

Part IV

Origins

Genetics of Intellectual and Personality Traits Associated with Creative Genius

Could Geniuses Be Cosmopolitan Dragon Kings?

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The constructs of genius and creativity have long eluded understanding. As a consequence, they are surrounded by mystique. This does not mean we know nothing about them. To the contrary, we know much at a descriptive level (see relevant chapters in this handbook). What we do not fully understand are the “causes” of the constructs, or the processes through which they develop or emerge (Lee, 2012; Pearl, 2009). In this chapter, we discuss the ways in which genetic variation might contribute to these constructs, and to their particular configurations in those we have identified historically as creative geniuses.

Most of the substantive evidence for genetic influences we discuss comes from quantitative genetic models presumed to be causal. These models are variations and elaborations on the basic model introduced into agricultural genetics long ago by Ronald Fisher (Lynch & Walsh, 1998). These models have been applied to behavioral traits in both animals and humans (Carey, 2003; van Oers & Mueller, 2010). Animal studies provide opportunities to reveal genetic influences on traits in a powerful causal manner (through experimental manipulation of breeding) that is not available in human work. Demonstration that behavioral traits can be selected in animal populations provides strong empirical evidence that human behaviors are similarly genetically influenced. Historically, all domesticated animals have been selected for behavioral traits as well as physical ones. A recent example of this is the striking domestication of the fox by the Russian geneticist Dmitry K. Belyaev (Hare *et al.*, 2005; Trut, 1999). This work has been replicated elsewhere with a different breeding design (Kenttämies *et al.*, 2002). Thus, genetic influences on the human behavioral traits associated with creativity and genius should be no surprise (Turkheimer, 2000). It is clear, however, that they are also far from the whole story.

We take the perspective that creative genius in any domain is multidimensional and cannot be characterized as the extreme of any single dimension (e.g., IQ). Creative genius requires that a number of traits be present simultaneously (Simonton, 2013).

Galton (1869/1914) was clear about this long ago as he spoke about the “triple event, of ability, combined with zeal and with capacity for hard labour” (p. 78). By its very definition, creative genius lies at the extremes of the relevant distributions and thus is rare. This makes it very difficult to gather samples of people likely to include even one case, never mind the sample sizes necessary to estimate associations of genius with other psychological characteristics reliably. Thus, most researchers have worked with historical records of people society has come to regard as geniuses, tried to define and study the intuitively relevant characteristics in their more common moderate forms, or studied groups of young people who seem intuitively likely to achieve very highly in future. Other chapters in this volume treat the historical approach. We focus on the latter two.

Associations of psychological characteristics with creativity have generally been studied in samples unlikely to contain any actual geniuses, and thus involve creativity in its more common moderate form. As discussed in other chapters in this volume, many different definitions and measures of “everyday” creativity (Richards, Kinney, Benet, & Merzel, 1988) have been developed. Many suffer from poor psychometric properties and/or low face validity with creative genius, and they often correlate with each other only very poorly. One basic problem is that it is not clear that the kinds of mental activity that go into, for example, adapting a recipe to beef rather than fish are the same as those that go into conceptualizing the dish in the first place, never mind those that go into developing something like the theory of relativity, and none of these may relate well to the number of things one might dream up in 90 s to do with a brick (typical of everyday creativity measure items). And studies of young people thought likely to achieve very highly in future have tended to focus on IQ as the sample selection criterion, thus presuming that, rather than testing whether and how, IQ is related to genius. Still, these studies have generated at least intuitively reasonable results. We first address studies of the characteristics that have been associated with creativity and the evidence for genetic influences on them, focusing especially on those in Galton’s triple event. We then go on to consider recent studies that have attempted to understand the characteristics of the extremes of data distributions in general, and their relevance to understanding how genetic and environmental influences may transact to bring about the kinds of configurations of these traits we recognize as creative genius.

The general genetic and environmental transaction processes we describe have firm roots in developmental embryology and genetics, but their applications to humans and in particular to creative genius have not been explored. The mystique that continues to surround creative genius stems, however, from the failure of either classical genetic or environmental models to account for it adequately. Consequently, we believe that the processes we discuss deserve consideration. We begin this chapter with the classical models. The limitations of these models for understanding how genetic influences may be involved in the emergence of creative genius will, however, rapidly become clear in our discussion. We use these limitations to motivate our speculative discussion of alternative processes that may be involved.

Classical Quantitative Genetic Models in Humans

Though we do not experimentally manipulate human breeding, human quantitative genetic models do make use of experimental designs. Monozygotic (MZ) twins are

naturally occurring genetic clones. Nature also gives us dizygotic (DZ) twins (full biological siblings born at the same time) who share half their segregating genes. They thus provide a dose–effect comparison: similarity due to full doses versus similarity due to half doses of the same configurations of the genes that contribute to human genetic variance, when raised in the same environments. The differences in similarity between MZ and DZ twins tell us the influence of the half doses. The actual methodology is more complicated, but this simplification captures the essential point.

Quantitative genetic studies are as much about estimating the relative impacts of environmental as genetic influences. Differences between MZ cotwins point to the influences of differences in their environments. And DZ twin similarity that is greater than half the MZ twin similarity indicates the presence of shared environmental influences that act to make the twins, either kind, similar (unless their parents have tended to select each other for similarity in the trait of interest). A second quantitative genetic experiment is adoption, a social experiment in which individuals are raised by parents who did not contribute to their genetic complement. Unless adoptive children are selectively matched to adoptive parents, any similarities among them and their adoptive parents and/or adoptive siblings also indicate such shared environmental influences. A particularly strong natural experiment combines these: twins separated at birth and raised by adoptive parents. Though such cases are rare, similarity in such MZ twins is a direct estimate of genetic influences, and the difference in similarity between MZ twins reared together and apart provides another estimate of shared environmental influences.

As with any experimental design, assumptions are necessary.¹ The most important of these is that genetic and environmental influences are independent. This assumption is most important because it is most likely often violated, and the violations likely tell us much about how traits such as those associated with creative genius develop and are maintained. One way to identify assumption violations is to compare results from application of a variety of experimental designs. We thus refer to a series of studies in our discussions, along with their underlying assumptions.

