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Title: Integrating the how and why of within- and among-individual variation and plasticity in behavior

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ABSTRACT: While phenotypic variation within and among individuals in the same population may represent “noise”, it can also be the adaptive plasticity that allows organisms to adjust to varying environments or the heritable variation that fuels evolutionary change. Behavioral variation arises from a complex combination of adaptive and non-adaptive individual plasticity and consistency. Differentiating these sources of behavioral variation will require an integrated combination of evolutionary and mechanistic understanding. Yet, this integration comes with a variety of challenges. Here I argue that we will need concrete a priori predictions to make sense of the large and complex datasets this integration will require.

INTRODUCTION

Significant phenotypic variation exists within and among individuals in most populations, even in traits fundamentally connected to fitness such as reproduction [1-11]. This empirical reality has motivated extensive theory aimed at understanding the evolutionary processes that allow genetic and phenotypic variation to arise and persist [12-23]. Yet our empirical understanding of behavioral plasticity (i.e. the production of different behaviors by a single genotype in response to environmental cues and conditions) remains somewhat limited by our ability to make sense of “messy” empirical patterns [4,9,20-28]. How do we know if the variation we are observing is simply “noise” (i.e. non-adaptive genetic or phenotypic variation), adaptive plasticity or heritable phenotypic variation?

At a conceptual level, the answer to this question seems simple. We need only know whether the variation is heritable and how it affects fitness. In reality, it is much more challenging. One reason for this challenge is that real behavioral variation does not fit neatly into these simple conceptual categories (Figure 1) [6,11,18,29,30]. Instead, genetic variation for behavior and plasticity in behavior can coexist and observed patterns involve a complex mix of adaptive and non-adaptive variation [15,31]. Organisms exhibit both consistency and plasticity in behavior, and we now realize that understanding one requires explaining the presence or absence of the other [22,32]. There is also an increasing appreciation that unexplained within-individual variation (or intra-individual variability) is not just “noise”; it can inform our understanding of selection on and the constraints underlying plasticity and consistency [20,22,23,32-34]. Furthermore, the mechanisms underlying behavioral plasticity likely influence the fitness of plastic genotypes and an organism’s ability to exhibit plasticity; these mechanisms may therefore bias, facilitate or even constrain phenotypic evolution [35,36]. Fully understanding how behavioral plasticity evolves and affects observed patterns of behavior therefore requires knowing more about the genetic and mechanistic basis of behavioral plasticity.

Here, I focus on behavioral variation and plasticity, though many of the arguments apply to other forms of phenotypic variation. I first briefly review some of the evolutionary explanations for the existence of behavioral variation and plasticity. Second, I review recent arguments for the importance of integrating evolutionary (i.e. ultimate or why explanations) and mechanistic (i.e. proximate or how explanations) perspectives in the study of behavior and suggest that concrete evolutionary theory incorporating the genetic, regulatory and neuroendocrine basis of behavioral variation is needed. Finally, I argue that if we want to truly understand the forces that shape within- and among-individual variation in behavior and plasticity, we need to integrate recent advances in our evolutionary understanding of behavioral and plasticity and consistency with the ever-increasing knowledge of the genetic and mechanistic basis of behavioral variation and plasticity. Though challenging, the answer to the seemingly basic question of how and why individuals vary over time and from one another is fundamental to many topics in biology, including why and how the sexes differ from one another and how organisms are predicted to respond to human-induced environmental change.

THE EVOLUTION OF BEHAVIORAL VARIATION AND PLASTICITY

Variation among individuals in the same species can arise from a variety of sources: First, genetic variation among individuals may cause phenotypic variation. This genetic variation may be neutral (e.g. arising from recent mutations or selectively neutral alleles) or adaptive (e.g. maintained by selection). Second, variation arises when identical genotypes produce different phenotypes. This phenotypic variation among individuals of the same genotype can also represent either adaptive phenotypic plasticity (e.g. phenotypic variation that increases the fitness of the genotype on average across environments) or non-adaptive “noise” (phenotypic variation that does not increase the fitness of the genotype on average). Finally, within-individual variation in behavior can arise in response to variation in endogenous and exogenous variables over time and through development. Here, I focus on how and why adaptive variation exists within and among individuals in the same populations, particularly behavioral variation arising from plasticity. It is important, however, to keep in mind that neutral genetic variation and “noise” in the developmental or physiological systems will also produce variation within and between individuals. The challenge is to be able to tease apart how much of the behavioral variation we see represents “noise”, adaptive plasticity or heritable variation and what these patterns of variation tell us about the evolutionary basis, maintenance, and consequences of this variation.

