

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Issue: *The Year in Evolutionary Biology***Neuroendocrine mechanisms underlying behavioral stability: implications for the evolutionary origin of personality**

Renée A. Duckworth

Department of Ecology and Evolutionary Biology, University of Arizona, Tucson, Arizona

Address for correspondence: Renée A. Duckworth, Department of Ecology and Evolutionary Biology, University of Arizona, Biosciences West, 1041 E. Lowell St., Tucson, AZ 85721. rad3@email.arizona.edu

Personality traits are behaviors that show limited flexibility over time and across contexts, and thus understanding their origin requires an understanding of what limits behavioral flexibility. Here, I suggest that insight into the evolutionary origin of personality traits requires determining the relative importance of selection and constraint in producing limits to behavioral flexibility. Natural selection as the primary cause of limits to behavioral flexibility assumes that the default state of behavior is one of high flexibility and predicts that personality variation arises through evolution of buffering mechanisms to stabilize behavioral expression, whereas the constraint hypothesis assumes that the default state is one of limited flexibility and predicts that the neuroendocrine components that underlie personality variation are those most constrained in flexibility. Using recent work on the neurobiology of sensitive periods and maternal programming of offspring behavior, I show that some of the most stable aspects of the neuroendocrine system are structural components and maternally induced epigenetic effects. Evidence of numerous constraints to changes in structural features of the neuroendocrine system and far fewer constraints to flexibility of epigenetic systems suggests that structural constraints play a primary role in the origin of behavioral stability and that epigenetic programming may be more important in generating adaptive variation among individuals.

Keywords: developmental constraint; epigenetic programming; behavioral flexibility; sensitive periods; ontogeny of behavior

Introduction

Personality traits present a paradox as behavior is often considered the most flexible of phenotypic traits; yet, by definition, personality traits, as consistent differences between individuals in behavior across time and contexts (Box 1), are limited in flexibility (i.e., the ability of individuals to express the full range of possible behavioral variation over time). Recent studies have shown that consistent individual differences in behavior are not only ubiquitous among animals,¹ but also can have important ecological and evolutionary consequences.^{2–6} However, the evolutionary origin of animal personality traits remains poorly understood.^{7,8} Most empirical work has focused on two main aspects of personality traits: explaining variation among individuals and

explaining the frequently observed correlations among suites of distinct personality traits.^{7,9,10} While these components of personality variation are important for understanding the evolutionary maintenance and adaptive significance of personality traits, I focus here on understanding what limits behavioral flexibility and argue that explaining such limits will provide unique insight into the evolutionary origin of personality variation.

Behaviors are often treated as unique, particularly in comparison with morphological traits, because of their seemingly unlimited and open-ended flexibility. Yet, as I discuss below, behavior and morphology are more similar than different with respect to flexibility. This is important to recognize because it means that, rather than developing a novel framework to investigate personality

Box 1. Defining personality

Personality is difficult to define because, until recently, its use has been reserved for the characterization of human traits, and therefore, it is often thought of as a uniquely human attribute. In psychology, a common definition of personality is “characteristics of individuals that describe and account for consistent patterns in feeling, thinking, and behaving.”^{27,167} This definition is not suitable for animal personality research because we rarely have direct insight into what nonhuman animals are thinking and feeling. Therefore, most researchers of animal personality focus strictly on patterns of behavior and define personality as “consistent differences between individuals in behavior across time and contexts.”¹⁶⁷ Recognizing the importance of potential sensitive periods in development for personality, in which large changes in behavior are expected as neuroendocrine systems mature, I would further restrict this definition to adult organisms.

Personality variation describes a pattern of behavioral variation in a population that includes both a temporal component—a limitation to flexibility over time—as well as a comparative component—differences among individuals. This definition does not make any assumptions about either the underlying proximate mechanisms for personality variation or what types of behavior should be considered personality traits. Similar to the term *morph*, which describes a pattern of individual differences in morphological traits, personality provides an easy shorthand for bulkier descriptions, such as “consistent individual differences.” Moreover, explicit adoption of the term *personality* facilitates drawing on the vast resources present in the human personality literature.¹ Finally, adherence to this simple and straightforward definition of personality leaves open multiple levels of evolutionary inquiry. For example, Do species vary in which behavioral traits are personality traits? Are personality traits always correlated with the same suite of behaviors? When does personality variation emerge in development and does this vary among species? and What are the proximate mechanisms underlying personality variation and do they vary among species?

evolution, well-established concepts from the fields of evolutionary morphology and development can be used to understand the origin and evolution of consistent differences in expression of behavior.

In one respect, behaviors are unique in that they constitute the activity of an organism, and therefore, flexibility is an inherent component of every behavior, because organisms, through behavior, move from one state to another (e.g., resting versus active states), making the expression of any particular behavior reversible.^{11,12} Because of this inherent reversibility, behaviors are often assumed to be the most plastic of phenotypic traits.^{13,14} However, there are different categories of trait plasticity.^{12,15} In addition to the aforementioned reversibility, these include developmental plasticity, in which the level of expression of a trait is determined early in an organism’s life and remains stable after an organism reaches maturity, and within-individual flexibility, in which changes in trait expression are possible throughout adulthood. For behavioral traits these distinct types of plasticity are not mutually exclusive—all behaviors are reversible as they are only expressed in response to an internal or external stimulus; yet, at the same time, their

level of expression can be both developmentally plastic and highly consistent in adulthood or developmentally plastic but retain some level of flexibility in adulthood. For example, in birds, aggressive behavior is reversible in the sense that it is only displayed in response to a specific stimulus (e.g., territorial intrusion by a competitor), but at the same time, it can be developmentally plastic if the level of aggression (e.g., the rate at which they attack the intruder) is highly consistent in adulthood because their general aggression tendency was irreversibly set early in development (e.g., from the amount of testosterone exposure in the egg). Using an example from my work on aggression in western bluebirds, we have found a high consistency of expression in adults—repeatability of aggression measured across years ranges from 0.80 to 0.96—that is likely organized early in development through variable maternal allocation of hormones to the egg.^{6,16,17} Yet, western bluebirds still retain some flexibility in their aggressive responses and modulate their responses to better match their partners’ responses.¹⁸ However, this modulation to match their partners’ responses is still quite limited and by no means reverses an individual’s

aggressive personality—a highly aggressive male may dampen his aggression slightly if he pairs with a very nonaggressive female, but he does not become nonaggressive.¹⁸ Therefore, in this species, aggression is at once reversible, developmentally plastic, and shows some flexibility in adulthood.

In this review, I reserve the term *flexibility* to refer to the extent to which an individual can modify their behavior postdevelopment. Behaviors are rarely completely inflexible in their expression, and thus, by characterizing personality traits as behaviors showing limited flexibility, I am referring to limits in the expression of a particular behavior by an individual compared to what is possible as determined by the species or population range of variation. Such limits would be evident if individual trait values did not change over time at all or if they changed over time but only within a limited range of variation such that individual differences within a population were maintained over time. The former is simply an exaggerated case of the latter, whereas the latter is the more common scenario in nature.¹⁹ Both patterns of individual change in behavior indicate a core stability in expression of behavior over time. Exploring the proximate mechanisms that underlie this core stability is the focus of this review.

Current models for the evolution of personality traits assume that limits to flexibility of behavior evolved by natural selection;^{20–24} yet, intrinsic constraints to behavioral flexibility may explain the origin of personality traits without the need to invoke natural selection on flexibility per se.^{8,25} Thus, a key question is: What are the relative roles of adaptive evolution and intrinsic constraints in producing limits to behavioral flexibility?

In this review, I suggest that a greater understanding of neuroendocrine mechanisms underlying behavioral variation is crucial to resolving this debate and to ultimately understanding how personality traits originate and evolve. I argue that behavioral and morphological traits are likely to be analogous in the processes that shape evolution of both plasticity and robustness, as behavioral development is underlain by physical components of the neuroendocrine system that should be governed by the same constraints as other morphological traits. I suggest that a developmental perspective can provide new insight into the origins of personality variation by pinpointing components of the

neuroendocrine system that are inherently limited in flexibility and suggest that these components are the best candidates for understanding the underlying proximate basis of personality variation. Using evidence from recent work on the neurobiology of sensitive periods and maternal programming of offspring behavior and physiology, I suggest that personality differences are formed during a sensitive period very early in an organism's life, possibly even before conception, and that both structural constraints and transgenerational epigenetic effects are implicated in determining natural variation in animal personalities. I conclude with a summary of outstanding questions and future directions.

Limits to behavioral flexibility: insights from principles of evolutionary developmental biology

Behaviors are often assumed to be more plastic than morphological traits;^{13,14} yet, behavior and morphology share more similarities than differences in patterns of expression.^{11,12} On the one hand, many morphological traits change on timescales similar to behavioral change: for example, gut size changes within minutes of ingesting food, skin tone changes within hours of sun exposure, and muscle size changes within days in response to weight lifting. Even when the term *morphology* is equated with skeletal traits, which are often assumed to be highly stable in expression, perceptions of flexibility and stability depend on what components of bones are the focus, as bone density and growth are in constant flux and are remodeled in relation to activity levels.²⁶ On the other hand, many behaviors are highly consistent in their expression throughout an organism's life. Consistent differences in behavior have been found across animals, from butterflies to octopi and from fish to humans.²⁷ Thus, both morphological and behavioral traits span the range of stability and flexibility, and it is only when focusing on reversibility that behavior can be considered more plastic than morphology.

Recognizing analogous variation in behavioral and morphological traits is important because it means that principles of evolutionary developmental biology, a field that has largely focused on morphological traits,²⁸ can be applied to evolution of behavior. A major thesis of this field is that developmental constraints play a significant role in evolution. As such, knowledge of the developmental

underpinnings of trait variation can delineate the range of phenotypes available to selection, and when intrinsic properties of developmental processes limit this range, the evolution of a phenotype is developmentally constrained.^{29–32} “Absolute constraints,” which usually refer to limitations on organismal design due to physical laws, cannot be broken,^{32,33} whereas most constraints are not absolute but instead bias the evolutionary pathway because some phenotypes are easier to produce than others.³⁴ Developmental constraints determine the starting point for evolutionary change, making a developmental perspective well suited to provide novel insights into the origin of personality traits.

Personality variation is widely assumed to be the result of natural selection for stability in expression of behavior;²⁰ however, a developmental perspective suggests that intrinsic constraints to behavioral flexibility may also be important.^{8,30,32,35} The two hypotheses assume different starting points for the evolution of stability in expression of behavior. The selection hypothesis assumes that the default state of behaviors is one of high flexibility, and as such, to produce consistency in expression over time and across contexts, homeostatic buffering mechanisms must evolve. The constraint hypothesis assumes that the default state of some behaviors is one of limited flexibility, and unless there is extraordinarily strong selection for flexibility, expression will be consistent over time. Thus, the question is whether evolution of limits to behavioral flexibility is an end in itself that can only be attained through evolution of buffering mechanisms or whether stable expression is the default state of some behaviors and extraordinarily strong selection would be needed to evolve greater flexibility.