Finally, we devote a word or two to the role of practice in the manifestation of creative genius. Practice is without question necessary for outstanding accomplishment. Mozart may have made his musical genius clear very early in childhood, but his early compositions are only interesting musically today because of what he did in adulthood. Most researchers studying high ability have considered practice to be an exclusively environmental factor in the development of genius – after all, Mozart’s father made him practice for hours every day, and the “10,000-hours-to-expertise rule” is widely known (see Chapter 16). We have no reason to question its general accuracy, in the sense that those who achieve excellence tend to have practiced about that amount by the time they do. We believe, however, that it is a mistake to conclude from this that all individuals who practice this amount will achieve excellence and, in particular, that everyone is equally likely to come up with the drive and the will to put in those crucial 10,000 hr of intense effort. Factors that support practice (personality, temperament, stamina, etc.) as well as the ability to benefit from practice show genetic influences in patterns and magnitudes very similar to those on abilities (Turkheimer, 2000). In fact, because their influence is at best very indirect, it is only too possible that the very way that genetic variants make their contributions to the manifestation of genius is through the creation of drives to seek out the kinds of experiences that will lead to the emergence of high levels of skill and presence in (often at least immediately

fortuitous) situations that offer opportunities, for example, for scientific discovery. This idea has been developed and discussed in some detail by Bouchard (1997), Hayes (1962), and Johnson (2010), and Johnson (in press) has discussed its relevance specifically to creative genius.

There is far less documentation of genetic influences on practice itself than we would like. The only published evidence comes from a study of twins reared apart on the pursuit rotor task (Fox, Hershberger, & Bouchard, 1996). Over the course of three days of practice, everyone became more skilled. Nevertheless, the MZA twins became somewhat more similar, and the DZA twins became much less similar, implicating genetic influences on skill development. In many domains, the truly eminent appear to begin their skill acquisition or talent manifestation earlier and begin to asymptote sooner. In support of this, ability factors do appear to predict how much practice it takes to acquire some practical skills (McClusky, Ritter, Lederman, Gallagher, & Smith, 2005). Correlational studies of this sort and a small behavior genetic study are far from convincing proof that genetic influences underlie, to some degree, either the drive to practice or the effects of practice on the development of a skill or ability (Plomin & Daniels, 1987). They are, however, a start.

Intelligence

Intelligence is correlated with creative genius (see Simonton & Song, 2009, for recent data analysis and references). The correlations within restricted samples have generally been about $.25 \pm .10$, and the findings are robust to method of measurement – IQ tests or historiometric assessment of intelligence (Simonton, 2009). There is widespread agreement that IQ is a necessary but not sufficient condition for the expression of genius (Eysenck, 1995, chapter 2). We take a somewhat stronger position, that intelligence is an essential and critical prerequisite. In support of this view, we present three arguments before addressing the question of genetic influences.

First, there is widespread belief that IQ brings diminishing achievement returns at higher levels (Mackinnon, 1962, p. 493; Muller *et al.*, 2005). Even Arthur Jensen (1980, p. 114), the dean of research on human intelligence, espoused this position. A strong version of this belief is the threshold hypothesis: Once an IQ of about 120 is reached, IQ is no longer relevant, and the structure of abilities is meaningfully different (cf. Feist & Barron, 2003, p. 64). The threshold hypothesis is false (Wai, Lubinski, & Benbow, 2005). Monotonicity is the rule, and effects are linear when the entire range of ability is examined (Arneson, Sackett, & Beatty, 2011; Sackett, Borneman, & Connelly, 2008). Monotonicity even applies when one looks at the top 1% of the ability distribution (Robertson, Smeets, Lubinski, & Benbow, 2010). IQ tests are very far from perfect, but they are more robust than most critics acknowledge. From the perspective of researchers studying high achievement, their main flaw is usually low ceilings (Archer, Lubinski, & Benbow, 1996; Walberg, Strykowski, Rovai, & Hung, 1984). Out-of-age testing is necessary to assess the influence of early intelligence on achievement in very-high-ability samples because they answer all the questions correctly when tested at the intended age, and even with out-of-age testing there are ceiling effects (Kell, Lubinski, & Benbow, 2013).

Second, the importance of IQ can be illustrated at the group level. Ashkenazi Jews, but not other Jewish groups, have an average IQ between 107 and 110 (Lynn, 2011;

Murray, 2007). A mean difference of this size creates disproportional representation of Jews at very high IQ levels relative to other groups. The overrepresentation of Jews in virtually all fields of science since about 1830 has been documented by Berry (1999), Murray (2003, pp. 278–282), Storfer (1990), and many others. Ashkenazi Jews are also overrepresented in the Visual Arts, Literature, Music, and Philosophy. In Murray's analysis, the two domains in which they have been most disproportionate are Mathematics (12:1) and Philosophy (14:1). The combined overrepresentation in the sciences was only 6:1. In general, scientists and other academics have substantially higher-than-average IQs (Cox, 1926). Gibson and Light (1967) reported that, at Cambridge, mathematicians had the highest mean IQ (130.4) and highest lower bound (124). The physical scientists' IQs showed no significant difference. They were all around 129–130, confirming Ann Roe's (1952) estimate of a typical IQ of about 130 in scientists. Helson and Crutchfield (1970) reported an average IQ of 149 for mathematicians at the Institute for Advanced Study at Princeton, who were preponderantly Jewish. The percentages of winners of Nobel Prizes who have been Jewish as of 2011 were: Chemistry 20%, Economics 41%, Literature 12%, Peace 9%, Physics, 26%, Physiology and Medicine 27% (http://www.jinfo.org/Nobel_Prizes.html). Jews comprise about 0.2% of the world's population.

There are great dangers in focusing on any single population as an exemplar of a particular trait. Apparently advanced cultural groups relative to the rest of the world have come and gone many times, with ancient Greek, Arabic, and Roman cultures coming immediately to mind. We focused on the Ashkenazi for four reasons. First, they have shown outstanding achievement in the 20 countries in which there are sufficient data to carry out a review (Lynn, 2011). Second, they have a “distinct genomic signature” (Guha *et al.*, 2012). Third, there is a provocative and testable theory regarding genetic factors, fairly specific to this population, which contradicts the well-supported and widely held view that all good things go together, and may well explain their high average IQ (Cochran, Hardy, & Harpending, 2006). Fourth, there are numerous exemplars in this population who seriously challenge the argument that socioeconomic factors are powerful inhibitors of the development of IQ and the resultant achievement that might have gone with it (Howe, 1999, pp. 199–200).

