects development up with quantitative genetics by viewing developmental bias as closely related to character covariation. Developmental bias is a general category for Arthur, under which he subsumes developmental drive (the positive aspect) and developmental constraint (the negative aspect). It should not surprise that Arthur only came to adopt the term 'developmental bias' in the more recent stages of his work at the intersection of evolution and development (compare Arthur, 2001b with Arthur, 2006). Arthur (2015) lays out his personal history of thought, where an interesting motivation for the new terminology is that Arthur felt that the traditional 'constraint' had too many negative connotations, so he coined the term 'developmental drive' (in Arthur, 2001a)—an effort to emphasize the positive aspects of development that presumably carries over to his encompassing category of developmental bias.

The upshot of this historical discussion is that the idea that we need to study how phenotypic evolution exhibits bias has been clearly present at least since the 1980s. At the same time, the very term 'developmental bias.' was rarely used. The scarcity of this label suggests that this phenomenon was not considered as requiring special and dedicated attention within (or even beyond) the ongoing study of constraint and evolvability, and that establishing a specific account of developmental bias was not deemed to be necessary over and above a theory of evolvability. Despite this historical situation, in the following philosophical prong of my paper I will discuss reasons for why it may still be advantageous to conduct research specifically in terms of 'developmental bias.' This reflection will also return to some historical perspectives, and put them to better use for the promise of the study of developmental bias than the historical account has done so far.

3 Setting a research agenda without a definition

One challenge is to offer a definition of developmental bias. It is indeed a difficult task to advance a definition that would capture various instances of developmental bias in different taxa and pertaining to all sorts of phenotypic characters—while excluding those patterns of phenotypic variation and those developmental possibilities for variation that do not count as bias. Indeed, one may be skeptical of the very possibility of a principled and unique definition of developmental bias, given that such bias would have to be measured against the alternative scenario of the absence of 'bias.' But any null model of what unbiased (random?) phenotypic

variation may be is likely to be contentious (at least as the one authoritative model defining bias), and such an approach may make developmental bias contingent on our expectations about phenotypic variation, as opposed to it being an objective phenomenon in nature. In each taxon, development brings about the restrictions on and the possibilities for variation it does, but what would it mean for there to be a different type of development (it could not be the absence of development) that would then exhibit unbiased phenotypic variation? This is a genuine worry, as witnessed by Salazar-Ciudad's (2006) analogous argument that the notion of developmental constraint better be abandoned because it is impossible to know what alternative development without constraint would be. And without an agreed upon definition of 'bias' it may appear that there so no real phenomenon to be studied. Despite such issues, my discussion in this and the following sections attempts to make room for a positive role that the notion of developmental bias may have.

Fortunately, the absence (or even impossibility) of an agreed upon *definition* of developmental bias does not mean that this *concept* could not fulfill an important and fruitful scientific function, or so I will argue. Before making this case, it is instructive to take a look at analogous issues with the concept of *evolutionary novelty*. Here as well, definitions of novelty may be contentious (Hallgrímsson et al., 2012; Peterson & Müller, 2013). A genuine definition of novelty would draw a clear line between those phenotypic variants that are novelties and those that are not. But there may be no principled distinction between a mere quantitative variant (which is not novel) and a qualitative difference, which is genuinely novel (Palmer, 2012). There are many concrete cases of structures that are or were considered to be an evolutionary novelty, but where closer inspection reveals that there are in fact some ancestral precursors to this structure, at least on lower levels of organization (Hall & Kerney, 2012). For instance, the autopodium of the tetrapod limb, or at the very least the digits of the autopodium, have traditionally been considered to be a genuine novelty. Yet Hox gene expression patterns also seen in the distal part of fish fins and other data have been used to suggest that even the digits of tetrapods can be homologized with structures in fish (Boisvert, Mark-Kurik, & Ahlberg, 2008; Johanson et al., 2007). Although the neural crest has been deemed a major novelty of vertebrates, there are precursors in non-vertebrate chordates, often dubbed neural crest-like cells (Jeffery, 2007). Generally, a good deal of what seems novel to us may be due to rather minor rearrangements of ancestral developmental pathways, so that even if in addition to

morphological characterizations development is taken into account, the more we understand a novelty, the less novel it seems.[3]