At the most basic level, cellular metabolism, division, and death are inherently flexible processes and occur despite the maintenance of larger-scale components of the phenotype at a steady state.³⁶ Thus, it could be argued that the default state of all traits is flexibility and whenever traits show limited flexibility, it is because natural selection has favored homeostatic mechanisms that buffer the phenotype from environmental variation.³⁷ Such buffering mechanisms can include positive and negative feedbacks, modularity, and redundancy.^{36–39} Thus, if personality variation arises as a consequence of selection for greater stability of behavior, we should observe evidence of these types of buffering mechanisms

in the neuroendocrine components that underlie personality variation. Yet, despite intrinsic flexibility in biological systems, developmental processes must still obey the laws of physics and this can set an upper limit to phenotypic flexibility.^{32,33} The constraint hypothesis would be supported if personality variation is associated with components of the neuroendocrine system that are most limited in flexibility due to physical, energetic, or functional constraints. In the next section, I discuss several potential developmental constraints that could limit behavioral flexibility and produce personality variation as the default state of a particular behavior.

Potential constraints to behavioral flexibility

Determining how constraints on underlying physical components of neuroendocrine systems might affect the expression of behavior requires an understanding of the links between behavioral variation and variation in neuroendocrine systems and how difficult it is to make changes in them (with reference to time, energy, and integration with other components). Such understanding of proximate mechanisms can clarify when there is selection for consistency per se versus when the costs of achieving flexibility in underlying developmental processes exceed the benefits.

The physical components of the neuroendocrine system that underlie behavior are not easily observed and because specific links between the development of these structures and individual variation in behavior are often unclear,^{40,41} flexibility in the neuroendocrine system is rarely considered to limit behavioral flexibility. However, the expression of behavior can only change as fast as changes in the underlying neural and physiological circuits. Rapid changes in behavior, such as changes in activity, state, and thinking, are governed by changes in very rapid responses of the neuroendocrine system, such as neural activation and hormonal responses (Table 1). These responses can occur quickly because the pathways underlying the response are already present and the stimulus needs only to prompt a reaction. For example, transmission of an electrical signal occurs on the order of milliseconds and distribution of hormone can take only a few minutes. Thus, the behavioral reactivity that is underlain by these systems occurs very fast. Learning-related behavioral change

Table 1. Summary of the timescales of change in a sample of components of the neuroendocrine system and their relationship to behavioral change

Physical component	Nature of change	Timescale of change	Relation to behavioral variation	Organism	References
Brain	Overall size	Stable individual differences over life with decreases in old age	Stable differences related to personality? Changes related to mental decline with age	Humans	150,151
Amygdala and hypothalamus	Overall size	Across generation	Influence on personality	Guppies	58
		Years	Decreases in relation to posttraumatic stress, depression, and borderline personality disorder; bipolar disorder	Humans	62,64,152
Amygdala	Density of gray matter	8 weeks	Reduced anxiety in response to relaxation exercises	Humans	153
Cerebral cortex	Overall size	80 days	Environmental enrichment leads to increased size	Rats	154
	Prefrontal cortex size	Stable individual differences with incremental change over 5 years	Differences among individuals correlate with personality traits	Humans	151,155
Neurons	Synaptic function	Seconds to hours	Learning	Humans and various model spp	42
	Synaptic structural change	Highly variable (minutes to hours to days to weeks)	Learning	Various spp	42
	Dendritic spine presence	Large ones: stable for months	Memory	Mice	42
		Small ones: transiently appear for only a few days	Implicated in learning	Mice	156
	Neurogenesis	4 months for new neurons to completely mature	Response to brain injury: reestablishment of normal functions; learning and memory?	Humans	97,157
Neuron firing	Milliseconds	Any reactive response to stimulus	Animals	158	
Endocrine glands	Change in testes size	2 months	Onset of breeding behaviors	Seasonally breeding vertebrates	159
	Change in pituitary size	Typically stable in healthy adults, but may change over months to years with disease onset	Initial increase and then decrease associated with onset of schizophrenia	Humans	59
	Hormone release	Seconds to minutes to hours	Regulates changes in organismal state (e.g., hormone changes during stress response)	Vertebrates	160,161

Continued

Table 1. *Continued*

Physical component	Nature of change	Timescale of change	Relation to behavioral variation	Organism	References
Glucocorticoid (GC) and mineralocorticoid receptors (MRs)	Stability across age cohorts	Relatively stable over life with decreases in old age	Stable differences related to personality? Changes related to senescence?	Rats, mice, dogs, and humans	162,163
	Change in GR levels in response to stress	Change in as little as 12 h, then stable for months or years	Decreased activity, subordinate behavior, altered stress response	Tree shrews, rats, mice	164,164
	Change in MR levels across life-history stage	1–2 weeks	Associated with males changing from preparental to parental behavior	White-crowned sparrow	166

NOTE: All studies are based on changes that can occur in adult organisms. Changes that occur during development (embryo and juvenile stages) are expected to be qualitatively different (more rapid and on a much larger scale), as this is when the majority of tissue growth and organization occurs. GR, glucocorticoid receptor.

occurs over a longer period of time—perhaps days, months, or even years, depending on the complexity of the task and the number of different cognitive and motor systems that need to be trained (Table 1). One reason that learning cannot occur faster is that it takes time for new sensorimotor and neural circuits to be built.⁴² While we have some understanding of neuroendocrine changes related to flexible behavioral responses (e.g., fight or flight responses and learning-related changes), we have a much weaker understanding of the physical basis of stability in behavior.

There are numerous constraints that could limit the speed of changes in neuroendocrine components. Interactions among components of the neuroendocrine system might limit flexibility in adulthood if a postdevelopmental change in one component impedes the functioning of the system as a whole.^{8,43–45} Moreover, changes in the neuroendocrine system are physically limited by the rate of cell division, survival, shape changes, migration, and differentiation, which limits the speed at which tissue can be built and modified.^{46,47} Further, there are physical limitations to neuronal wiring (and rewiring) in the brain because a neuron's proximity to other neurons dictates the speed and likelihood of forming new connections.⁴² Faster tissue growth is also metabolically costly.^{47,48} These energetic costs, together with the aforementioned physical limits, can make rapid changes in neuroendocrine components either difficult or impossible to achieve

and thus should also impose constraints on how quickly changes in expression of behaviors that depend on these components can occur. Ultimately, high energetic costs of switching between behavioral phenotypes (e.g., owing to cortical rewiring) do not necessarily preclude evolution of behavioral flexibility, but may produce a developmental bias toward stability in behavioral expression even in the absence of selection for such stability. Similarly, physical limits to the speed of neuroendocrine changes do not preclude evolution of behavioral flexibility, but may dampen the benefits of changing the expression of behavior if such changes cannot occur fast enough to improve organismal function.

By identifying the most stable components of the neuroendocrine system, we can begin to identify the most likely candidates for the physical basis of personality. Table 1 shows the main components of the neuroendocrine system and the timescales of change in adult organisms. The most stable components are the size of neuroendocrine organs, such as the brain and endocrine glands, and hormone receptor distributions, which suggests that these are the most likely components of the neuroendocrine system to underlie personality variation. Not surprisingly, changes in hormone secretion and neural activation are the most flexible, and thus, behavioral flexibility is unlikely to be constrained by intrinsic limits to circulating hormone levels and current physiological state.^{17,45,49} Because hormones respond to environmental stimuli very rapidly, they are excellent

integrators of flexible phenotypes^{17,50,51} and, as such, it seems unlikely that the activational effects of hormones are a main proximate cause of personality variation.⁴⁹ This is not to suggest that circulating hormone levels are completely decoupled from personality differences; to the contrary, hormone profiles often differ between reactive versus proactive coping styles,^{52,53} and androgen elevation often covaries with variation in aggressive behavior.⁵⁴ However, these hormonal differences are as likely to be a consequence of personality variation as they are to be a cause,⁵² and distinguishing the causal links between neuroendocrine function and behavior remains a challenge for future studies. While the activational effects of hormones are unlikely to be a primary cause of personality variation, the organizational effects of hormones acting during early ontogeny can influence brain anatomy and neurochemistry and determine the distribution of hormone receptors.^{55–57} Thus, there is a much higher possibility that organizational effects of hormones might underlie personality variation. Moreover, such effects acting very early in development may often be difficult to reverse because they would require a system-wide reorganization of hormone levels, receptor density, and distribution, binding proteins, neuronal rewiring, and possibly even structural variation in neuroendocrine organs. Therefore, even if there is great flexibility in each of these individual components, their functional integration (which may be organized early in development through the effects of hormones) may constrain rapid reorganization later in life.

Overall, a comparison of flexibility in different components of the neuroendocrine system points to structural traits as the most constrained component with respect to the speed at which changes can occur (Table 1). It may seem overly simplistic to propose that personality variation is due to variation in the size of neuroendocrine components, such as distinct brain regions; surprisingly, however, there is substantial evidence for links between variation in brain size and personality variation. For example, artificial selection on natural variation in guppy (*Poecilia reticulata*) brain size produced a correlated response in personality traits.⁵⁸ Moreover, variation in brain morphology is linked to affective and personality disorders in humans—for example, pituitary size has been linked to schizophrenia;^{59–61} hippocampal volume has been linked

to depression;⁶² and hippocampal, hypothalamic, and amygdala volumes have been linked to borderline personality disorder.^{63,64} Even though these latter studies focus on abnormal behavior, it is often assumed that personality disorders are simply extreme variants of more modest natural personality variation observed in populations.⁶⁵ One of the few studies to examine natural personality variation in humans found that extraversion, neuroticism, agreeableness, and conscientiousness were correlated with the volume of different brain regions.⁶⁶ It is unclear whether such differences have any causal role in producing personality variation, but they are consistent with the idea that constraints to changes in gross morphology of the brain could underlie consistent individual differences in behavior. Why might individuals vary in relative proportions of different parts of the brain? A recent comparative study of brain evolution in carnivores found a negative relationship among brain regions across species, suggesting that increases in the size of one brain region come at the expense of other brain regions.⁶⁷ How and whether this tradeoff is expressed among individuals in a population is unknown.

A second component of the neuroendocrine system that is unlikely to change rapidly is not necessarily a property of individual systems but of the integration of the system as a whole. The neuroendocrine system comprises a complex set of interactions and feedback loops between multiple endocrine glands, the brain, major organ systems, as well as hormones, their receptors, and the enzymes that either metabolize or bind them. Functional integration among components of such a complex system can preclude large-scale reorganization of the phenotype postdevelopment.^{43,45,68–70} Evidence for this comes from recent studies on neuronal rewiring⁷¹ showing that the process of specializing and integrating neuronal circuits requires both strengthening of used, and destruction of unused, synapses.⁷¹ Mice that are deficient in microglia (cells that can destroy synapses) have weaker synaptic transmission, decreased functional brain connectivity, and behavior patterns that have been previously associated with autism and other neurodevelopmental disorders.⁷² This suggests that neurons that are not being used diminish the function of used neurons and limit the integration of functional networks. In other words, keeping extra neurons for the possibility of learning a new task in the future

can impede the functional competence of current pathways. Thus, tradeoffs between function and plasticity clearly limit flexibility of neuronal rewiring, which presumably limits flexibility of any behavioral changes that would result from such rewiring,⁴² but it is unclear whether such constraints apply only to learned behavior or to other behaviors, such as personality, as well.