Our third argument supporting intelligence as an essential and critical prerequisite for genius refutes those who have argued that IQ measures do not predict particular outcomes well, highlighting Terman's failure to pick up the Nobel laureates William Shockley and Luis Alvarez in his long-running study of people who showed high IQs as children. As Hunt (2011) pointed out, “such criticism sets unrealistic standards, by asking researchers to predict a one in a million event while ignoring major trends in the data” (p. 349). Such critics also note that other measures often predict achievement better than IQ in samples selected on IQ, ignoring the impact of range restriction. For example, in a longitudinal study of creativity in a sample of male graduate students, Feist and Barron (2003) measured intelligence using the Thurstone Primary Mental Abilities Spatial and Number subtests. The Number subtest involves the checking of simple addition problems, and in above-average populations it is a measure of perceptual speed and accuracy rather than reasoning. These tests undoubtedly had ceiling effects and severe restrictions of range in the sample. There was likely much less if any restriction of range in the personality tests. It has been demonstrated that not acknowledging these factors can lead to seriously misleading conclusions (Hunter & Schmidt, 2004). When these factors are taken into account in studies of work performance, the

validity of IQ tests generally increases, and that of personality tests decreases (Schmidt, Oh, & Shaffer, 2008).

Genetic and Environmental Influences on Intelligence

After a long history of often acrimonious debate, the presence of genetic influences on intelligence has come to be generally accepted (Deary, Penke, & Johnson, 2010). Estimates of the proportion of variance attributable to genetic influences typically range from about 30% in early childhood to as much as 85% in adulthood. This reflects a robust pattern of increasing genetic influences with age. These are offset by environmental influences shared by family members and acting to make them similar that fall from about 30% in young childhood to as little as 0% in mature adulthood, and by decreases in nonshared environmental influences from about 40% to about 20%, largely through increasing test reliability. These patterns show up consistently in studies using samples of twins reared together and apart, adoptive and biological families, and broader kinship studies of family groups, and in both cross-sectional and longitudinal analyses (Bouchard, *in press*).

There are several possible interrelated and not mutually exclusive reasons for these robust developmental patterns, and they highlight the strengths and weaknesses of the quantitative genetic models used to generate them. They also suggest possible processes involved in the development of creative genius. The first possibility is that the genes involved in intelligence act directly but “come online” only over time, as other developmental processes become ready for them. This would be consistent with, for example, the emergence of secondary sex characteristics during puberty and genetic disorders such as Huntington’s disease, which shows up only relatively late in adulthood. It would also be consistent with Piaget’s developmental stage theories. These are rather discrete examples, but it is also possible that genetic influences simply have gradually increasing power with development.

Other possibilities are more oriented around developmental processes. Very young children’s activities tend to be managed closely by their adult caretakers. That is, the caretakers create the children’s environments. The activities biological parents select for their children tend both to show genetic influences and to be related to their genetically influenced levels of intelligence, which they pass to their children, creating a gene-shared environmental correlation. As they grow, however, children increasingly select their own activities and companions, in short, their environments. Their choices of both tend to show genetic influences (Plomin, 2011), thus contributing to the creation of gene–nonshared environmental correlation when siblings make different environmental choices or respond differently to the same ones. We know these gene–environment correlations exist. What we do not know is to what extent they contribute to development and/or maintenance of intelligence.

As noted, quantitative genetic models rely on the assumption that genetic and environmental influences are independent. Thus the presence of these gene–environment correlations violates the modeling assumptions. The effects of these violations on the resulting estimates of genetic and environmental influences are well known (Purcell, 2002). When genetic and shared environmental influences are correlated, estimates of shared environmental influences are overstated. When genetic and nonshared environmental influences are correlated, estimates of genetic influences are overstated. This

suggests that one explanation for the apparently increasing genetic and decreasing shared environmental influences over the lifespan is that the gene–environment correlation gradually shifts from shared in childhood to nonshared in young adulthood, and continues to increase in strength throughout adulthood.

Gene–environment correlation is often associated with gene–environment interaction (Johnson, 2007), in which the same environmental circumstances have different effects on different genetic backgrounds, or different genetic backgrounds are differentially sensitive to environmental conditions. Several studies, for example, have suggested that genetic influences on intelligence are greater in high-socioeconomic-status (SES) environments (e.g., Harden, Turkheimer, & Loehlin, 2007; Turkheimer, Haley, Waldron, D’Onofrio, & Gottesman, 2003). These studies, to date, have all been done using samples of twin children, based on parental SES. This means that, by definition, the twins must share SES. As SES is generally correlated with intelligence, the estimates resulting from these studies can only reflect the genetic influences on intelligence not shared with SES, and so are incomplete. The common variance involved is of course exactly that most relevant to the gene–environment correlations in childhood and adulthood, so the missing variance in the study estimates would be crucial to understanding the processes involved. As for gene–environment correlation, however, we do know how straightforward univariate estimates of genetic and environmental influences are biased in the presence of gene–environment interaction. Estimates of genetic influences are overstated when genetic and shared environmental influences interact, and estimates of nonshared environmental influences are overstated when genetic and nonshared environmental influences interact. We do not know how these offsetting tendencies typically balance out in adulthood. Though many historically recognized geniuses have also been child prodigies, it is generally their adult contributions that have earned them their greatest recognition.

Personality and Psychopathology

There has long been interest in identifying the personality traits associated with creative genius. Most studies, however, have examined associations between personality and intelligence and creativity in the general population, using measures of everyday creativity. Studies have made use of different models of personality, but interpreting results across studies may be mostly a matter of understanding the different trait definitions. Gruzca and Goldberg (2007) demonstrated that 11 different personality inventories generated very similar associations between personality and six different clusters of behaviors. Everyday creativity was among the behaviors they considered. Its major personality associations (.30–.35) were with measures of openness to experience and intellect. This has been the most common pattern in studies using measures of everyday creativity (e.g., Hirsh & Peterson, 2008; Storme & Lubart, 2012), likely partly because most recent studies have made use of the Big Five Model that includes aspects of intellect within one of its major domains. Such studies also sometimes pick up smaller negative associations with conscientiousness, and occasionally positive associations with extraversion. The latter tend to show up primarily when the creativity measures assess divergent thinking or fluency (Batey & Furnham, 2006), and may reflect primarily sensation-seeking and gregariousness. These results are consistent with the intuitive, almost definitional, idea that creativity involves a combination of intelligence,

and willingness and ability to think and seek experiences beyond conventional boundaries, whether this would be considered particularly responsible at any given moment or not. The broad-brushed personality measures generally used and the usually low to at-best-moderate correlations, however, do little to elaborate beyond this.