The evolutionary maintenance of genetic variation: Selection is generally predicted to decrease genetic variation-- and thus likely also phenotypic variation—because genes associated with higher fitness will increase in frequency and replace genes or genotypes associated with lower fitness [37-39]. Some genetic variation is predicted to persist due to the new mutations that constantly arise and the persistence of selectively neutral genetic variation [38-40]. Therefore, even if a particular genotype always produces the same phenotype (i.e. there is no plasticity or “noise” in the production of phenotypes, Figure 1A), neutral or non-adaptive genetic variation will coexist in a population with genetic variation that is being maintained by selection [3,41]. Other factors such as gene interactions, trade-offs, pleiotropic effects and variable selection—particularly negative frequency-dependent selection—can also allow genetic variation to persist over evolutionary time [42-45]. Population genetics theory provides a baseline or “null” expectation for how much genetic variation we expect to see in a population. As a result, the amount and kind of genetic variation observed can be used to infer the selective history of a gene or population of interest. This means that our predictions regarding expected patterns of gene sequence variation, though still complex, are relatively firmly grounded in well-established principles of evolutionary theory. This does not mean that challenges do not arise when, for example, comparing large datasets across population or species [24]. But it does mean that first principles exist upon which concrete and a priori predictions can be made that guide the design of empirical studies and allow strong inferences to be made [46-48].

The evolution of plasticity and the maintenance of phenotypic variation:

Unfortunately, it is less clear what baseline predictions can be made regarding how much phenotypic variation one would expect to observe, especially in the presence of plasticity. When variation among individuals has no heritable basis, it may represent

unimportant phenotypic “noise” in behavioral, developmental or physiological systems. On the other hand, it may represent adaptive phenotypic plasticity that allows organisms to adapt to variation in their environment [4,6,11,16,30,32,49]. And in the likely circumstance that the plasticity has a genetic component, plasticity itself can evolve and the resulting phenotypic variation can fuel diversification and speciation [16]. How variation is partitioned within and among individuals in the same population is argued to convey information about the selective and mechanistic forces shaping phenotypic variation [8,22,33]. Finally, individuals vary in their past experiences, which may affect various aspects of their individual state, including growth and condition. These differences in individual “state” will affect not only their phenotype directly (e.g. less food leads to less energy which may lead to lower fecundity) but may also affect individual phenotypes through adaptive phenotypic plasticity (e.g. smaller individuals may invest less in reproduction as a result of adaptive plasticity). While we know a lot about the environmental conditions that favor evolution of phenotypic plasticity and how individual state affects predicted patterns of behavior, teasing apart adaptive plasticity from phenotypic “noise” remains a challenge.

Distinguishing noise from pattern is hard but important: As argued above, knowing whether observed variation represents noise, plasticity or heritable variation seems simple but is actually both challenging and important to our understanding of observation patterns of behavior both within and between populations and species [4,6,8,20,22,23,32-34,50]. While adaptive behavioral variation can be explained by either plasticity or genetic variation, it is most likely caused by a complex combination of the two (Figure 1). Furthermore, though phenotypic variation may be adaptive, at least some of the observed variation will arise from non-adaptive variation in the neural, endocrine and other regulatory processes that turn a genotype into a phenotype and stochastic variation among individuals in experience and state [23,28,51]. Differentiating the line between noise (e.g. stochastic variation in food) and adaptive processes (e.g. adaptive plasticity in response to condition) will require a deeper understanding of the fitness effects of the variation as well as the mechanisms underlying plasticity [8,22,26,33]. Here, I argue that one way to move forward is to integrate evolutionary and behavioral perspectives on phenotypic plasticity and consistency with recent advances in our understanding of the genetic, regulatory, neuroendocrine and physiological basis underlying the behavioral variation within and among species.