This disagreement about how to define novelty is not a devastating issue, because, as Alan Love and I have argued, the concept of evolutionary novelty fulfills an important scientific function by setting a *problem agenda* (Brigandt & Love, 2012). The concept points to a general issue in need of explanation (an issue that earlier traditions in evolutionary biology tended to neglect), and concomitantly motivates research efforts to address this problem. Our point is that generating an explanation of the evolutionary origin of a trait is an important achievement, regardless of whether this trait really counts as novel on most definitions. Therefore, rather than engaging in debates about how to define novelty, the more fruitful approach is to develop explanatory frameworks accounting for the origin of various structures. Some scientific concepts do serve the purpose of precise description and classification (which in the present case would consist in categorizing traits into novel and non-novel). But there are other scientific functions of concepts (Brigandt & Love, 2012), and in the case of the concept of evolutionary novelty the primary function may well be to set an explanatory agenda. Moreover, a problem agenda consists of several interrelated questions, where in the case of novelty it is clear that contributions from several biological fields are needed, including paleontology, phylogenetics, evolutionary genetics, developmental biology, and ecology. Thereby the problem agenda of novelty coordinates integrative and interdisciplinary research (Brigandt, 2010; Love, 2008).

The implication for my focal topic of *developmental bias* is that it is not essential to have a definition of bias that would lay out which patterns of phenotypic variation or which propensities for generating variation count as bias. Instead, the concept of developmental bias can play a vital scientific role by setting an explanatory agenda and by guiding research. This is possible because scientific concepts can be complex, where a concept may contain a brief definition merely picking out a phenomenon, a larger theory explaining the phenomenon, and/or a research agenda for a scientific discipline. Different such possible components of a concept may play different

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[3] Something similar holds for developmental bias: the better we are able to explain an instance of variational bias as resulting from the developmental system, the more expected it becomes and thus the less biased it seems. But as we will see very soon, this does not make the concept of developmental bias scientifically pointless.

functions for science, indeed, picking out or explaining some phenomenon pertains to features of the natural world, whereas setting an agenda pertains to the activities of scientists.

My position on the concept of developmental bias does not mean that definitions are utterly irrelevant. A glossary-style definition of developmental bias can be useful to get across the basic idea or to teach graduate students. A more specific definition of bias can bring focus on some aspects or instances of developmental bias, although other definitions of bias are then needed to capture other aspects or instances of this phenomenon. My point is rather that even if there is disagreement within a research community about the definition of 'bias' (as one possible component of this concept), there may still be agreement on how to investigate developmental bias and how to develop explanations of bias (as another component of the concept of developmental bias). In my view, it is less important to be able to capture various variational propensities involving different kinds of traits—structural, functional anatomical, physiological, and behavioral—in disparate taxa by means of a unique definition of 'bias', than it is to have a *shared investigative agenda* among the biologists addressing these various cases. Rather than viewing the concept of developmental bias as describing a phenomenon that has been uncovered, my recommendation is to emphasize a forward-looking function of this concept: the way in which it coordinates ongoing investigation and motivates future research.

Once a problem agenda has been put forward, questions about what an adequate explanatory framework must include immediately arise. How to fully explain developmental bias are discussions worth having, so that it more important to reach widespread agreement on such criteria of explanatory adequacy than on what really counts as bias and how to define it. First, while experimental studies pertain to some select extant species, to my mind an explanatory framework would be deficient if it could not (at least in principle) account for the variational patterns seen in extinct species. While there are obvious limits to uncovering the developmental basis of morphological variation for extinct species, research on developmental bias still needs to have paleontological cases and the range of variation seen in the *fossil record* on view.