A classic older study shed considerably more light on personality–creativity associations. Barron (1957) studied a sample of 100 US Air Force captains in groups of 10 over three full living-in days of informal social interactions, arranged situations, interviews, group discussions, games of charades, and so forth. As a group, the sample was well above average in intelligence, education, and physical and mental health. Most had seen combat in World War II and/or Korea, and many had been decorated for valor then. The creativity measure was a composite of eight different scores on tasks ranging from naming unusual uses for common objects to Rorschach projection tests to writing an original story using every word from a list of 50. Personality was assessed by the staff that interfaced with the men during the three days of activities, who were blind to their creativity scores, using Q-sort and adjective checklist measures. The men completed general and specific cognitive ability measures, interest inventories, and self-report personality scales. The staff ratings indicated that the men who scored highest on creativity were verbally fluent and persuasive, communicated intellectual ideas effectively, and took leadership roles with their peers. In contrast, the lowest scorers were conforming and stereotyped in responses, had narrow ranges of interests, tended to hang back from participation, were suggestible, and lacked insight into themselves.

The findings strongly suggested that intelligence was primary, so Barron (1957) examined the measures controlling for a measure of general cognitive ability. This generated substantive correlations between creativity and fluency, openness to stimulation, drive, dominance, impulsivity, and femininity (within a group of unusually masculine men). A related larger group of military officers completed many of the same measures without the living-in assessment. Noting that some lack of control of impulses appeared to characterize those more creative individuals, Barron compared the 15 who scored at least one SD above the mean on creativity and at least one SD below the mean on cognitive ability with the 23 who scored at least one SD below the mean on creativity and at least one SD above the mean on cognitive ability. Those more creative than intelligent tended to be aggressive and demanding, dependent yet dominant, impatient, outspoken, sarcastic, and suggestible. Those more intelligent than creative tended to be mild and pleasant, unselfish, and optimistic. This reinforced the idea that some lack of ego control characterizes creativity, with intelligence helping to channel this in a constructive direction. Barron speculated that

Perhaps when the cortex is most efficient, or intelligence greatest, the ego realizes that it can afford to allow regression – because it can correct itself. A basic confidence in one's ability to discern reality accurately would thus facilitate the use of the powers of imagination.... the creative genius may be at once naive and knowledgeable, being at home equally to primitive symbolism and to rigorous logic. He is both more primitive and more cultured, more destructive, and more constructive, occasionally crazier and yet adamantly saner, than the average person. (pp. 739–740)

Barron notwithstanding, anecdotal evidence and literary references dating back to Aristotle have associated genius with madness rather than sanity, and the high suicide rate particularly among creative writers reinforces the impression. Diagnosing

psychopathology in historical figures considered geniuses has recently become something of a cottage industry, with retrospective diagnoses ranging from bipolar disorder in Beethoven and Van Gogh to autism in Einstein, late-onset schizophrenia in Newton and depression in Hemingway, Plath, Poe, and a passel of other writers. More systematically gathered empirical data suggest two contradictory patterns. One strand of evidence suggests that creative achievement is associated with better-than-average physical health and lower rates of psychopathology. Accumulation of this strand of evidence began with Lewis Terman's famous gifted "termites" (Terman, 1959), but has continued with recent studies of associations between early cognitive ability and mental and physical health. Both kinds require that the inference that the association is between creativity and mental health rely on the assumption that it is high IQ that primarily drives the emergence of creative genius. The studies explicitly addressing rates of psychopathology have generally been based on population-level samples, in which geniuses would be at best rare, and have often used tests that could not distinguish among IQs over about 125 (e.g., Gale, Batty, Tynelius, Deary, & Rasmussen, 2010). Even then, they have often indicated some fall-off in the rate of decline in prevalence of psychopathology at the top range of IQ assessed, particularly for bipolar disorder.

Another strand of evidence indicates that symptoms of mental disorder among the highly creative run about twice those in the general population, with rates among those in the arts higher than those among scientists (Ludwig, 1992). Moreover, higher levels of creativity appear to be associated with greater severity of symptoms (Ludwig, 1995). These two strands could be reconciled if IQ were the primary driver with the relation an inverted U shape, and the peak of the inverted U somewhere well, but not extremely, above average. Another nonmutually exclusive possibility is that, as Barron's (1957) data suggest, creativity involves some essentially involuntary "looseness" of thinking and drive, which intelligence helps to channel constructively. If this is the case, the greater the looseness and/or drive, the harder it would be to channel, so the greater would be the intelligence required to keep it from splashing over into madness.

DeYoung, Grazioplene, and Peterson (2012) have attempted to address this latter issue. In their model, intelligence and bizarre ideation both loaded on a higher order Openness factor, but they lay at its opposite poles. On a scale of +2 to -2, the facets of Openness were arrayed with Intelligence at +2, Need for Cognition at 1, Aesthetics at 0, Absorption at -1 and Magical Ideation at -2. The scale was at best weak, however, as Intelligence and Magical Ideation correlated only -.13, suggesting instead relative independence. High Openness may thus "work" to characterize everyday creativity, but with regard to genius it probably hides as much as it reveals. High Openness without its intellectual facet is generally called psychotic thinking (Wright *et al.*, 2012). Another term often used in place of psychotic thinking is schizotypy, a trait marked by cognitive disorganization and the reporting of unusual experiences. Schizotypy is apparently related to artistic ability but not mathematical ability (Nettle, 2006). Much empirical work remains to be done in this potentially fruitful domain.

Genetic and Environmental Influences on Personality and Psychopathology

As with intelligence, the presence of moderate genetic influences on normal-range personality traits is now well established (Bouchard & Loehlin, 2001; Krueger &

Johnson, 2008; Spinath & Johnson, 2011). The precise proportions of variance vary from study to study, but have generally fallen in the .30–.50 range. There have been few discernible patterns suggesting that any specific personality traits show stronger genetic influences than others. Some studies have shown evidence of nonadditive as well as additive genetic influences, but there has been little consistency in which traits have shown such influences either. The strongest patterns probably relate to scale reliability: More reliable scales tend to show greater proportions of genetic influences, simply because measurement error is included with estimates of nonshared environmental influences (Johnson, Penke, & Spinath, 2011).