Given that the structural components of the nervous and endocrine systems that underlie behavior are subject to the same types of physical constraints as morphology, they should also have similar lag times for change that can prevent evolution of adaptive plasticity.^{8,46,73} There are many examples of morphological traits that can take many hours, days, or years to respond to environmental change.⁷⁴ In contrast to these morphological responses, behavioral responses are assumed to have minimal lag times, and therefore, lag times are rarely considered a significant constraint to behavioral flexibility. Yet, Table 1 shows significant lag times for change in many neuroendocrine components, and so any change in behavior that requires large-scale reorganization of these components will also have substantial lag times.⁷⁵ Thus, the assumption that lag time for behavioral changes is minimal^{73,76} is not warranted as it does not take into account changes that may be necessary in underlying physiological and neurological networks in order to change the level or pattern of expression of a particular behavior.

Recent studies on the neurological basis of imprinting support the prediction that adaptive evolution of behavioral stability should be associated with evolution of specific stabilization and buffering mechanisms. Horn and colleagues have shown that visual imprinting in the chick leads to a cascade of neurological events (see Horn⁷⁷ for review; Fig. 1), during which an initially flexible object preference becomes concretized.⁷⁸ During the imprinting window, a chick is presented with a novel moving object and this stimulates neurons in the hyperstriatum. Directly after this “training period” and after the novel object is removed, inhibitory neurotransmitters are released, dampening neuronal responsiveness in the hyperstriatum—this is thought to protect the newly acquired and potentially unstable imprint from any subsequent visual stimuli.⁷⁹ This is important as, in the wild, the first object that a newly hatched chick sees is

the parent. Once the parent leaves the nest and the chick follows, it will see many more moving non-parent objects and so modification of or replacement of this initial preference with new stimuli would be highly maladaptive. Over the next several hours, various signaling cascades lead to physical changes in the neurons (Fig. 1): first, postsynaptic densities located on dendritic spines increase in length; several hours later *N*-methyl-D-aspartate (NMDA) receptor density increases; and finally, after 24 h, there is an increase in neural cell adhesion molecules (NCAMs), which interact with each other and bind cells together.⁷⁷ Learning-related increases in NCAMs, in particular, are thought to strengthen the binding between synapses, possibly stabilizing dendritic spines and reducing the likelihood of disruption by other learning experiences⁸⁰ (Fig. 2). Thus, there are mechanisms to stabilize the physical connections in the brain following imprinting that mirror in timing the formation of the irreversible behavioral preference of the chick to the imprinted object. This example is instructive for providing insight into the neural mechanisms underlying the formation of stability in expression of behavior and, in particular, demonstrating the types of mechanisms that evolve when there has been strong selection for such stabilization.⁸¹

One interesting finding from studies on the neurobiology of imprinting is that there appears to be both modularity and redundancy—two important mechanisms for evolution of robustness^{37,82,83}—in the storage of the imprinting preference in the brain. Imprinting induces biochemical and physical changes that occur in the intermediate and medial part of the hyperstriatum ventrale (IMHV), but changes on the left and right side of the IMHV are not symmetrical despite the fact that neuronal responsiveness to an imprinted stimulus is equally strong on both sides.⁸⁴ Therefore, there seems to be overlapping, but not identical, roles of the two sides in this learning process. Moreover, there is also evidence for the formation of a parallel storage system, *S'* (whose location is currently unidentified), which is formed after the visual image is stored in the IMHV.⁷⁷ Redundancy of biological pathways is a common mechanism to achieve robustness of trait function, as one pathway can fail without changing the expression of the trait.³⁷ Modularity is also an important mechanism for a robust phenotype as it enables functioning of the system as a

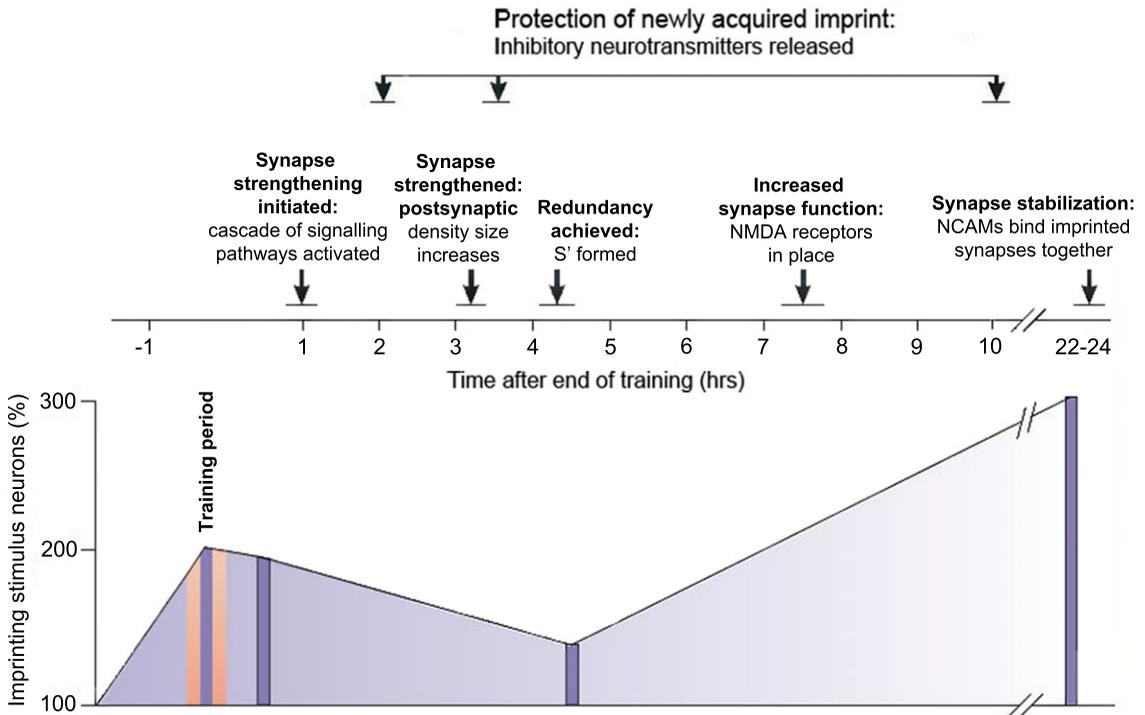


Figure 1. Changes in the intermediate and medial part of the hyperstriatum ventrale (IMHV) after training produce inflexible expression of imprinted behavior through multiple mechanisms, including synapse stabilization as well as redundancy of the stored imprint. Timing of specific events is indicated above the graph. Shown is the percentage of neurons responding to the imprinting stimulus during presentations of the stimulus (dark purple boxes) relative to the percentage responding before training (100%). Important physical changes occur at ~3 h (increase in postsynaptic densities), 7 h (NMDA receptors now present), and 24 h (NCAMs bind synapses together). Even though the imprint is not yet stable, release of inhibitory neurotransmitters at ~2 h is thought to be crucial in protecting it from disruption by further stimuli until irreversible stabilization has occurred. Adapted from Horn.⁷⁷

whole even when one module fails. For example, in imprinted birds, once the window of imprinting is over, because the visual imprint is stored in multiple locations of the brain, the IMHV can be destroyed without altering the bird's imprinted preference.⁸⁴ Imprinting is a clear example of behavioral stabilization that is adaptive—a more flexible object preference in chicks would be maladaptive in nature as it would increase the chances of offspring following the wrong object and losing their mother. Also, in nature, there is little chance that chicks will imprint incorrectly as the mother is usually present when her eggs are hatching—the time when newly emerged chicks are ready for imprinting. Thus, this example provides support for the prediction that when stability in expression of behavior is itself a target of selection, we should observe evolution of mechanisms that maintain phenotype robustness.

We can compare this evolution of robustness to the neurological mechanisms underlying two other examples of behavioral changes during sensitive periods. In these examples, the main target of selection is probably not for stability of behavior but for enhanced function. During the sensitive period for song learning in birds, a loss of dendritic spines leads to selective elimination of unused synaptic inputs⁸⁰ (Fig. 2B). Such synaptic pruning is a general feature of neurological development and is crucial to learning,⁸⁵ but at the same time, it also places a limit on future flexibility and so most songbirds cannot substantially change their song after the critical window for song learning has closed.⁸⁶ Another example of a neural change that limits behavioral flexibility occurs during a critical period for ocular representation in the visual cortex, where input from visual experience from both eyes is necessary

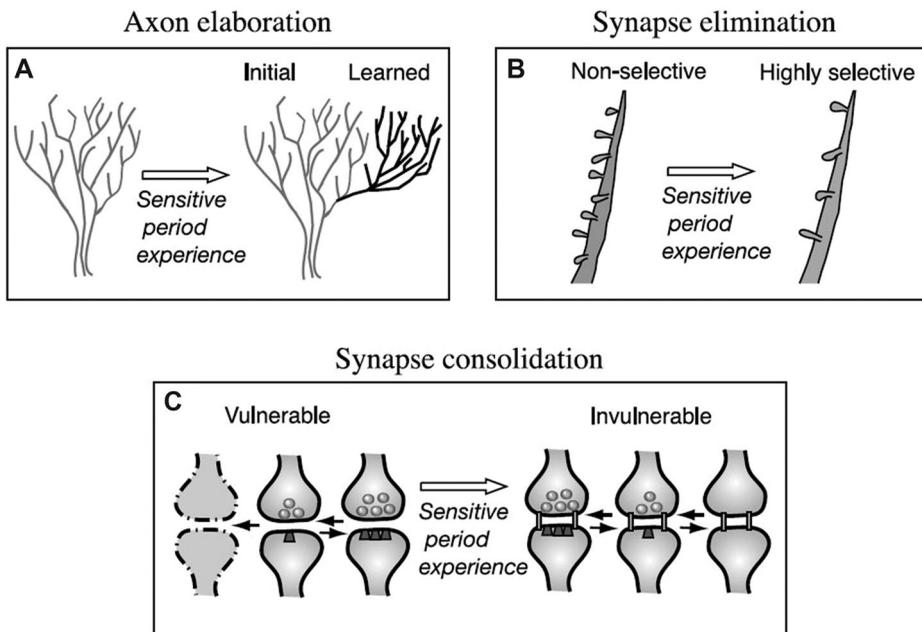


Figure 2. Mechanisms of architectural change that can stabilize a behavioral response during a sensitive period. (A) In axon elaboration, novel connections are created in response to experience. For example, this mechanism underlies irreversible changes in wiring of the visual cortex in cats, depending on input from the right and left eye. (B) Synapse elimination (also known as synaptic pruning), along with neuronal and axon pruning, underlies many processes of learning and enables the retention of only relevant information. During the sensitive period, some synapses are strengthened and others are eliminated. Examples include song learning in birds and language development in humans. (C) Synapse consolidation occurs when repeated activation of a synapse and the postsynaptic neuron during a sensitive period results in insertion of CAMs (vertical bars cross-linking the synaptic membranes), which structurally consolidate the synapse, making it invulnerable to subsequent elimination. Adapted from Knudsen.⁸⁰

for normal development of vision.⁸⁷ Experiments in cats show that, if one eye is shut during the sensitive period, neurons are eliminated in the primary visual cortex of the brain in the region that would have received input from the closed eye and are replaced by overproduction of neurons from the open eye⁸⁷ (Fig. 2A). After the sensitive period is over, the cats can only see out of one eye even when the previously closed eye is opened. Both eyes are functioning normally, but information is only processed from the eye that was open during the critical period because the necessary neuronal connections were not made for the other eye. Subsequent studies in humans have found that any visual impairment in young children during a sensitive period similarly results in a reduction of innervation to the occluded eye.⁸⁸ Unlike the imprinting example, where inflexibility of the imprinted preference itself is likely the target of selection, in the examples related to song learning and the visual cortex, it is more likely that functional competence, not song or visual

inflexibility, is the target of selection. It is easy to imagine that individuals who could tweak their songs as they observe how females respond to them, or kittens that could recover some vision in an eye that was clouded by infection early in life, would be at a selective advantage. Thus, to make sense of limited flexibility in these examples it is necessary to understand constraints to neural plasticity. Limited space in the brain produces a tradeoff between maintaining the potential for future flexibility versus specializing neural circuits on the basis of available information from current input.⁸⁹ If one eye is not functionally properly early in life, it is likely better to use available space to increase acuity of the remaining senses rather than saving flexibility of neural development for the possibility that the eye will begin functioning again.