Second, although by 'bias' one can mean a product (patterns of variation), the issue at hand is the underlying processes that generate *propensities* for (biased) variation, which then result in certain patterns. Quantitative genetics, be means of addressing character covariation, may very well measure variational tendencies, but the agenda is to account for how such tendencies arise based on the underlying *developmental mechanisms*. Moreover, current character covariation

only predicts short-term evolutionary trends, but not how (developmentally based) covariation structure itself is transformed in evolution, so that an account of developmental bias involves understanding how developmental mechanisms can be changed (Salazar-Ciudad, 2006). The basic argument that a scientific problem at hand requires the study of development is of course not new. It was part and parcel of the idea that the phenomenon of developmental constraint requires the involvement of development to understand the trajectories of morphological evolution. But even nowadays it useful to point out that developmental bias sets a problem agenda for evolutionary biology that necessitates explanatory frameworks involving development. Generally, the approach of evo-devo is being advocated precisely because of scientific questions that could not be answered without such an integrative approach (Moczek et al., 2015).

Third, there are still further questions of what additional explanatory components are needed and even what aspects of 'development' are relevant. Many will argue that an explanation of developmental bias requires more than the study of gene regulatory mechanisms. Indeed, several of the contributions to this special issue investigate cases where *phenotypic plasticity* (Draghi, 2019; Levis & Pfennig, 2019; Parsons, McWhinnie, Pilakouta, & Walker, 2019; Uller, Feiner, Radersma, Jackson, & Rago, 2019), *niche construction* (Hu et al., 2019; Laland, Toyokawa, & Oudman, 2019), and *symbiosis* (Gilbert, 2019) form the basis for biases in phenotypic variation. Generally, phenotypic variation is not only generated by means of mutations, but also by environmental changes, where such environmentally induced variation can matter for evolution (Sultan, 2017; West-Eberhard, 2003). As a result, phenotypic plasticity and environmental perturbations are one source of developmental bias (Uller, Moczek, Watson, Brakefield, & Laland, 2018), so that an explanatory framework involving epigenetic and ecological interactions will often be needed to tackle the research agenda set by the concept of developmental bias.

Beyond the three basic criteria I have mentioned, further and more detailed aspects about the shape that an explanatory framework of has to take are needed, if the concept of developmental bias is to successfully guide investigation. But some of this yet has to be established, so that the concept as it will look in the near future may provide enhanced coordination of research.

4 Generating disciplinary and intellectual identity

My suggestion so far has been that even without an agreed upon definition of what counts as developmental bias, the concept of developmental bias could still fulfill an important function for ongoing and future research by setting an explanatory agenda. For it is more important to *explain* propensities for phenotypic variation and variational patterns (and debate the completeness of explanatory frameworks suggested) than to *classify* variational patterns into those that constitute bias and those that do not. Related to having the potential for motivating and guiding explanatory efforts is that the concept of developmental bias may also generate disciplinary identity—which would be another important scientific function for a concept. More precisely, I prefer to speak of *intellectual identity*. But before explaining why, I will motivate my account by a look at the current status and history of evo-devo.

On the one hand, modern evo-devo can be considered a discipline, and even has some of a discipline's institutional hallmarks, such as journals and societies specifically dedicated to this domain. On the other hand, different characterizations of the nature of evo-devo have been advanced (Love, 2015). One option is to say that evo-devo is an *autonomous* discipline, on the grounds that evo-devo has its own methods, concepts, and explanatory models and that it poses its questions and determines the acceptability of answers on its own (Hendrikse et al., 2007). Yet evo-devo methods and concepts are also of relevance to other biological fields, and most importantly, the notion of being an autonomous field obscures that evo-devo has to rely on methods, findings, and concepts from other fields, or at the very least thrives because of its connections to other fields. Indeed, a traditional way to frame evo-devo is as a *synthesis*, a synthesis of at least evolutionary biology and developmental biology (Gilbert, Opitz, & Raff, 1996; Wake, 1996). Additional fields such as ecology may well be involved in this, as more recent calls for an extended evolutionary synthesis emphasize (Laland et al., 2015; Pigliucci, 2009). However, the label 'synthesis' tends to erroneously suggest that several disciplines have been fully unified into a whole, resulting in what were originally separate disciplines being merged into one single discipline. Of course, there are many strands of developmental biology (and even of evolutionary biology) that have not just been synthesized into an evo-devo super-discipline. Likewise, the *approach* of 'eco-evo-devo'—as an important widening of the scope of evo-devo (Abouheif et al., 2014; Gilbert, Bosch, & Ledon-Rettig, 2015; Sultan, 2017)—should not be misconstrued as three disciplines having come to fuse into one discipline.