Dimensional measures of psychopathology such as the Minnesota Multiphasic Personality Inventory (MMPI) have generally shown very similar patterns of genetic influences, partly because they can be reasonably subsumed by the major personality models, and in particular the Five Factor Model (Samuel & Widiger, 2008). For example, in the only behavior genetic study of the MMPI scales, the average proportion of variance attributable to genetic influences across the scales was .44 (DiLalla, Carey, Gottesman, & Bouchard, 1996). Very similar results have been obtained for inventories of personality disorder (Livesley & Jang, 2008) and measures of schizotypy (Jang, Woodward, Lang, Honer, & Livesley, 2005). Common dimensionality is not the only reason for similarity of estimates of genetic influences on personality and psychopathology, however, as studies of psychiatric disorders using standard diagnostic categories generally report similar estimates. Genetic influences on lifetime depression in a very large Swedish cohort were .29 for males and .42 for females, with the sex difference significant (Kendler, Gatz, Gardner, & Pedersen, 2006). Genetic influences on schizophrenia were higher: ~.70–.80 with no sex difference (Lee *et al.*, 2012).

Genetic Influences on Miscellaneous Traits Relevant to Creative Genius

Specific measures of creative personality

Two self-report scales have been used to measure creative personality, one from the Adjective CheckList (The Creative Personality Scale; Gough, 1979) and one from the CPI (The Creative Temperament Scale; Gough, 1990). In the MISTRA sample, they have shown estimated genetic influences of .54 and .55, respectively.

Novelty-seeking/sensation-seeking Numerous studies of genetic influences on his five Sensation-Seeking Scales have been summarized by Zuckerman (2005, chapter 5). The estimates ranged from .43 for Boredom Susceptibility to .57 for Disinhibition. Similar results have been reported by subsequent studies.

Flow Flow is a positive state of total engagement that occurs during the performance of a task. It has been associated with creativity and genius because many report such a state during creative acts. It appears unrelated to intelligence and only slightly related to personality (Ullén *et al.*, 2012). Using a large sample of Swedish MZ and DZ twins, Mosing *et al.* (2012) reported genetic influences of .29–.35 for three flow scales, with large genetic correlations among them indicating a common genetic factor.

Psychological interests

Psychological interests are considered important in understanding creativity/genius. Geniuses turn up in both scientific and artistic domains, and the question as to why an individual chooses a particular domain always arises. In the Institute of Personality Assessment and Research (IPAR) studies of creative samples, the Q-sort item “has a wide range of interests” consistently correlated significantly with creativity ratings and vocational interests predicted creativity ratings as well as personality tests (Hall & Mackinnon, 1969). Contrary to widespread belief, psychological interests are not simple manifestations of personality, and the overlap between personality traits and measures of vocational interests is modest (Waller, Lykken, & Tellegen, 1995, table 4). In addition, interests are not only related to choice of domain of work, but also related to level of performance (Nye, Su, Rounds, & Drasgow, 2012). Early behavior genetic studies of vocational interest were summarized by Nichols (1978), with estimates of genetic influences running from .44 to .55. Subsequent studies have not altered this general conclusion (Schermer & Vernon, 2008), though, as is typical (Johnson, Penke, & Spinath, 2011), shorter and otherwise less reliable scales have provided slightly lower estimates.

The Barron–Welsh Art Scale

The Barron–Welsh Art Scale (BWAS) was used extensively in the IPAR studies of creativity and has repeatedly been shown to be a valid predictor of various creativity criteria (Gough, Hall, & Bradley, 1996). There have only been two behavior genetic studies of the BWAS. One used a small sample of ordinary twins (Barron & Parisi, 1976), and one was based on twins reared apart (Bouchard & Lykken, 1998). Neither was able to demonstrate any genetic influence on the trait. In the latter study, a different measure of Aesthetic Judgment showed a heritability of .43, quite comparable to most other psychological measures.

Molecular Genetics and Genius

While molecular methods confirm that cognitive abilities are strongly under the influence of genes (Plomin *et al.*, 2013), despite considerable effort, often in the form of very large genome-wide association consortium studies, we currently know of no genetic variants reliably associated with intelligence, personality, or psychopathology, whether related to genius or not. Munafò and Flint (2011) summarized one of the commonly offered explanations as

Small effects dominate, and are consistent with available data on the genetic architecture of complex traits.... This finding suggests that the genetic architecture of schizophrenia is, in large part, simply a very long tail of infinitesimal effects, which together nevertheless produce substantial heritability. The same is likely to be true for personality [and intelligence]. (p. 398)

A contrasting view was offered by Weiss (2008):

Complex biological traits have many redundant, interlaced, stochastic, interacting, variable, emergent properties. Consistent with this, disease-related genes show every

conceivable type of mutation. To the extent that each instance of a phenotype is etiologically unique, it can be resistant to science that depends on replication. Yet the strategies currently proposed are for even more technologically intense enumerative reductionism. (p. 1751)

Weiss referred to disease, but the genetic and environmental processes involved in development of the specific maladaptive configurations we label as disease are very likely similar to those involved in development of the special configurations we label as genius. Both thus argue that the focus of research should be on within-individual processes, or what has been repeatedly referred to as “special cases.”

Emergenesis

Whatever else they may be, geniuses are idiosyncratic in behavior, if only for the uniqueness of the creations for which they become known. Striking similarities in idiosyncracies of behavior have also been noted consistently in MZ but not to nearly the same extent in DZ pairs in all the formal studies of twins reared apart (Lykken, McGue, Tellegen, & Bouchard, 1992). Some of these similarities have unquestionably been coincidental, but their pervasiveness, much greater frequency in MZ pairs, and specificity suggest that much of what becomes observable as human individuality may have its origins in particular configurations of independently segregating genes that, in combination, exert multiplicative influences. If so, only the broad components underlying these idiosyncracies would be passed from one generation to the next. Many such characteristics have been described, from fingerprints to frequency of the brain’s alpha rhythm, to beauty. Beauty serves as a good example because of its familiarity. Everyone can probably think of families in which similarities of appearance are clear throughout, yet one member of the family stands out as having much more beautiful facial features than the others. This is consistent with the pattern of emergence of genius within families: Many, from Johann Sebastian Bach to Charles Darwin, came from families that showed prior and subsequent prominence in similar areas but not to the same extent, and at least as many have come seemingly out of nowhere.