These examples of critical periods in brain development and learning are instructive in that they suggest how neuronal connectivity and function can be stabilized and buffered from further input.

Importantly, they also show that limited flexibility of some behavioral responses occur proximately because of the underlying physical changes that occur in the brain (Fig. 2). Could these types of mechanisms also underlie stability in personality traits? Most studies on neuronal rewiring focus on the relatively open-ended process of learning that occurs throughout an organism's life. While there is little information about whether differences in neuronal wiring are related to variation in personality traits, there is evidence that there are early developmental differences among individuals in how the brain is wired—a recent study found that, in newborn mice, neuronal circuits were wired differently depending on the timing of their mother's high-fat diet consumption, and this had long-term effects on their metabolism.⁹⁰ Could such variation in early developmental environments also influence the neural wiring that affects personality variation?

Sensitive periods for personality development?

A distinction needs to be made between flexibility that is retained throughout an organism's life and flexibility that is possible during development. All multicellular organisms must go through a period of development in which tissues differentiate, grow, and mature; this is a unique window when traits are particularly sensitive to environmental variation. Once the window of development has closed, some components of the trait are essentially fixed in expression for life. The physical basis of behavioral traits—the nervous and endocrine systems—must also go through a process of cellular differentiation and growth.^{80,91} These systems have a finite period of growth and organization that leads to a window of development when environmental information can be incorporated to make large-scale system-wide changes.⁹¹ In this section, I explore the possibility that personality differences might arise early in life during critical windows of neuroendocrine development.

The idea that there are sensitive periods of behavioral development is not new;^{80,92,93} however, this concept has typically not been applied to personality. In addition to song learning, imprinting, and visual cortex studies, sensitive periods of behavioral development have also been studied extensively in the field of environmental toxicology and medicine, with a focus on abnormal development of

behavior and cognition.⁹¹ Assuming that abnormal phenotypes are simply extreme variants of natural variation,⁶⁵ such studies can be informative about sensitive periods of personality development. For example, recent research suggests that autism, which is highly correlated with many personality traits,⁹⁴ may develop as a result of a disruption of neuronal circuit refinement during critical periods.⁹⁵ Further, childhood exposure to trauma, in the form of abuse or neglect, is associated with a reduced size and neuronal density in several brain regions that may lead to personality disorders later in life.⁹⁶ While these studies are suggestive of a sensitive period for personality development, the most direct evidence would come from studies linking developmental variation in neuroendocrine systems to natural personality variation; to date, there has been very little research on this topic.

The occurrence of sensitive periods in development does not mean that traits cannot be plastic outside of developmental windows, but instead, that the potential for trait plasticity is greater during versus outside of a developmental window. Trait maintenance may require fewer resources than trait development, and it is also easier for the organism as a whole to resist environmental fluctuations once other systems (e.g., liver to metabolize toxins and immune system to protect against pathogens) are in place and fully functioning. Thus, after a developmental window has closed, system-wide reorganization is limited while smaller scale and more local responses to environmental variation are still possible. For example, even though some neural plasticity persists throughout the life span,⁹⁷ there is also evidence that it is highly constrained in the adult brain compared to the developing brain.^{40,80} Changes in large-scale reorganization of axons, dendrites, and myelination are limited as these structures provide a stable scaffold underlying neural circuits, and thus, any changes in structure of the adult brain is local and often short term.⁹⁸ Moreover, there is growing evidence for a link between early developmental stress and its influence on physiology and behavior later in life, which I turn to in the next section.

Maternal programming and early developmental stress: epigenetic mechanisms for personality variation

Most studies of the development of personality focus on the influences of the postnatal environment and

very few investigate the influence of the prenatal environment.^{25,99} However, in the literature on human health, there is abundant evidence for the importance of the prenatal environment for physiology and behavior. While these largely human-based studies mainly focus on disease phenotypes (and hence abnormal behavior), they offer unique insight into potential windows of sensitivity and mechanisms underlying the development of personality differences. Thus, I first summarize the findings of these studies (focusing on human physiology and abnormal behavior) and then connect this work to the animal personality literature.

One of the best documented examples is the Dutch Hunger Winter, a period in the Netherlands from roughly late November 1944 to April 1945 when a combination of a German ban on food transport and a particularly severe winter resulted in food rations of less than 800 calories/day (compared to a normal ~2000 calories/day diet) for people living in the western part of the country.¹⁰⁰ A unique aspect of the Dutch Hunger Winter was that healthcare and reporting services remained intact, allowing identification of individuals who were prenatally exposed to the famine. As a result, individuals that were conceived and born during this time have been the focus of intensive study for over six decades.¹⁰⁰

Exposure to the famine *in utero* resulted in a lower birth weight and a multitude of long-term consequences for health and behavior.¹⁰¹ Decades later, these individuals showed a higher predisposition to obesity, diabetes, heart disease, lung disease, schizophrenia, and antisocial personality disorder.¹⁰¹ Interestingly, these effects vary in relation to the timing of exposure (Fig. 3); individuals exposed only in late gestation had higher glucose intolerance (a measure of risk for diabetes) but exhibited none of the other disease risks, whereas those exposed in midgestation, showed heightened glucose intolerance, as well as a higher risk of lung and kidney disease. Those exposed in early gestation, showed higher risk of both heart disease and diabetes. Individuals whose mothers experienced the famine during the periconceptual period (up to 14 weeks before conception to about 10 weeks into pregnancy) had a heightened risk for schizophrenia, personality disorders, and other psychological problems.^{102–108} Because the only system that can be affected before conception is the epigenetic system, it suggests that such behavioral variation may be

particularly sensitive to early developmental stress that results in epigenetic modifications.^{109–111}

The most striking finding of the Dutch Hunger Winter studies is that all of these effects on health and behavior were the result of prenatal exposure alone. After the liberation of the Netherlands by Allied forces in May 1945, food rations returned to 2000 calories/day and the prenatally exposed babies thereafter experienced normal nutrition for the rest of their infancy and childhood; yet, the prenatal effects on physiology and behavior persisted through life and, in some cases, across multiple generations.^{101,112} What can account for such long-term effects and why can subsequent experience not reverse them?

Some of these effects are thought to be due to the direct effects of malnutrition on specific organs during their period of rapid growth—for example, exposure to famine midgestation results in increased risk of both kidney and lung disease¹⁰¹ (Fig. 3). This timing coincides with the period of rapid increase in nephron number in the kidneys and bronchial tree growth in the lungs, suggesting that impaired function is a direct consequence of organismal systems being deprived of adequate resources during periods of peak growth and differentiation. Such deprivation can also directly affect the growth and development of the brain—a study comparing famine-exposed and nonexposed individuals showed that famine-exposed individuals had more brain abnormalities than nonexposed individuals.¹¹³ Thus, prenatal exposure to malnutrition *in utero* during system-specific periods of sensitivity can have long-term consequences on brain development.

However, the direct effects of nutrition on organogenesis cannot explain all of the problems experienced by famine-exposed individuals. Instead, maternal programming is implicated because, even in the absence of a poor diet, maternal stress hormones are sufficient to cause lower infant birth weights and higher levels of adult hypertension, glucose intolerance, and psychological disturbances.¹¹⁴ Evidence for this comes from studies in rats where famine-induced effects disappear if maternal glucocorticoid synthesis is inhibited (via either drugs or adrenalectomy), demonstrating that many of the negative effects in offspring are likely due to the organizational effects of maternal stress hormones rather than direct effects of nutrient

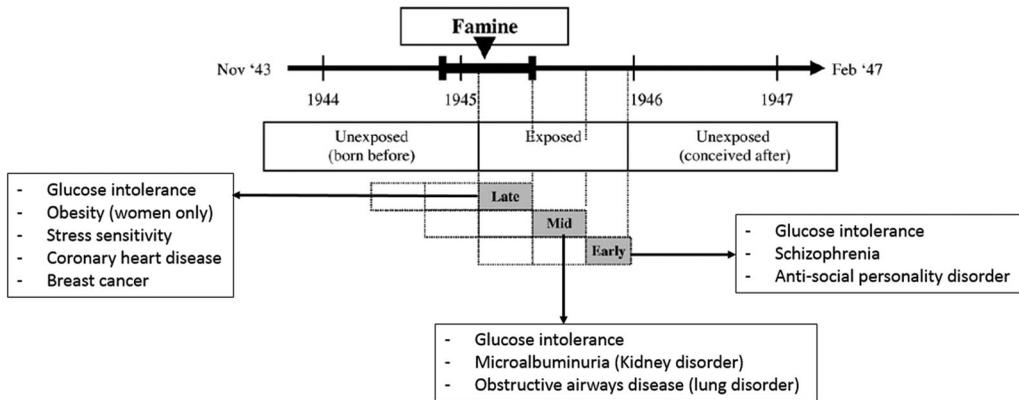


Figure 3. The Dutch famine birth cohort: famine exposure and birth in relation to the timing of the Dutch Hunger Winter. Variable phenotypic effects were observed depending on the timing of exposure. Solid gray boxes indicate timing of birth. Adapted from Roseboom *et al.*¹⁰⁰

deprivation.¹¹⁴ Moreover, the effects are not limited to famine and can be induced by *in utero* exposure to maternal stress across a variety of contexts, such as exposure to terrorist attacks, natural disasters such as earthquakes and floods, and even less intense stressors such as more generalized stress in the work environment.^{115,116}