Rather than either asserting that evo-devo is an autonomous discipline or that instead it is the

synthesis of several past disciplines, I am tempted to adopt the less committal position that evo-devo is an intersection of different approaches, or a coordination among different fields. However, my point is ultimately that we do *not* need to settle on a specific, overarching account of the nature of evo-devo to be able to point to factors that clearly feed into the intellectual coherence and disciplinary identity of evo-devo. Of particular interest are the *core scientific problems* that evo-devo pursues. One such problem is the explanation of evolvability (Hendrikse et al., 2007), and another important issues is to account for the evolutionary origin of novelty (Brigandt & Love, 2012; Wagner, 2000). It is the pursuit of such problem agendas and core explanatory questions that generates evo-devo's *disciplinary identity*. If one wants to avoid implying that evo-devo is exactly one field (especially given that evo-devo's disciplinary nature is in constant flux), one can instead say that these explanatory problems generate evo-devo's *intellectual identity*.

A look at the 1980s provides an instructive reason for my preference to use the label 'intellectual' identity. At this point in history, there was clearly no discipline of evolutionary developmental biology. Instead, researchers working at or close to the intersection of evolution and development came from several quite different fields: population genetics and evolutionary genetics, paleontology, morphology, developmental biology, and even cell biology. A look at the participants of the Dahlem 1981 workshop on evolution and development alone illustrates this diversity (Bonner, 1982). But even without any unique discipline, different studies pursuing the agenda of 'developmental constraint' in the 1980s were clearly part of some joint effort and had a significant degree of intellectual coherence. Thereby, the *concept* of developmental constraint generated intellectual identity to research involving different fields and approaches (Brigandt, 2015).

More so than my historical Section 2 (where it was simply noted that earlier traditions had bias in view, but hardly employed the term 'developmental bias'), this renewed look at the 1980s provides a much more fruitful way to use the history of the forerunners of evo-devo for the current concept of developmental bias. For now my suggestion is that the *concept of developmental bias* may turn out to likewise generate intellectual identity for current or at least future research. This is important because *many different* approaches and fields (even fields outside of evo-devo) are needed in the study of developmental bias. Beyond the investigation of developmental mechanisms, my above discussion has adduced two further criteria for what an

adequate explanatory framework for developmental bias has to include. One was the inclusion of the fossil record and thus the field of paleontology, the other the study of phenotypic plasticity and niche construction and thereby contributions from the fields of ecology and behavioral biology (or at least from ecophysiology).

In a similar vein, the contributions to this special issue illustrate that the study of developmental bias spans different biological domains (and thus implicates different fields): gene regulation (e.g., Hu et al., 2019), parthenogenesis (Galis & van Alphen, 2019), phenotypic plasticity (Draghi, 2019; Levis & Pfennig, 2019; Parsons et al., 2019; Uller et al., 2019), the morphology of extant and fossil species (Jablonski, 2019; Jackson, 2019), brain development (Finlay & Huang, 2019), symbiosis and interactions involving microbial species (Gilbert, 2019), development of the vertebrate skeleton (Kavanagh, 2019), and behavior, learning, and niche construction (Hu et al., 2019; Laland et al., 2019), among others. Some of the studies are experimental, some include field work, and others make primarily use of theory and computational simulation (Draghi, 2019; Hordijk & Altenberg, 2019). Given this diversity of individual projects and biological fields involved, it would indeed be beneficial to have all the researchers united by a common intellectual identity. Whether the concept of developmental bias will generate sufficient identity across scientists and coherence across research projects still remains to be seen (and since intellectual identity is a matter of degree, a future situation can only be judged in terms of how coherence across diverse projects has increased). But as I have argued, at least the absence of an agreed upon definition of what developmental bias really is should not hamper the prospects for this concept to generate intellectual identity, as pursuing a shared explanatory agenda and agreeing on what a complete explanatory framework must include are more crucial.