David Lykken (1982) coined the term “emergenic” (adj.) or “emergensis” (n.) to refer to novel or emergent properties resulting from the interaction of more elementary and partly genetic properties. An emergenic trait may be influenced by a configuration of independently segregating genes and situational circumstances interacting multiplicatively rather than additively, or a configuration of independently genetically influenced traits that contribute synergistically to behavior in specific circumstances. The distinctive feature is genetic involvement in configuration, in which a difference in any one component may mean a qualitative, or a large quantitative, difference in the emergenic trait (Lykken, 2006). E. O. Wilson asserted that genius is configural in this sense:

Since each individual produced by the sexual process contains a unique set of genes, very exceptional combinations of genes are unlikely to appear twice even within the same family. So if genius is to any extent hereditary, it winks on and off through the gene pool in a way that would be difficult to measure or predict. Like Sisyphus rolling his boulder

up to the top of the hill only to have it tumble down again, the human gene pool creates hereditary genius in many ways in many places only to have it come apart in the next generation. (Wilson, 1978, p. 198)

But so may be psychopathology. As discussed, there are many direct links between genius and psychopathology, and many forms of psychopathology show configural properties. Psychopathology is much more common than genius and understanding its genetics is a very active area of current research. We suggest that recent developments in this area may be relevant to understanding the genetics of genius/creativity and use autism as a relevant example because it has been diagnosed retrospectively in several historical geniuses.

Autism

Until recently, autism was considered a taxonomic disorder. Contemporary research, however, suggests that it is continuous, and the term Autism Spectrum Disorders (ASDs) has come into use. The concordance rate for ASDs in MZ twins has been reported to be very high, generally between 80% and 100% (Rosenberg *et al.*, 2009), with many genetic variants influencing the trait (Berg & Geschwind, 2012). Somewhat different genetic variants may be in play at different ages (Ronald & Hoekstra, 2011). A recent study, using careful diagnostic standards but a modest-sized though population-based twin sample, has questioned the strong genetic influences estimated by previous investigators (Hallmayer *et al.*, 2011). It reported genetic influences of .37 for autism and .38 for ASD, and shared environmental influences of .55 and .58. When measured continuously in a sizable general population, autistic characteristics yielded a relatively normal distribution and a heritability of .57, with nonsignificant shared environmental influence (Hoekstra, Bartels, Verweij, & Boomsma, 2007), and no evidence of assortative mating. Contemporary research strongly suggests that autism will prove to be genetically heterogeneous in origin (Berg & Geschwind, 2012; Miles, 2011).

Autism has been considered more characteristic of people in Scientific, Technical, Engineering, and Mathematical (STEM) disciplines than in Artistic and Humanistic disciplines, which tend to be characterized by depressive disorders. These two groups represent Snow's (1959) "Two Cultures" and are reflected in the Thing-versus-People dimension in the domain of vocational interests. A study of relatives of an entire cohort of students at an elite university showed that students in STEM disciplines were more likely to report siblings with an ASD (Campbell & Wang, 2012). In contrast, students in the humanities were more likely to report family members with depressive disorders or substance abuse. These student groups can be easily discriminated on the basis of abilities and interests as well (Wai *et al.*, 2005). Autistic relatives also appear to be common among prodigies (Ruthsatz & Urbach, 2012). Autism is neurobiological in origin (Via, Radua, Caardoner, Happé, & Mataix-Cols, 2011) and probably characterized by atypical network connectivity (Ecker *et al.*, 2012). Age of father but not mother has been linked to de novo mutations associated with both autism and schizophrenia (Kong *et al.*, 2012; Sasanfar *et al.*, 2010).

De novo mutations are largely paternal in origin (Keightley, 2012) and increase in frequency with paternal age. This may explain some interesting anomalies/peculiarities in the creativity/genius literature. For example, Simonton (1999) has

noted that early parental loss, which would tend to be more common among older fathers, has been influential in the lives of creative geniuses. Moreover, historical geniuses have displayed a “disproportionate number of physical and sensory disabilities” (p. 115). These physical and sensory disabilities are called “minor physical anomalies” in the sizeable literature documenting their associations with *de novo* mutations and psychopathology (Ozgen, Hop, Hox, Beemer, & van Engeland, 2010; Weinberg, Jenkins, Marazita, & Maher, 2007). If this is correct, early paternal death is often not the purely psychosocial environmental influence generally assumed. Instead, the *de novo* mutations themselves could create deviation in genetically controlled neurological development processes that results in a stable and normal (at least for itself) form analogous to the kinds of extreme outliers that have been documented in many different kinds of physical and social systems that we discuss below.

An Aside on Distributions

The not-so-normal normal curve

Distributions of ability, and in particular intelligence and creativity, are generally assumed to be normal, but this is at best only approximately correct (Micceri, 1989; O’Boyle & Aguinas, 2012). Normality generally breaks down at the tails in empirical ability data with appropriate measurement precision and thorough sampling, and the resulting positive skew is often attributed to multiplicative or configural combinations of variables (Walberg *et al.*, 1984). Murray (2003, chapter 6) provided a discussion of this skew as described by the Lotka curve, noting that William Shockley showed how individual components that are normally distributed can be combined to create Lotka-like distributions. He also noted that Herbert Simon showed that the Lotka curve is not the extreme tail of the normal distribution. Simonton’s “chance configuration theory” (Simonton, 2004) can also generate a Lotka curve. Standard IQ measures are restricted in range. Thus, we do not know the true distribution of IQ for the population, and it is possible that intelligence alone could account for more of the positive skew of human accomplishment than is currently believed.