At least some of these long-term effects are caused by a resetting of fetal hypothalamic–pituitary–adrenal (HPA) axis sensitivity,¹¹⁷ which is a major cause of variation in many behavioral traits, including many personality traits.¹¹⁸ The HPA axis comprises the hypothalamus, anterior pituitary, and adrenal gland, and the hormones that they secrete and to which they respond (Fig. 4). In the brain, activity in the interconnected amygdala, hippocampus, and hypothalamus can activate and regulate the HPA axis.¹¹⁹ Interestingly, these are the parts of the brain that are most frequently implicated in personality disorders.¹²⁰

Prenatal treatment with glucocorticoids reduces birth weight, alters metabolism and HPA axis function, and is associated with mood disorders in later life.¹¹⁸ In fact, many of the famine-induced adult diseases are thought to involve disruption in tissues that are particularly responsive to glucocorticoids, such as the liver, adipose tissue, and brain.¹¹⁸ Excess glucocorticoid exposure in late pregnancy can also induce long-lasting effects on the expression of glucocorticoid-sensitive genes that affect insulin resistance and glucose tolerance in adulthood. Finally, and perhaps most importantly from the perspective of understanding the effects of

maternal exposure to stress on offspring personality, exposure of the fetus to stress or high levels of glucocorticoids affects the distribution of glucocorticoid receptors (GRs), particularly in the brain.¹¹⁴ Variation in GR density alters stress responsiveness, and because stress-exposed offspring have a lower receptor density than nonexposed offspring, they have reduced feedback control of the HPA axis and a higher reactivity to stress¹¹⁶ (Fig. 4). Such variation in reactivity to stress correlates with variation in personality traits across diverse taxa,¹²¹ including shyness and boldness in Richardson’s ground squirrels (*Urocitellus richardsonii*),¹²² exploratory behavior in eastern chipmunks (*Tamias striatus*),¹²³ and aggression in Nazca boobies (*Sula granti*)¹²⁴ and rainbow trout (*Oncorhynchus mykiss*).¹²⁵ In artificial selection experiments in fish and birds, selection for a high or low cortisol response to a stressor has been shown to produce correlated changes in coping styles, exploration, and risk-taking behavior.^{125,126} Moreover, selecting for differences in personality traits, such as exploratory behavior, boldness, and aggressiveness, has been shown to lead to changes in glucocorticoid levels in mammals and birds.^{127,128} Thus, there is abundant evidence for a link between HPA programming and stress-induced variation in personalities, and more recent studies suggest that these effects may be mediated proximately through epigenetic mechanisms acting during development.^{116,118,129,130}

Is it possible that maternal programming of the epigenetic system in response to stress can explain the generation of personality variation? Are these

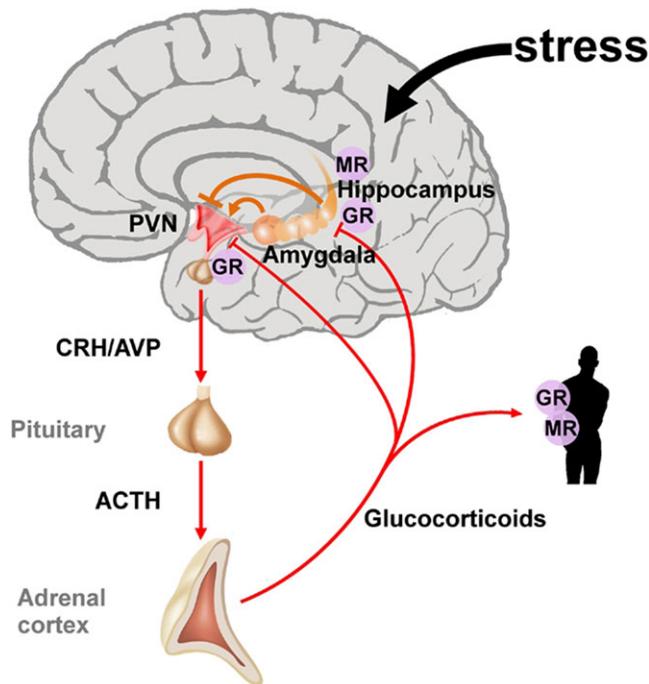


Figure 4. The hypothalamic–pituitary–adrenal axis. Fear and anxiety activate the amygdala and magnify the stress response via neuronal projections to the paraventricular nucleus (PVN). The hippocampus plays an important role in the assessment of stressors and as a site of GR-mediated negative feedback regulation. The hypothalamus produces the neuropeptides corticotrophin-releasing hormone (CRH) and arginine vasopressin (AVP), which stimulate the pituitary to produce adrenocorticotrophic hormone (ACTH), which, in turn, stimulates the adrenal gland to produce cortisol in humans (corticosterone in most other vertebrates). These hormones circulate throughout the whole body and brain and bind to steroid receptors. Hippocampal mineralocorticoid receptors (MRs), which have a higher affinity for glucocorticoids, are important in initiating the onset of a stress response, while GRs in the hippocampus, PVN, and anterior pituitary have a lower affinity, require higher levels of hormone to activate, and are more important in terminating the stress response. Shown is the HPA axis in humans, but the main components are the same across vertebrates. Adapted from Raabe and Spengler.¹⁶⁸

effects adaptive? What are the implications of such epigenetic programming for the relative importance of constraint versus selection in the origin of personality variation? In the next section I address these questions and lay out a hypothesis for the origin and evolution of personality variation that takes into account the relative importance of constraint and selection in explaining personality variation.

Structural constraints and adaptive epigenetic programming: relative role of constraints and selection for personality evolution

It has been suggested that the fetal response to maternal stress is adaptive, enabling the fetus to respond to suboptimal conditions in the womb and a potentially harsh environment outside of the womb. Stress-exposed offspring have a “thrifter

phenotype”¹³¹ that requires fewer resources and that reacts to stress more quickly. If harsh conditions experienced by the mother continue for the offspring, such stress-induced phenotypes will enable greater survival. They only become problematic when there is a mismatch between generations in environmental conditions, as occurred for the individuals exposed *in utero* to the Dutch Hunger Winter who then experienced good or even overnutrition for the rest of their lives.¹¹⁴ Thus, assuming that HPA axis programming has some influence on personality variation, as has been shown in numerous studies,^{121,132,133} the thrifty phenotype hypothesis might provide an adaptive explanation for evolution of maternally induced variation in offspring personality. However, this still does not explain why the HPA axis needs to be programmed so early in life and why there is not more flexibility throughout

life.¹³⁴ Given that mismatches between quality of maternal and offspring environments are likely to occur frequently (especially for a species such as humans with a long generation time), why do we not see evolution of the ability to reprogram the HPA axis in response to changing environmental conditions? In fact, some studies have found that the effects of stress on embryos persists across multiple generations,¹³⁵ making the chances for mismatch even more likely. The main hypothesis to explain the long-term effects of HPA programming is that selection for plasticity is not particularly strong.¹³⁶ The reasoning is that environmental mismatch, even if it affects longevity, will not necessarily negatively affect overall fitness because diabetes, cardiovascular disease, and mental health problems typically begin to develop later in life, well after reproductive age. Therefore, it is assumed that the fitness benefits of plasticity would be low in comparison to the potential survival cost of not programming the HPA axis for a harsh environment. However, this assumption has not been tested empirically (e.g., by comparing fitness of famine-exposed versus nonexposed individuals), and long-term studies in humans show significant negative selection on cholesterol levels and blood pressure and significant stabilizing selection on blood glucose levels,¹³⁷ suggesting that there are fitness costs of stress-induced phenotypes. Presumably, such costs should favor evolution of greater flexibility in programming of the HPA axis. Given that we do not observe such flexibility, an alternative explanation is that flexibility may be limited by various developmental constraints.

It is unlikely that epigenetic markings and their consequences for HPA programming by themselves are highly constrained by costs or lag times as cells must actively maintain methylation patterns, and in the absence of homeostatic mechanisms for maintenance, they would disappear with cellular mitosis.¹³⁸ Moreover, several recent studies have shown that, despite the lifetime stability of stress-induced methylation patterns that influence behavior, they can be reversed experimentally with methionine supplementation.¹³⁹ Epigenetic mechanisms span the full range of stability to flexibility—methylation patterns that underlie cellular differentiation are highly stable for the lifetime of a cell lineage,¹⁴⁰ whereas at the other end of the spectrum, daily fluctuations in cellular methylation patterns underlie plasticity of circadian clock gene

expression.^{141,142} Similarly, the link between HPA axis variation and behavioral traits may be more labile than originally thought. For example, in rainbow trout (*O. mykiss*), the typically highly consistent dominance status of genetically distinct proactive and reactive behavioral lines reversed, despite maintaining consistent differences in stress responses, following a stressful move to a novel environment.¹⁴³ In humans, nonhuman primates, and rodents, the quality of postnatal care can dampen the negative effects of prenatal stress exposure.¹⁴⁴ Thus, it seems that epigenetic mechanisms and the behaviors that are correlated with them are not highly constrained to be inflexible as they can be reversed, and instead their flexibility and stability appear to evolve depending on the function of variable patterns of gene expression.

A more likely constraint to epigenetic “reprogramming” is functional integration. Epigenetic marks that are present at the very earliest stages of development will perpetuate through entire cell lineages, and if, for example, tissue function requires coordinated patterns of gene expression, then it would be very difficult to coordinate reprogramming of cells that vary in age across tissue without disrupting function. This problem is greatly magnified for something as complex as the HPA axis, which targets, coordinates, and influences functions across every organismal system. Such functional integration may explain why, once programmed, the HPA axis is difficult, but not impossible, to reprogram. At the same time, examples of epigenetic mechanisms show that flexible changes are possible and sometimes even crucial to organismal function.^{138,142,145} These examples of flexibility in epigenetic mechanisms suggest that, despite the need for functional integration, flexibility is possible given strong enough selection.

What do these findings, in conjunction with findings of the influence of structural variation, suggest about the relative role of selection and constraint in limiting flexibility of personality traits? For structural traits that underlie personality variation (Table 1), there are numerous physical and energetic constraints to flexibility. However, for the epigenetic mechanisms discussed in the last section, because epigenetic markings need to be actively maintained and appear to easily evolve flexibility when it is crucial to trait function, constraints may be less important. On the basis of these

observations on the nature of epigenetic and structural variation, I suggest that structural constraints on the neuroendocrine system may play a primary role in the origin of behavioral stability and that epigenetic programming may be an adaptation that allows individuals to function at their highest level given investment patterns in various structural traits early in life. There is evidence that even fairly mild variation in nutritional stress can have long-term effects on brain development.^{146,147} Thus, the quality of the developmental environment can produce long-lasting effects on the physical structures underlying behavior. Because these physical structures are inherently limited in flexibility postdevelopment (Table 1), selection may have favored programming of the HPA axis in response to nutritional or stress signals early in ontogeny to alter neuroendocrine function to compensate for these differential patterns of investment. Thus, I suggest that structural constraints are a primary cause of stable differences among individuals in behavior, and epigenetic modifications may be a mechanism for channeling stable differences in an adaptive way given predictable patterns of structural variation produced during development under differing environmental conditions.