INTEGRATING EVOLUTIONARY AND MECHANISTIC PERSPECTIVES

Evolutionary studies of behavior have often (but certainly not exclusively) focused on the fitness consequences of variation in behavior. And immense insights have been gained by documenting the relationship between phenotype and fitness. Understanding the evolution of behavioral plasticity further requires knowing how this phenotype-fitness “map” changes with the environment (e.g. social and non-social biotic and abiotic factors) including the individual’s “environment” or state (such as age, sex, size and experience) [11,16,30]. This means we need not only a phenotype-fitness map but also a “map” between the individual’s environment, phenotype and fitness. A complete evolutionary perspective, however, will also require documenting the genetic variation

underlying plasticity [4,6,49]. It is this heritable variation in plasticity that will allow the evolution of plasticity itself over time and between populations and species [4,6,15,52]. A number of excellent reviews have made the case and suggested frameworks for integrating evolutionary and mechanistic perspectives [25-27,53-58]. These proposed integrative frameworks do not, however, make concrete predictions about how the mechanisms underlying behavioral variation will interact with evolutionary forces that shape and maintain behavioral variation or explicitly consider the evolution of plasticity or within-individual variation [but see 26]. I argue that a complete integration of evolutionary and mechanistic understanding would require an individual-genotype-environment-phenotype-fitness map that includes explicit knowledge of the mechanisms that create the genotype-phenotype map and how these mechanisms affect fitness (Figure 2). Documenting and making sense of such a complex “map” represents a conceptual and empirical challenge.

WHAT DO WE NEED?

Concrete theory based on evolutionary and mechanistic understanding:

In order to make sense of the data this integration will require, I argue that we need to develop concrete a priori evolutionary predictions for 1) how the mechanisms underlying behavioral variation within and among individuals will evolve in response to selection and 2) how and when the mechanisms underlying variation in behavior will constrain or bias the evolution of behaviors and their plasticity. At present, very little theory has incorporated realistic mechanisms underlying variation in behavior into models that predict the evolution of behaviors. An exception is recent work by McNamara, Houston and colleagues [59-64] asking how the cognitive and sensory mechanisms underlying behavioral rules are predicted to affect individual fitness and therefore evolve in response to selection and affect evolutionary outcomes. I suggest that further work of this kind is needed. In particular, I suggest that a useful way forward is to integrate the extensive evolutionary theory on phenotypic plasticity and social reaction norms [16,32,52,65-73] with recent advances in our understanding of the genetic, transcriptomic and neuroendocrine basis of behavior and plasticity [9,25,26,54,74-76]. This approach would allow one to predict the evolution of the mechanisms underlying behavioral consistency and plasticity within and between individuals and ask how these mechanisms constrain plasticity or bias the direction of evolution. This will require balancing the complexity and generality required to make concrete testable predictions.

Empirical data integrating the how and why of behavioral variation: Moving from the existing verbal conceptual frameworks to concrete predictions linking mechanisms to behavior to fitness will require not only more information on how genes interact with the environment through neural, physiological and developmental mechanisms to produce phenotypes, but also a detailed understanding of the genetic basis of plasticity and selection on the mechanisms underlying behavioral plasticity (Figure 2). I suggest that combining evolutionary approaches (such as quantitative genetics, selection gradient analyses, comparative phylogenetic analyses or experimental evolution) with measurement of the genetic, regulatory and neuroendocrine mechanisms underlying variation in behavior will yield the most useful insights because this will allow us to ask