Lotka-like distributions

There is a large literature documenting the appropriateness of Lotka-like distributions in describing distributions of eminence, with nice examples presented by Martindale (1995). Perhaps the most highly researched domain is the distribution of publication citations. These distributions are typically highly positively skewed, and their feature of most research interest has been the upper tail. Is it a log-normal distribution, a Pareto Type-II distribution, a Yule process, or some other distribution? Different distributions support one explanatory process (theory, mechanism) over another. For example, a cumulative advantage model (“Matthew effect,” Merton, 1968) predicts that a Yule process will fit the data, whereas a model that contains a stochastic component predicts that a power law will fit better. But in very large citation datasets (over 10,000), even the power law typically does not fit, and there are a few “runaways.” Runaways are papers that initially have typical citation histories but then diverge dramatically

from the rest and accumulate vastly more citations than others over much longer periods. For example, as of this writing, Baron and Kenny (1986) has been cited over 20,300 times. Such papers are highly individualized events, special cases (Golosovsky & Solomon, 2012; Redner, 2005) generated by unusual processes (Kitano, 2004). In science, citations reflect both influence and productivity, making their authors candidates for genius status above and beyond the potential relevance of the similarities in distributional properties between genius prevalence and citation counts (Albert, 1975; Simonton, 1999, chapter 5). Several characterizations of these kinds of events have been suggested.

Are Geniuses Black Swans, Dragon-Kings, or Hopeful Monsters?

Black swans

Expanding on Shockley's (1957) argument that productivity in science is a multiplicative function of many components, Montroll and Shlesinger (1982) generalized the argument to the distribution of income, suggesting that "runaway rich guys" such as Bill Gates tend to be special cases. Taleb (2007/2010) has labeled such special cases "black swans." In the financial world, the most recent financial collapse is considered an example, but the idea is more general. The term comes from a Latin expression referring to black swans as the rare birds they are, but it was commonly used in 16th-century London as a statement of impossibility because the English of that period thought there was no such thing. It is thus a metaphor for undirected, unpredicted, often catastrophic events beyond what would be expected under normal conditions. Taleb has suggested that black swan events are generally unpredicted because we overlook their possibility, but they are not actually unpredictable and can be characterized and their causes identified if they are properly studied. This is precisely the purpose of researchers studying "dragon-kings."

Dragon-kings

The term "dragon-kings" combines the idea of a mystical beast outside the ordinary animal kingdom that hoards treasure with that of kings, whose wealth lies outside the ordinary distributions of wealth in their kingdoms. The metaphor thus implies that at least two different processes are at work in the emergence of a creature of crazily great wealth: One generates the positively skewed distribution of "ordinary" wealth, and the other generates and supports the rare class of kings, who have completely different means of access to wealth than ordinary citizens. Both processes are in practice and theory "understandable," but they reflect very different causal mechanisms. Dragon-kings are, consequently, extreme events that do not belong to the same population as others with which they are typically classed, created by amplifying mechanisms not necessarily active in the rest of the population to the same degree. These mechanisms lead to the development of specific characteristics unique to the dragon-kings (Sornette, 2009). Examples commonly offered are the cities of London and Paris in the United Kingdom and France, which are so much bigger than any other cities in those nations that they lie outside all known distributions. Beyond population size, these cities serve

as economic and cultural hubs that completely dominate their nations and regions. A different kind of example comes from the Braxton-Hicks contractions that precede human parturition, with the dragon-king Braxton-Hicks contraction being the one that brings on actual labor (Sornette & Ouillom, 2012). In physical systems such as water turbulence and hurricanes, dragon-kings can be defined in precise quantitative and mechanistic senses. This makes them predictable from the dynamics of preceding small events. Sornette (2009; Sornette & Ouillom, 2012) reviewed relevant mathematically models to do so, when the underlying processes can be described.

Hopeful monsters

Similar ideas have been proposed in evolutionary biology. The notion of hopeful monsters was introduced by Goldschmidt (1940) as part of his attempt to integrate genetics and development. Believing that the differences among species were too large to arise as fast as they had through the kinds of gradual, atomistic changes described by Darwin, he proposed that new species arise through the rare occurrence of very large mutations that introduce fundamental metabolic or morphological changes. These changes in turn alter the developmental course by triggering new patterns of selection augmented by further much smaller mutations. A hopeful monster is an individual that deviates radically from the norm in a population because of a genetic mutation that confers a potentially adaptive advantage. Goldschmidt suggested that, in the “right” environmental circumstances, the hopeful monster can be the source of a new species, and proposed two mechanisms that might generate the monster. The first of these mechanisms involved systemic rearrangements of chromosomes and has been completely rejected as incompatible with modern understanding of the genome. The second has also generally been disregarded, but has recently received renewed historical attention because it is consistent with recent observations and ideas under discussion in evolutionary developmental biology. This mechanism is mutation in genes that control fundamental aspects of early development through timing and/or level of expression, so that such a mutation, which does not have to be large itself, has large downstream effects on the phenotypic development of the individual.

From an evolutionary perspective, the problem with hopeful monsters is that they alone cannot create new species. Even if they reproduce readily with members of the species from which they originated or others, there are no potential mates likely to facilitate transmission of their key characteristics. Moreover, it is clear that most mutations are deleterious, and most models of mutation processes have indicated that fitness of mutants tends to be negatively associated with deviation from typical form, so that mutations tend to generate “hopeless” rather than hopeful monsters (Tooby & Cosmides, 1990). Nevertheless, some mutations are function-enhancing, and many mutants live relatively normal lives, even when their mutations are not explicitly function-enhancing (Leroi, 2003). Because evolutionary biology was dominated throughout most of the 20th century by assumptions of the accuracy of quantitative genetic models specifying static additive genetic contributions to discrete traits, Goldschmidt’s developmental proposal did not seem relevant. The ability to map genomes, however, has changed this situation by showing that major morphological differences can coexist despite only very small genetic differences, and that many if not most of the genetic differences among species lie in genes that control the timing or position, rather than presence or absence, of development of characteristic features.

This has led to recognition that developmental processes must be considered to understand both evolutionary processes and genetic variance within species (e.g., Blumberg, 2009; Jablonka & Lamb, 2005; Jaeger, Irons, & Monk, 2012; Kirschner & Gerhart, 2005; West-Eberhard, 2005).

Most examples that have been discussed as hopeful monsters come from plants, but there are some among animals as well. Consider the turtle (Ohya, Kuraku, & Kuratani, 2005). All turtles share a highly unusual body plan among tetrapods that lay their eggs on land. Many fish and reptiles have what are called “osteoderms,” or bony material formed at the surface of the skin (e.g., fish scales), but these are generally arranged in a single layer, and they are completely separate from the internal skeleton forming vertebrae and ribs. The turtle shell often consists of several layers of osteoderms, and their arrangement in both a distinct dorsal carapace, or back shell, and ventral plastron, or front shell, is unique (Rieppel, 2001). Moreover, instead of developing as coherent bones in the endoskeleton, the ribs are “spread” as increased thickening in both the carapace and the plastron. This creates the turtle’s other unique feature: the location of its scapula, or shoulder blade, inside what amounts to its ribcage (Rieppel, 2001).