Future directions

This hypothesis leads to several questions and potential directions for future work on the evolutionary origin of personality traits. Studies are needed that link natural variation in behavior to natural variation in neuroendocrine mechanisms. Currently, most studies in neurobiology and psychology focus either on abnormal personality disorders in humans or use model organisms to induce variation that may be out of the natural range of variation found in wild populations. There are very few studies that combine investigation of the natural range of variation in personality with study of their underlying neuroendocrine mechanisms. This makes sense to some degree as such studies depend on the availability of genomic and neuroimaging tools, which are difficult to use in nonhuman and nonmodel organism populations. However, both the genome sequencing of nonmodel organisms and the adaptation of noninvasive imaging tools, such as magnetic resonance imaging (MRI) and functional MRI, will make answering these questions possible in the future.

Second, studies are needed that compare neuroendocrine mechanisms underlying personality variation across taxa. Personality variation has been described across diverse taxa from insects to mammals. Do similar neuroendocrine mechanisms underlie personality variation across disparate taxa? The nervous systems of vertebrates and invertebrates are clearly very different, but the tradeoffs and constraints on neural tissues are likely to be similar. Moreover, all organisms face the common problem of resource allocation to offspring, and restricted access to resources and stressful environments are ubiquitous. The question is whether structural variation in neuroendocrine organs is ubiquitously affected by this sort of environmental variation. If common constraints to flexibility underlie personality variation, we would expect similar developmental mechanisms for it across disparate taxa. There is some evidence of this as there is evolutionary conservation of many neuroendocrine pathways, including the HPA axis, across diverse taxa.^{121,148} One particularly well-studied axis of personality variation—aggressiveness—is linked to variation in the serotonergic system across a wide variety of species, from crayfish to foxes to humans.¹⁴⁹ However, not enough is known about the developmental basis of individual differences in behavior across species to draw conclusions about whether such universality of neuroendocrine pathways also translates to evolutionary conservation of their links to specific behaviors.

Thus, determining whether constraints are important requires integrating empirical data on the proximate mechanisms that underlie behavioral development with studies of personality variation across a wide range of taxa. Such integration would not only enable a better understanding of the evolution of personality traits, but would also provide new insight into the more general problem of understanding the relative roles of constraints and selection in evolution.

Acknowledgments

I thank A. Potticary, D. Higginson, C. Gurguis, E. Morrison, A. Badyaev, and two anonymous reviewers for their insightful comments on an earlier version of this manuscript. This work was funded by NSF CAREER Award DEB-1350107.

Conflicts of interest

The author declares no conflicts of interest.

References

1. Gosling, S.D. 2008. Personality in non-human animals. *Soc. Personal Psychol. Compass* **2**: 985–1001.
2. Ingley, S.J. & J.B. Johnson. 2014. Animal personality as a driver of reproductive isolation. *Trends Ecol. Evol.* **29**: 369–371.
3. Fogarty, S., J. Cote & A. Sih. 2011. Social personality polymorphism and the spread of invasive species: a model. *Am. Nat.* **177**: 273–287.
4. Sih, A., J. Cote, M. Evans, *et al.* 2012. Ecological implications of behavioural syndromes. *Ecol. Lett.* **15**: 278–289.
5. Duckworth, R.A. & A.V. Badyaev. 2007. Coupling of aggression and dispersal facilitates the rapid range expansion of a passerine bird. *Proc. Natl. Acad. Sci. U. S. A.* **104**: 15017–15022.
6. Duckworth, R.A., V. Belloni & S.R. Anderson. 2015. Cycles of species replacement emerge from locally induced maternal effects on offspring behavior in a passerine bird. *Science* **374**: 875–877.
7. Wolf, M. & F.J. Weissing. 2010. An explanatory framework for adaptive personality differences. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **365**: 3959–3968.
8. Duckworth, R.A. 2010. Evolution of personality: developmental constraints on behavioral flexibility. *Auk* **127**: 752–758.
9. Sih, A., A. Bell & J.C. Johnson. 2004. Behavioral syndromes: an ecological and evolutionary overview. *Trends Ecol. Evol.* **19**: 372–378.
10. Dall, S.R., A.M. Bell, D.I. Bolnick & F.L. Ratnieks. 2012. An evolutionary ecology of individual differences. *Ecol. Lett.* **15**: 1189–1198.
11. Duckworth, R.A. 2009. The role of behavior in evolution: a search for mechanism. *Evol. Ecol.* **23**: 513–531.
12. Piersma, T. & J. Drent. 2003. Phenotypic flexibility and the evolution of organismal design. *Trends Ecol. Evol.* **18**: 228–233.
13. West-Eberhard, M. 2003. *Developmental Plasticity and Evolution*. Oxford: Oxford University Press.
14. Pigliucci, M. 2001. *Phenotypic Plasticity: Beyond Nature and Nurture*. Baltimore, MD: Johns Hopkins University Press.
15. Gabriel, W., B. Luttbeg, A. Sih & R. Tollrian. 2005. Environmental tolerance, heterogeneity, and the evolution of reversible plastic responses. *Am. Nat.* **166**: 339–353.
16. Duckworth, R.A. 2006. Behavioral correlations across breeding contexts provide a mechanism for a cost of aggression. *Behav. Ecol.* **17**: 1011–1019.
17. Duckworth, R.A. & K.W. Sockman. 2012. Proximate mechanisms of behavioural inflexibility: implications for the evolution of personality traits. *Funct. Ecol.* **26**: 559–566.
18. Duckworth, R.A. & L.E.B. Kruuk. 2009. Evolution of genetic integration between dispersal and colonization ability in a bird. *Evolution* **63**: 968–977.
19. Dingemanse, N.J., A.J.N. Kazem, D. Réale & J. Wright. 2009. Behavioural reaction norms: animal personality meets individual plasticity. *Trends Ecol. Evol.* **25**: 81–89.
20. Dall, S.R.X., A.I. Houston & J.M. McNamara. 2004. The behavioural ecology of personality: consistent individual differences from an adaptive perspective. *Ecol. Lett.* **7**: 734–739.
21. Stamps, J.A. 2007. Growth-mortality tradeoffs and 'personality traits' in animals. *Ecol. Lett.* **10**: 355–363.
22. Wolf, M., G.S. van Doorn, O. Leimar & F.J. Weissing. 2007. Life-history trade-offs favour the evolution of animal personalities. *Nature* **447**: 581–584.
23. McElreath, R. & P. Strimling. 2006. How noisy information and individual asymmetries can make 'personality' an adaptation: a simple model. *Anim. Behav.* **72**: 1135–1139.
24. McNamara, J.M., P. Stephens, S. Dall & A.I. Houston. 2009. Evolution of trust and trustworthiness: social awareness favours personality differences. *Proc. R. Soc. Lond. B* **276**: 605–613.
25. Holekamp, K.E., E.M. Swanson & P.E. Van Meter. 2013. Developmental constraints on behavioural flexibility. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **368**: 20120350.
26. Cowin, S. & D. Hegedus. 1976. Bone remodeling I: theory of adaptive elasticity. *J. Elast.* **6**: 313–326.
27. Gosling, S.D. 2001. From mice to men: what can we learn about personality from animal research. *Psychol. Bull.* **127**: 45–86.
28. Atchley, W.R. & B.K. Hall. 1991. A model for the development and evolution of complex morphological structures. *Biol. Rev.* **66**: 101–157.
29. Arnold, S.J. 1992. Constraints on phenotypic evolution. *Am. Nat.* **140**, S85–S107.
30. Atchley, W.R. 1987. Developmental quantitative genetics and the evolution of ontogenies. *Evolution* **41**: 316–330.
31. Arthur, W. 2004. The effect of development on the direction of evolution: toward a twenty-first century consensus. *Evol. Dev.* **6**: 282–288.
32. Maynard Smith, J. *et al.* 1985. Developmental constraints and evolution: a perspective from the Mountain Lake Conference on development and evolution. *Q. Rev. Biol.* **60**: 265–287.
33. Brakefield, P.M. 2006. Evo-devo and constraints on selection. *Trends Ecol. Evol.* **21**: 362–368.
34. Schwenk, K. & G.P. Wagner. 2003. The relativism of constraints on phenotypic evolution. In *Phenotypic Integration: Studying the Ecology and Evolution of Complex Phenotypes*. Massimo Pigliucci & K. Preston, Eds. Oxford: Oxford University Press.
35. Cheverud, J.M. 1984. Quantitative genetics and developmental constraints on evolution by selection. *J. Theor. Biol.* **110**: 155–171.
36. Nijhout, H.F. & M.C. Reed. 2014. Homeostasis and dynamic stability of the phenotype link robustness and plasticity. *Integr. Comp. Biol.* **54**: 264–275.
37. Kitano, H. 2004. Biological robustness. *Nat. Rev. Genet.* **5**: 826–837.
38. Badyaev, A.V. 2007. Evolvability and robustness in color displays: bridging the gap between theory and data. *Evol. Biol.* **34**: 61–72.
39. Whitacre, J.M. & A. Bender. 2010. Networked buffering: a basic mechanism for distributed robustness in complex adaptive systems. *Theor. Biol. Med. Model.* **7**: 20.
40. Kolb, B. 1995. *Brain Plasticity and Behavior*. Hillsdale, NJ: Lawrence Erlbaum Associates.
41. Coppens, C.M., S.F. de Boer & J.M. Koolhaas. 2010. Coping styles and behavioural flexibility: towards underlying