more concrete questions that truly integrate genetic, behavioral and mechanistic understanding (Table 1). For example, if we want to understand the evolution of plasticity under natural conditions, we might first compare gene expression among individuals that differ in behavior. Ideally, however, we should conduct such studies using “animal model” or pedigree analyses combined with measures of individual fitness [3,25-27,56,77] as this would allow us to not only document the gene expression underlying behavioral variation but also begin to understand selection on gene expression and make predictions about the evolution of behavioral plasticity. An alternative approach is to study the quantitative genetics of gene expression underlying behavioral plasticity in the lab [50,78]. Experimental evolution and artificial selection on plasticity coupled with studies of gene expression and the mechanistic basis of plasticity would also allow us to test predictions of theory regarding how the mechanisms underlying plasticity are expected to evolve. Finally, comparative analyses (across population or species) of both behavioral evolution and the mechanisms underlying observed patterns of behavior will inform the degree to which the mechanisms constrain or bias patterns of evolution and how the mechanisms underlying behavioral patterns evolve to allow the evolutionary gain and loss of plasticity.

CONCLUSION

This is an exciting but challenging time to study behavioral variation and plasticity. New methods are bringing exciting new insights. Yet our ability to collect complex data may be outpacing our ability to make sense of observed patterns and rigorously test a priori theoretical predictions. We need to build on the strengths of methods from both evolutionary and mechanistic perspectives and truly combine these approaches rather than simply studying these processes in parallel on the same system or behavior. For this integration of evolutionary and mechanistic perspectives on behavioral plasticity to yield insights it will also have to involve a tight integration of theory and data that directly examines the evolution of the genes and mechanisms underlying behavioral plasticity and their consequences for selection and the evolution of behavioral variation within and among individuals in the same population. Important questions exist and if we rise to the challenge, exciting new insights are possible.

FIGURE LEGENDS AND TABLES

Figure 1: Disentangling the basis of behavioral variation can be challenging. Each panel shows how the phenotype (such as amount of parental care provided, time spent on territory defense or courtship rate) of different genotypes (represented by blue lines) will change as a function of the environment (such as individual condition, ambient temperature or social interactions with conspecifics) A) When behavioral variation is purely genetic in basis (i.e. no plasticity exists) then behavior is predicted to differ between genotypes but will not vary across environments. B) When behavioral variation arises only from plasticity, then no genetic variation exists but behavior varies across environmental conditions. C) Behavioral variation can arise from both plasticity and genetic variation in behavior even if variation among genotypes in plasticity does not exist. D) In reality, behavioral variation likely arises from a combination of genetic variation in behavior, variation arising from plasticity and variation among genotypes in plasticity. While panels A) and B) would be relatively easy to differentiate, panel D) is most likely what actually occurs in most species. The real question is not whether variation arises from genetic variation or plasticity (i.e. A versus B), but instead how much variation in behavior is caused by genetic variation, plasticity or the interaction between the two.

Figure 2: A framework for studying selection on the molecular mechanisms underlying behavior. Ideally, we would like to have information on the mechanisms underlying observed behavior patterns, how these mechanisms interact with environmental conditions to generate behavior patterns and how interactions between individuals affect behavior as well. Finally, we need information linking this understanding of the genetic, environmental and mechanistic basis of behavior with social interactions and fitness variation so that we can estimate selection on the basis of behavioral variation and plasticity. This represents a significant conceptual, theoretical and empirical challenge. Solid black arrows represent endogenous influences on behavioral variation; dashed arrows represent exogenous influences on behavioral variation. Blue solid lines represent the evolutionary feedback between fitness and the mechanisms underlying behavioral variation.

Table 1: Suggested studies on the evolution of mechanisms underlying behavioral plasticity that integrate evolutionary and mechanistic methods.

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Figure 1

Figure 2

Table 1

Evolutionary Approach	Mechanistic Approach	Research Question
Quantitative genetics studies of the genetic basis of reaction norms	Changes in gene expression in response to social environment	What is the heritability of gene expression profiles?
Selection gradient analyses in wild populations	Neuropeptide measurement and manipulation	How does selection on the peptides underlying behavioral plasticity vary across environments?
Phylogenetic comparative analyses	Gene regulatory networks underlying behavior	Does the regulation of behavioral plasticity constrain or facilitate evolutionary transitions?
Artificial selection on behavioral plasticity	Neurogenomics of behavior	How do the neural circuits underlying behavior evolve in response to selection?