5 Why specifically study ‘developmental bias’?

Many scientific notions and frameworks are only as good as the novel research they inspire. I have pointed to the potential that the concept of developmental bias holds for motivating explanatory efforts at the intersection of evolution, development, and other domains and for achieving intellectual identity that holds together diverse biological fields and approaches. However, we have also seen that although bias has been in view ever since the concept of developmental constraint highlighted the connection between evolution and development, up to

the present other terms—including evolvability and evolutionary novelty—have been more prominent in scientific discourse. So we now have to ask why one should conduct research specifically under the label of 'developmental bias.' What advantages may the concept of developmental bias have over other notions?

One potential strength of the notion of developmental bias is that it creates an obvious connection with the concept of *character covariation*, as Arthur (2004) has emphasized for some while. Covariation is a central notion of quantitative genetics, so that the concept of developmental bias may provide a way for evo-devo approaches to integrate or at least coordinate with more traditional approaches focusing on population genetics and quantitative genetics. At the same time, the concept of developmental bias cannot just be replaced with the notion of character covariation. Approaches focusing on covariation may measure it quantitatively and theoretically investigate the effects that covariation has on downstream phenotypic evolution. But as Section 3 already emphasized, there is the additional task of mechanistically explaining why a certain covariation structure is present in the first place and how it can be transformed in the course of evolution (Salazar-Ciudad, 2006). A proper explanation involves developmental mechanisms and organism-environment interactions. Unlike the mathematical notion of covariation, the concept of *developmental* bias explicitly highlights this mechanistic explanatory agenda, and why developmental and organismal approaches are needed.

The concept of developmental bias may mesh well with notions that pertain to *quantitative* relations among phenotypic traits in one organism or different lineages. Developmental bias also evolves, so that these quantitative relations are subject to change. However, this evolutionary change still pertains to relations among characters that already existed. This suggest that the concept of developmental bias—focusing on bias in the direction and amount of variation—may obscure qualitative evolutionary change and the evolutionary origin of completely new morphological traits. In contrast, the prominent notion of *evolutionary novelty* explicitly highlights the generation of qualitatively different phenotypic variants. To be sure, research centered on what creates developmental bias may well provide tools for accounting for the origin of novelty, insofar as the evolution of novelty consists in breaking or reconfiguring the specific developmental bias that was present in an ancestral taxon. But the very notion of 'developmental bias' does not capture the generation of novelty particularly well. Overall, this just illustrates the

trivial point that just like any other scientific concept, the concept of developmental bias cannot function as an all-purpose tool. I have emphasized the role that concepts have for setting explanatory agendas. The notion of developmental bias does motivate the mechanistic explanation of how variational biases arise (unlike the concept of covariation), but for highlighting the need to account of generation of novelty other concepts (such as 'evolutionary novelty') are still needed.

Apart from developmental bias, the concept of *evolvability* has been a very widespread notion used by evolutionary developmental biologists to refer to the ways in which phenotypic variation is generated, including the direction of variation (Hendrikse et al., 2007). Still, I can see two virtues that the concept of developmental bias possesses. First, the notion of evolvability encompasses different issues. The reason is that 'evolvability' is often understood quite generically for any biological system that may evolve. The notion is often used in quantitative genetics (Hansen, 2016), where the primary agenda is not to uncover the developmental mechanisms that generate morphological variation and evolvability. If 'evolvability' is abstractly construed as the probability to get to a specific derived state from a given ancestral starting point (Brown, 2013), this includes the way in which *selection* acts on variation, as selection and considerations about the adaptiveness of intermediate and derived traits matter for how evolvable a derived target state is. And even if we restrict our consideration to how 'evolvability' is used within evo-devo (which typically focuses on developmental mechanisms), one can find instances where it is acknowledges that evolvability also has a selection component (Kirschner & Gerhart, 2005). In contrast, the concept of developmental bias more consistently refers to how development and related organismal processes accounts for the structure of phenotypic variation, so as to foreground this important explanatory agenda without conflating it with other issues such as selection and adaptation.