- mechanisms. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **365**: 4021–4028.
42. Chklovskii, D.B., B.W. Mel & K. Svoboda. 2004. Cortical rewiring and information storage. *Nature* **431**: 782–788.
 43. Merilä, J. & M. Björklund. 2004. Phenotypic integration as a constraint and adaptation. In *Phenotypic Integration: Studying the Ecology and Evolution of Complex Phenotypes*. Massimo Pigliucci & K. Preston, Eds.: 107–129. Oxford: Oxford University Press.
 44. Badyaev, A.V. & R.L. Young. 2004. Evolution of morphological integration: I. Functional units channel stress-induced variation. *Am. Nat.* **163**: 868–879.
 45. Adkins-Regan, E. 2008. Do hormonal control systems produce evolutionary inertia? *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **363**: 1599–1609.
 46. Jacobs, J.D. & J.C. Wingfield. 1999. Endocrine control of life-cycle stages: a constraint on response to the environment? *The Condor* **102**: 35–51.
 47. Livnat, A. & N. Pippenger. 2006. An optimal brain can be conflicting agents. *Proc. Natl. Acad. Sci. U. S. A.* **103**: 3198–3202.
 48. Kety, S.S. 1957. *Metabolism of the Nervous System*. Oxford: Pergamon Press.
 49. Ball, G.F. & J. Balthazart. 2008. Individual variation and the endocrine regulation of behaviour and physiology in birds: a cellular/molecular perspective. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **363**: 1699–1710.
 50. Dufty, A.M., J. Clobert & A.P. Møller. 2002. Hormones, developmental plasticity and adaptation. *Trends Ecol. Evol.* **17**: 190–196.
 51. Badyaev, A.V. & R.A. Duckworth. 2005. Evolution of plasticity in hormonally-integrated parental tactics: an example with the house finch. In *Functional Avian Endocrinology*. A. Dawson & Peter J. Sharp, Eds.: 375–386. New Delhi: Narosa Publishing House.
 52. Koolhaas, J.M., S.F. de Boer, C.M. Coppens & B. Buwalda. 2010. Neuroendocrinology of coping styles: towards understanding the biology of individual variation. *Front. Neuroendocrinol.* **31**: 307–321.
 53. Øverli, Ø. *et al.* 2007. Evolutionary background for stress-coping styles: relationships between physiological, behavioral, and cognitive traits in non-mammalian vertebrates. *Neurosci. Biobehav. Rev.* **31**: 396–412.
 54. Wingfield, J.C. 2005. A continuing saga: the role of testosterone in aggression. *Horm. Behav.* **48**: 253–255; discussion 256–258.
 55. Moore, M.C. 1991. Application of organization-activation theory to alternative male reproductive strategies: a review. *Horm. Behav.* **25**: 154–179.
 56. Adkins-Regan, E. 2007. Hormones and the development of sex differences in behavior. *J. Ornithol.* **148**: 17–26.
 57. Rhen, T. & D. Crews. 2002. Variation in reproductive behaviour within a sex: neural systems and endocrine activation. *J. Neuroendocrinol.* **14**: 517–531.
 58. Kotrschal, A. *et al.* 2014. Artificial selection on relative brain size reveals a positive genetic correlation between brain size and proactive personality in the guppy. *Evolution* **68**: 1139–1149.
 59. Pariante, C.M. *et al.* 2004. Pituitary volume in psychosis. *Br. J. Psychiatry* **185**: 5–10.
 60. Takahashi, T. *et al.* 2011. Longitudinal volume changes of the pituitary gland in patients with schizotypal disorder and first-episode schizophrenia. *Prog. Neuropsychopharmacol. Biol. Psychiatry* **35**: 177–183.
 61. Nordholm, D. *et al.* 2013. Pituitary gland volume in patients with schizophrenia, subjects at ultra high-risk of developing psychosis and healthy controls: a systematic review and meta-analysis. *Psychoneuroendocrinology* **38**: 2394–2404.
 62. Campbell, S., M. Marriott, C. Nahmias & G.M. MacQueen. 2004. Lower hippocampal volume in patients suffering from depression: a meta-analysis. *Am. J. Psychiatry* **161**: 598–607.
 63. Kuhlmann, A., K. Bertsch, I. Schmidinger, *et al.* 2013. Morphometric differences in central stress-regulating structures between women with and without borderline personality disorder. *J. Psychiatry Neurosci.* **38**: 129–137.
 64. Schmahl, C.G., E. Vermetten, B.M. Elzinga, *et al.* 2003. Magnetic resonance imaging of hippocampal and amygdala volume in women with childhood abuse and borderline personality disorder. *Psychiatry Res.* **122**: 193–198.
 65. Markon, K.E., R.F. Krueger & D. Watson. 2005. Delineating the structure of normal and abnormal personality: An integrative hierarchical approach. *J. Pers. Soc. Psychol.* **88**: 139–157.
 66. DeYoung, C.G. *et al.* 2010. Testing predictions from personality neuroscience: brain structure and the big five. *Psychol. Sci.* **21**: 820–828.
 67. Swanson, E.M., K.E. Holekamp, B.L. Lundrigan, *et al.* 2012. Multiple determinants of whole and regional brain volume among terrestrial carnivorans. *PLoS One* **7**: e38447.
 68. Pigliucci, M. & K. Preston. 2004. *Phenotypic Integration: Studying the Ecology and Evolution of Complex Phenotypes*. Oxford: Oxford University Press.
 69. Cheverud, J.M. 1982. Phenotypic, genetic, and environmental morphological integration in the cranium. *Evolution* **36**: 499–516.
 70. Whyte, L.L. 1965. *Internal Factors in Evolution*. New York: George Braziller.
 71. Bavelier, D., D.M. Levi, R.W. Li, *et al.* 2010. Removing brakes on adult brain plasticity: from molecular to behavioral interventions. *J. Neurosci.* **30**: 14964–14971.
 72. Zhan, Y. *et al.* 2014. Deficient neuron-microglia signaling results in impaired functional brain connectivity and social behavior. *Nat. Neurosci.* **17**: 400–406.
 73. DeWitt, T.J., A. Sih & D.S. Wilson 1998. Costs and limits to phenotypic plasticity. *Trends Ecol. Evol.* **13**: 77–81.
 74. Padilla, D.K. & S.C. Adolph. 1996. Plastic inducible morphologies are not always adaptive: the importance of time delays in a stochastic environment. *Evol. Ecol.* **10**: 105–117.
 75. Kolb, B. & R. Gibb. 2014. Searching for the principles of brain plasticity and behavior. *Cortex* **58**: 251–260.
 76. Miner, B.G., S.E. Sultan, S.G. Morgan, *et al.* 2005. Ecological consequences of phenotypic plasticity. *Trends Ecol. Evol.* **20**: 685–692.
 77. Horn, G. 2004. Pathways of the past: the imprint of memory. *Nat. Rev. Neurosci.* **5**: 108–120.

78. Immelmann, K. 1975. Ecological significance of imprinting and early learning. *Annu. Rev. Ecol. Syst.* **6**: 15–37.
79. Horn, G. 1998. Visual imprinting and the neural mechanisms of recognition memory. *Trends Neurosci.* **21**: 300–305.
80. Knudsen, E. 2004. Sensitive periods in the development of the brain and behavior. *J. Cogn. Neurosci.* **16**: 1412–1425.
81. Bateson, P. 1979. How do sensitive periods arise and what are they for? *Anim. Behav.* **27**: 470–486.
82. Wagner, G.P., M. Pavlicev & J.M. Cheverud. 2007. The road to modularity. *Nat. Rev. Genet.* **8**: 921–931.
83. Nijhout, H.F. 2002. The nature of robustness in development. *Bioessays* **24**: 553–563.
84. Cipolla-Neto, J., G. Horn & B. McCabe. 1982. Hemispheric asymmetry and imprinting: the effect of sequential lesions to the hyperstriatum ventrale. *Exp. Brain Res.* **48**: 22–27.
85. Craik, F.I. & E. Bialystok. 2006. Cognition through the lifespan: mechanisms of change. *Trends Cogn. Sci.* **10**: 131–138.
86. Immelmann, K. 1969. “Song development in the zebra finch and other estrildine finches.” In *Bird Vocalizations*. R.A. Hinde, Ed.: 61–74. Cambridge: Cambridge University Press.
87. Antonini, A. & M.P. Stryker. 1993. Rapid remodeling of axonal arbors in the visual cortex. *Science* **260**: 1819–1821.
88. Mendola, J.D. *et al.* 2005. Voxel-based analysis of MRI detects abnormal visual cortex in children and adults with amblyopia. *Hum. Brain Mapp.* **25**: 222–236.
89. Bullmore, E. & O. Sporns. 2012. The economy of brain network organization. *Nat. Rev. Neurosci.* **13**: 336–349.
90. Cakir, I. & U. Ozcan. 2014. Mom’s milk molds neural wiring for metabolism. *Cell* **156**: 396–397.
91. Rice, D. & S. Barone. 2000. Critical periods of vulnerability for the developing nervous system: evidence from humans and animal models. *Environ. Health Perspect.* **108**: 511–533.
92. Scott, J. 1962. Critical periods in behavioral development. *Science* **138**: 949–958.
93. Stockard, C. 1921. Developmental rate and structural expression: an experimental study of twins, ‘double monsters’ and single deformities, and the interaction among embryonic organs during their origin and development. *Am. J. Anat.* **28**: 115–277.
94. Austin, E.J. 2005. Personality correlates of the broader autism phenotype as assessed by the Autism Spectrum Quotient (AQ). *Pers. Individ. Dif.* **38**: 451–460.
95. LeBlanc, J.J. & M. Fagiolini. 2011. Autism: a “critical period” disorder? *Neural Plast.* **2011**: 921680.
96. Teicher, M.H., A. Tomoda & S.L. Andersen. 2006. Neurobiological consequences of early stress and childhood maltreatment: are results from human and animal studies comparable? *Ann. N.Y. Acad. Sci.* **1071**: 313–323.
97. Lledo, P.M., M. Alonso & M.S. Grubb. 2006. Adult neurogenesis and functional plasticity in neuronal circuits. *Nat. Rev. Neurosci.* **7**: 179–193.
98. Mizrahi, A. & L.C. Katz. 2003. Dendritic stability in the adult olfactory bulb. *Nat. Neurosci.* **6**: 1201–1207.
99. Stamps, J.A. & T.G. Groothuis. 2010. Developmental perspectives on personality: implications for ecological and evolutionary studies of individual differences. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **365**: 4029–4041.
100. Roseboom, T., S. de Rooij & R. Painter. 2006. The Dutch famine and its long-term consequences for adult health. *Early Hum. Dev.* **82**: 485–491.
101. Roseboom, T.J., R.C. Painter, A.F. van Abeelen, *et al.* 2011. Hungry in the womb: what are the consequences? Lessons from the Dutch famine. *Maturitas* **70**: 141–145.
102. Brown, A., E. Susser, S. Lin, *et al.* 1995. Increased risk of affective disorders in males after second trimester prenatal exposure to the Dutch hunger winter of 1944–45. *Br. J. Psychiatry* **166**: 601–606.
103. Franzek, E.J., N. Sprangers, A.C. Janssens, *et al.* 2008. Prenatal exposure to the 1944–45 Dutch ‘hunger winter’ and addiction later in life. *Addiction* **103**: 433–438.
104. Hock, H., A. Brown & E. Susser. 1998. The Dutch famine and schizophrenia spectrum disorders. *Soc. Psychiatry Psychiatr. Epidemiol.* **33**: 373–379.
105. Susser, E. & S. Lin. 1992. Schizophrenia after prenatal exposure to the Dutch hunger winter of 1944–1945. *Arch. Gen. Psychiatry* **49**: 983–988.
106. Hoek, H. *et al.* 1996. Schizoid personality disorder after prenatal exposure to famine. *Am. J. Psychiatry* **153**: 1637–1639.
107. Neugebauer, R., H. Hoek & E. Susser 1999. Prenatal exposure to wartime famine and development of antisocial personality disorder in early adulthood. *J. Am. Med. Assoc.* **282**: 455–462.
108. Susser, E. *et al.* 1997. Schizophrenia after prenatal famine. *Arch. Gen. Psychiatry* **54**: 578.
109. Heijmans, B.T. *et al.* 2008. Persistent epigenetic differences associated with prenatal exposure to famine in humans. *Proc. Natl. Acad. Sci. U. S. A.* **105**: 17046–17049.
110. Tobi, E.W. *et al.* 2009. DNA methylation differences after exposure to prenatal famine are common and timing- and sex-specific. *Hum. Mol. Genet.* **18**: 4046–4053.
111. Tobi, E.W. *et al.* 2012. Prenatal famine and genetic variation are independently and additively associated with DNA methylation at regulatory loci within IGF2/H19. *PLoS One* **7**: e37933.
112. Franklin, T.B. *et al.* 2010. Epigenetic transmission of the impact of early stress across generations. *Biol. Psychiatry* **68**: 408–415.
113. Pol, H. *et al.* 2000. Prenatal exposure to famine and brain morphology in schizophrenia. *Schizophr. Res.* **41**: 6.
114. Cottrell, E.C. & J.R. Seckl. 2009. Prenatal stress, glucocorticoids and the programming of adult disease. *Front. Behav. Neurosci.* **3**: 19.
115. Talge, N.M. *et al.* 2007. Antenatal maternal stress and long-term effects on child neurodevelopment: how and why? *J. Child Psychol. Psychiatry* **48**: 245–261.
116. Weaver, I.C. *et al.* 2004. Epigenetic programming by maternal behavior. *Nat. Neurosci.* **7**: 847–854.
117. Cottrell, E.C., M.C. Holmes, D.E. Livingstone, *et al.* 2012. Reconciling the nutritional and glucocorticoid hypotheses of fetal programming. *FASEB J.* **26**: 1866–1874.
118. Seckl, J.R. & M.J. Meaney. 2004. Glucocorticoid programming. *Ann. N.Y. Acad. Sci.* **1032**: 63–84.