I am actually not sure whether developmentally generated variation and natural selection are fully distinct phenomena (Brigandt, 2015). The scheme of Oster and Alberch (1982) that we see in Figure 1 conveys the common idea that first variation is generated and only then selection can act on it. However, variation generation and the action of selection cannot be distinguished by saying that they are separate, consecutive temporal stages of an organism's life-cycle, because characters arising late in development can exhibit variation, and selection can act at very early developmental stages. One cannot make the separation either by saying that variation generation

is due to features internal to an organism, whereas selection results from the organism's external environment. For external factors and the organism-environment interaction also impacts what phenotypic variation is generated or can be generated, as the phenomena of phenotypic plasticity, behavioral learning, and niche construction show, and features internal to an organism also influence selection pressures. Ultimately, given that the generation of variation is always about *viable and functional* phenotypic variants, considerations about the adaptiveness of phenotypes and thus selection may be implicated, so that the generation of variation and natural selection appear to be entwined.

But even if the generation of variation and the operation of natural selection are not *ontologically* distinct processes in nature, it is to my mind legitimate to distinguish two *epistemological* perspectives. One explanatory project is to account for adaptation, where considerations about selection are important (and variation may be taken as a background condition). Another agenda is to specifically account for how phenotypic variation with a certain structure is produced, and the concept of developmental bias highlights this task, without conflating it with considerations about natural selection as the notion of evolvability tends to do.[4] To be sure, the developmental bias present in a taxon is an evolved property and can be modified by subsequent evolution—both of which are causally influenced by selection. But the explanatory agenda that I view as going under the banner of 'developmental bias' is not to understand how selection and other features of the past causally led to developmental bias, but to account for how the developmental bias of a target taxon is constituted by underlying developmental and organismal mechanisms.

The second advantage that the concept of developmental bias has over the concept of evolvability is that while evolvability pertains to the occurrence of *any* phenotypic variation, including largely random and continuous quantitative variation, the notion of developmental *bias* singles out instances of peculiar variational tendencies that make an explanation in terms of developmental and organismal mechanisms particularly important. Apart from several characters

[4] Not only calls for an extended evolutionary synthesis are motivated by the idea that inheritance, variation, and selection are not independent. But even in this investigative context, it may be legitimate and possibly fruitful to adopt an epistemological perspective that primarily focuses on accounting for the mechanisms generating phenotypic variation (including variational biases).

of an organism exhibiting biased variation with respect to each other, this includes biased phenotypic variation in different lineages that results in convergence, which then is *not* to be explained in terms of natural selection (similar selection pressures in these lineages), but in terms of the developmental processes generating the variational biases. Thereby the concept of developmental bias explicitly recalls the scientific argument that philosopher Ron Amundson (1989) articulated in debates about developmental constraint: In an empirical context where phenotypic variation largely conforms to neo-Darwinian assumptions of being spontaneous, heritable, abundant, as well as small and continuous in its effect, an explanation in terms of natural selection has indeed a high 'explanatory force' (as Amundson called it). But in an empirical context where there is a significant deviation from these assumptions because variation is clearly biased (due to development), relevant features of *development* actually carry the explanatory force.

Although this point was already made in the past in the context of developmental constraints, it has repeatedly been noted that the term 'constraint' too often raises negative connotations, so as to obscure the generation of new variation (Arthur, 2015; Gould, 1989). And constraint may erroneously been taken to mean universal constraint, which is an easy target for counterexamples and also fails to convey that constraints and biases themselves are subject to evolutionary change (Uller et al., 2018). The term 'developmental bias' is clearly preferable over 'constraint' because it highlights the generation of positive variation, while also having an edge on 'evolvability' by pointing to the production of very distinctive trajectories of phenotypic evolution, which lend support an explanatory strategy in terms of development (without conflating it with the role of selection).

Salazar-Ciudad (2006) made the suggestion to replace the concept of developmental constraint with the concept of the *variational properties of a developmental mechanism*, which might also be a possible alternative to 'developmental bias.' Although the idea of a developmental mechanism's variational properties is an empirically adequate notion, it again includes any instance of variation. As a result, my view is that for the purpose of setting a compelling explanatory agenda and of generating significant intellectual identity across different research projects the label of 'developmental bias' is preferable (similar to how the notion of novelty emphasizes the origin of quantitatively new structures). Moreover, in addition to simply indicating that there is some evolutionary issue worthy of study, in Section 3 I emphasized that