119. Charmandari, E., C. Tsigos & G. Chrousos. 2005. Endocrinology of the stress response. *Annu. Rev. Physiol.* **67**: 259–284.
120. Phillips, L.J. *et al.* 2006. Stress, the hippocampus and the hypothalamic-pituitary-adrenal axis: implications for the development of psychotic disorders. *Aust. N. Z. J. Psychiatry* **40**: 725–741.
121. Koolhaas, J.M. *et al.* 1999. Coping styles in animals: current status in behavior and stress-physiology. *Neurosci. Biobehav. Rev.* **23**: 925–935.
122. Clary, D. *et al.* 2014. Shyness-boldness, but not exploration, predicts glucocorticoid stress response in Richardson's Ground Squirrels (*Urocitellus richardsonii*). *Ethology* **120**: 1101–1109.
123. Montiglio, P.-O., D. Garant, F. Pelletier & D. Réale. 2012. Personality differences are related to long-term stress reactivity in a population of wild eastern chipmunks, *Tamias striatus*. *Anim. Behav.* **84**: 1071–1079.
124. Grace, J.K. & D.J. Anderson. 2014. Corticosterone stress response shows long-term repeatability and links to personality in free-living Nazca boobies. *Gen. Comp. Endocrinol.* **208**: 39–48.
125. Overli, O. *et al.* 2004. Stress coping style predicts aggression and social dominance in rainbow trout. *Horm. Behav.* **45**: 235–241.
126. Martins, T.L.F., M.L. Roberts, I. Giblin, *et al.* 2007. Speed of exploration and risk-taking behavior are linked to corticosterone titres in zebra finches. *Horm. Behav.* **52**: 445–453.
127. Stowe, M., B. Rosivall, P.J. Drent & E. Mostl. 2010. Selection for fast and slow exploration affects baseline and stress-induced corticosterone excretion in Great tit nestlings, *Parus major*. *Horm. Behav.* **58**: 864–871.
128. Aubin-Horth, N., M. Deschenes & S. Cloutier. 2012. Natural variation in the molecular stress network correlates with a behavioural syndrome. *Horm. Behav.* **61**: 140–146.
129. McGowan, P.O. *et al.* 2009. Epigenetic regulation of the glucocorticoid receptor in human brain associates with childhood abuse. *Nat. Neurosci.* **12**: 342–348.
130. Szyf, M., I.C. Weaver, F.A. Champagne, *et al.* 2005. Maternal programming of steroid receptor expression and phenotype through DNA methylation in the rat. *Front. Neuroendocrinol.* **26**: 139–162.
131. Hales, C. & D.J.P. Barker. 1992. Type 2 (non-insulin-dependent) diabetes mellitus: the thrifty phenotype hypothesis. *Diabetologia* **35**: 595–601.
132. Ahmed, A.A., W. Ma, Y. Ni, *et al.* 2014. Embryonic exposure to corticosterone modifies aggressive behavior through alterations of the hypothalamic pituitary adrenal axis and the serotonergic system in the chicken. *Horm. Behav.* **65**: 97–105.
133. Mustoe, A.C., J.H. Taylor, A.K., Birnie, *et al.* 2014. Gestational cortisol and social play shape development of marmosets' HPA functioning and behavioral responses to stressors. *Dev. Psychobiol.* **56**: 1229–1243.
134. Wells, J.C.K. 2003. The thrifty phenotype hypothesis: Thrifty offspring or thrifty mother? *J. Theor. Biol.* **221**: 143–161.
135. Francis, D. 1999. Nongenomic transmission across generations of maternal behavior and stress responses in the rat. *Science* **286**: 1155–1158.
136. Bateson, P., P. Gluckman & M. Hanson. 2014. The biology of developmental plasticity and the predictive adaptive response hypothesis. *J. Physiol.* **592**: 2357–2368.
137. Stearns, S.C., S.G. Byars, D.R. Govindaraju & D. Ewbank. 2010. Measuring selection in contemporary human populations. *Nat. Rev. Genet.* **11**: 611–622.
138. Reik, W. 2007. Stability and flexibility of epigenetic gene regulation in mammalian development. *Nature* **447**: 425–432.
139. Weaver, I.C. *et al.* 2005. Reversal of maternal programming of stress responses in adult offspring through methyl supplementation: altering epigenetic marking later in life. *J. Neurosci.* **25**: 11045–11054.
140. Gan, Q., T. Yoshida, O.G. McDonald & G.K. Owens. 2007. Concise review: epigenetic mechanisms contribute to pluripotency and cell lineage determination of embryonic stem cells. *Stem Cells* **25**: 2–9.
141. Fustin, J.M. *et al.* 2013. RNA-methylation-dependent RNA processing controls the speed of the circadian clock. *Cell* **155**: 793–806.
142. Azzi, A. *et al.* 2014. Circadian behavior is light-reprogrammed by plastic DNA methylation. *Nat. Neurosci.* **17**: 377–382.
143. Ruiz-Gomez Mde, L. *et al.* 2008. Behavioral plasticity in rainbow trout (*Oncorhynchus mykiss*) with divergent coping styles: when doves become hawks. *Horm. Behav.* **54**: 534–538.
144. Kaplan, L.A., L. Evans & C. Monk. 2008. Effects of mothers' prenatal psychiatric status and postnatal caregiving on infant biobehavioral regulation: can prenatal programming be modified? *Early Hum. Dev.* **84**: 249–256.
145. Day, J.J. & J.D. Sweatt. 2011. Epigenetic mechanisms in cognition. *Neuron* **70**: 813–829.
146. Dobbing, J. 1964. The influence of early nutrition on the development and myelination of the brain. *Proc. R. Soc. B* **159**: 503–509.
147. Walhovd, K.B. *et al.* 2012. Long-term influence of normal variation in neonatal characteristics on human brain development. *Proc. Natl. Acad. Sci. U. S. A.* **109**: 20089–20094.
148. Denver, R.J. 2009. Structural and functional evolution of vertebrate neuroendocrine stress systems. *Ann. N.Y. Acad. Sci.* **1163**: 1–16.
149. Popova, N.K. 2006. From genes to aggressive behavior: the role of serotonergic system. *Bioessays* **28**: 495–503.
150. Dekaban, A.S. & D. Sadovsky. 1978. Changes in brain weights during the span of human life: Relation of brain weights to body heights and body weights. *Ann. Neurol.* **4**: 345–356.
151. Raz, N. *et al.* 2005. Regional brain changes in aging healthy adults: general trends, individual differences and modifiers. *Cereb. Cortex* **15**: 1676–1689.
152. Ganzel, B.L., P. Kim, G.H. Glover & E. Temple. 2008. Resilience after 9/11: multimodal neuroimaging evidence for stress-related change in the healthy adult brain. *NeuroImage* **40**: 788–795.

153. Holzel, B.K. *et al.* 2010. Stress reduction correlates with structural changes in the amygdala. *Soc. Cogn. Affect. Neurosci.* **5**: 11–17.
154. Diamond, M.C., M.R., Rosenzweig, E.L. Bennett, *et al.* 1972. Effects of environmental enrichment and impoverishment on rat cerebral cortex. *J. Neurobiol.* **3**: 47–64.
155. Wright, C.I. *et al.* 2006. Neuroanatomical correlates of extraversion and neuroticism. *Cereb. Cortex* **16**: 1809–1819.
156. Kasai, H., M. Matsuzaki, J. Noguchi, *et al.* 2003. Structure-stability-function relationships of dendritic spines. *Trends Neurosci.* **26**: 360–368.
157. Ming, G.L. & H. Song. 2011. Adult neurogenesis in the mammalian brain: significant answers and significant questions. *Neuron* **70**: 687–702.
158. Schmidt-Nielson, K. 1997. *Animal Physiology: Adaptation and Environment*. 5 ed. Cambridge: Cambridge University Press.
159. Hill, R.W., G.A. Wyse & M. Anderson. 2012. *Animal Physiology*. Sunderland, MA: Sinauer Associates, Inc.
160. Barton, B.A. 2002. Stress in fishes: a diversity of responses with particular reference to changes in circulating corticosteroids. *Integ. Comp. Biol.* **42**: 517–525.
161. Wingfield, J.C. & A.S. Kitaysky. 2002. Endocrine responses to unpredictable environmental events: stress or anti-stress hormones? *Integ. Comp. Biol.* **42**: 600–609.
162. Roth, G.S. & G.D. Hess. 1982. Changes in the mechanisms of hormone and neurotransmitter action during aging: current status of the role of receptor and post-receptor alterations: a review. *Mech. Ageing Dev.* **20**: 175–194.
163. Wang, Q. *et al.* 2013. Glucocorticoid receptor protein expression in human hippocampus; stability with age. *Neurobiol. Aging* **34**: 1662–1673.
164. Meyer, U., M. van Kampen, E. Isovich, *et al.* 2001. Chronic psychosocial stress regulates the expression of both GR and MR mRNA in the hippocampal formation of tree shrews. *Hippocampus* **11**: 329–336.
165. De Kloet, E., J. Reul, De Ronde, *et al.* 1986. Function and plasticity of brain corticosteroid receptor systems: action of neuropeptides. *J. Steroid Biochem.* **25**: 723–731.
166. Krause, J.S., M.A. McGuigan, V.R. Bishop, *et al.* 2015. Decreases in mineralocorticoid but not glucocorticoid receptor mRNA expression during the short Arctic breeding season in free-living Gambel's white-crowned sparrow (*Zonotrichia leucophrys gambelii*). *J. Neuroendocrinol.* **27**: 66–75.
167. Réale, D., S.M. Reader, D. Sol, *et al.* 2007. Integrating animal temperament within ecology and evolution. *Biol. Rev.* **82**: 291–318.
168. Raabe, F.J. & D. Spengler. 2013. Epigenetic risk factors in PTSD and depression. *Front. Psychiatry* **4**: 80.