that an agenda setting concept plays a substantial *coordinating* function to the extent to which it also encompasses criteria of explanatory adequacy, which guide research by indicating what an explanatory framework must include and what its shape it has to take. The generic notion of 'variational properties' (or the notion of a 'developmental mechanism') does not seem to offer such criteria. Regarding the alternative concept of developmental bias, apart from the relevance of cases from the fossil record, I have highlighted criteria that call for an eco-devo perspective, which Salazar-Ciudad's (2006) reliance on 'developmental mechanism' could obscure. Biases result not only from the organization of gene regulatory networks, but in many cases also from the nature of phenotypic plasticity, so that the interaction between development and an organism's environment has to be part of the explanatory story (Draghi, 2019; Levis & Pfennig, 2019; Parsons et al., 2019; Uller et al., 2019). Cases of niche construction and animal learning can lead to biases, in which case organism-environment mutual influences, organism-organism interactions, and animal behavior are part of the 'developmental' account (Hu et al., 2019; Laland et al., 2019). Examples of developmental biases due to symbiosis likewise broaden the scope of a general explanatory framework that can include metabolic and physiological interactions between organisms of different species (Gilbert, 2019).

One issue that is hard to capture with the notion of developmental bias is the way in which several characters of an organism can be integrated so as to vary in a coordinated and functional fashion. This developmental-functional integration was already mentioned in the 1980s (Wagner, 1986) and nowadays is seen as an important phenomenon because it is the basis for few mutational changes resulting in functional, adaptive change in a variety of different characters at the same time. In addition to variational tendencies across several taxa (e.g., supporting convergence), the concept of developmental bias does capture various cases of character covariation in one taxon, but when focusing on cases where some sort of bias is present, it is difficult to convey a connotation where the covariational bias is specifically of a functional-adaptive nature. Rather, developmental-functional integration is more naturally suggested by the concept of evolvability (Hendrikse et al., 2007) or the related notion of 'facilitated variation' (Kirschner & Gerhart, 2005). But this shows again that a scientific concept such as developmental bias may focus on certain scientifically important aspects, while obscuring others that are better addressed with different concepts.

In summary, research on one of the topics of evolutionary novelty, evolvability, and

developmental bias may well shed light on the other issues. So the question is in what scientific context a particular concept is particularly suitable to play an agenda setting and research coordinating function; and my discussion has covered relative benefits and limitations of different concepts. Although the concept of evolvability may have been the most prominent one to address the generation of phenotypic variation, the concept of development bias does have the advantage of not conflating the generation of variation with the influence of natural selection, and it clearly highlights distinctive variational tendencies that mandate an explanation in terms of a developmental-ecophysiological account.

6 Conclusion

A scientific concept can have several components, including a short definition picking out a phenomenon, a larger theory explaining a phenomenon, or an investigate agenda for a scientific community. Because of this, there can be significant consensus on one component in the face of scientific disagreement over another component; and different concepts may have different primary functions (e.g., classifying, explaining, or mapping out an investigative agenda). In the case of developmental bias, my discussion has granted the challenges of putting forward a *definition* of bias (which also the notion of developmental constraint previously encountered; Salazar-Ciudad, 2006). But I still have argued that the *concept* of developmental bias can play an important scientific role, by means of setting an agenda and coordinating explanatory efforts. More so than debating possible definitions of 'bias,' it is relevant to discuss the adequacy of explanatory frameworks put forward to account for developmental bias, for example, the significance of capturing fossil data or the explanatory relevance of eco-devo processes such as phenotypic plasticity, behavior, and niche construction. My position is that as opposed to a definition that would classify instances of bias and unify disparate variational patterns as all being 'bias,' what we need is a concept of developmental bias that by means of motivating new scientific projects and providing intellectual identity unites the various fields and approaches that are concerned with the study of bias. Although the prominent notion of evolvability addresses the generation of phenotypic variation, I have pointed out that research under the alternative heading of 'developmental bias' has the specific advantage of highlighting distinctive variational tendencies that mandate an explanation in terms of development, and is less likely to conflate this with considerations about natural selection than an 'evolvability' agenda may do.

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Figure legends

FIGURE 1 A diagram from Oster and Alberch (1982), which shows how (despite random genetic transitions) bifurcations in developmental programs result in structured, non-random phenotypic transitions, with these phenotypes then being presented to selection. Reprinted with permission from John Wiley & Sons.