It has been impossible to construct a plausible scenario of continuous, gradual evolution from any possible turtle ancestor so far found in the fossil record, consistent with turtles’ abrupt appearance in the late Triassic (Theissen, 2006). Initial embryonic development of the somites, or blocks of tissue that go on to become the back and its vertebrae, is the same in turtles as in all other tetrapods (Rieppel, 2001), but Ohya *et al.* (2005) have mapped out subsequent unique differences in their embryonic expression of the *Hox* genes that control the head–tail axis development of all bilaterally symmetrical animals from worms to humans. This suggests that their strikingly unique features arose not from genetic mutations that created their morphological uniqueness, *per se*, but from rather subtle changes in embryonic gene expression that had major consequences for their subsequent development. At this point in evolutionary history, turtles are found commonly throughout the world in highly varied environments and have fossil records dating back more than 200 million years. Just as Goldschmidt suggested, they may have originated as hopeful monsters, but they are now well-adapted, even ordinary, members of the animal kingdom (Theissen, 2006).

A more apt example of an actual hopeful monster might be a two-legged goat reported by a Dutch morphologist (Slijper, 1942). The goat was born with an unexplained congenital defect of the forelegs that made them unable to support its weight. Despite this deformation (monster status?), the goat adapted to its condition, developing the (hopeful?) ability to walk and even run on its two hind legs. Slijper dissected it after its accidental death from a fall while walking downstairs. He documented extensive differences from normal goats in the structure of its pelvic and thoracic skeleton, the bones of its hind legs, the arrangement of small tendons in the leg muscles, and a greatly thickened and elongated gluteal tongue. Similar patterns have been observed in other normally tetrapod animals trained or forced to walk upright, and they resemble the features in humans that allow bipedal running. Human bipedalism has long been assumed to have been a difficult evolutionary step involving many mutations, which each determined a specific morphological alteration, but Slijper’s goat suggests that the necessary changes could have arisen much more rapidly and directly through much smaller changes in the timing of development of morphological features (Slijper, 1942; West-Eberhard, 2005). Thus, Slijper’s goat may have been a hopeful monster whose hopes for contributing to evolution did not pan out.

The Relevance of Dragon-Kings and Hopeful Monsters to Our Understanding of the Emergence of Creative Genius

Geniuses as statistical dragon-kings

Geniuses do not appear to transmit their complex configurations of traits to their offspring (Eysenck, 1995, pp. 14–16; Lykken *et al.*, 1992). This strongly reinforces the claim that genius is an emergent phenomenon. Geniuses are certainly special cases and extreme outliers, usually on several dimensions, much like dragon-kings. This leads us to conclude that the idea that a confluence of many different processes is fundamental to producing dragon-kings is relevant to genius as well. The models developed to predict the occurrence of dragon-kings in physical systems are grounded in complex systems theory and statistical physics. One of the fundamental principles in these areas is that even small perturbations in common processes can generate major catastrophic events. They take place through qualitative changes that emerge from smooth variations in parameters that control an interlocked network of characteristics, and go by labels such as phase transitions, ruptures, bifurcations, and tipping points (Sornette, 2009). For example, stress increases basically linearly over time on rocket pressure tanks made of multilayer carbon composites. The stress damage to date at any one time, however, exerts positive feedback that impacts future damage. The feedback process has been modeled sufficiently to enable prediction of the point where the pressure tanks will rupture, and it is in common use in the aerospace industry in Europe. Models developed to predict financial collapses have been grounded in similar ideas, but they are focused on the roles of market investors' expectations about continuing price rises and therefore earnings in creating "bubbles" that at some point must burst. This makes the point that, though many of the same principles may be involved in very disparate dragon-king situations, the specifics must be closely tailored to a clear understanding of each individual dragon-king situation. The same thing is likely to be true in the different domains of genius.

Geniuses as hopeful monsters

The hopeful monster examples are also directly relevant to understanding the emergence of genius. Geneticists use the term "complex traits" for traits that do not occur in simple Mendelian ratios. Such traits also inevitably show involvement of environmental factors. Virtually all (normal and abnormal) psychological traits are highly polygenic. Contemporary discussions of the genetics of such traits suggest that the processes underlying them may well be much more complex than has been typically assumed. Even traits widely considered Mendelian are more complex than they originally appeared. For example, hundreds of different mutations underlie phenylketonuria. It is now described in varying degrees of severity, and standardization of treatment has revealed that children of women who are recessive for the mutations but have been successfully prevented from experiencing their negative effects can manifest those negative effects themselves, even when they are only heterozygous for the involved allele, because of high exposure to phenylalanine during gestation. Most individuals with mental illness actually do not have a single diagnosis; comorbidity is instead the norm. The belief that there are discrete psychiatric diseases is probably false. It is useful to think of creative genius as similar to a rare disease or as a catastrophe

such as a financial collapse, in order to apply modern genetic thinking to it. We know that some diseases and catastrophes are mixes of simplicity and complexity, and that many involve phase transitions from one stable condition to another. For example, our bodies regularly produce irregular cells that are sloughed by our immune systems. Occasionally, however, something happens, often a somatic genetic mutation, to increase the rate of production of such cells greatly, so that it exceeds the immune system's coping capacity. This creates a phase transition to the persistent illness we call cancer.

It is commonly assumed that the human brain is some sort of elegantly designed computer. The opposite is the case. Insect brains are somewhat computer-like, depending on simple neural circuits. Mammalian brains, however, depend on signals controlled by populations of neurons (Eberhard & Wcislo, 2012), which means that their functions are rarely dependent on any one specific aspect. At the same time, the human brain is a Kluge (Marcus, 2008): a work-around, quick-and-dirty solution, band-aid-upon-band-aid pile of immediate evolutionary adaptations to specific, often long-gone circumstances, the result of Darwinian "modification by descent" that requires that new structures be jerry-built on top of old ones. Allman (2000) provides a striking analogy that reveals another important property of the brain. Describing his visit to an old power plant, he noticed

an array of pneumatic controls, an intricate maze of tiny tubes that opened and closed various valves; there was a system of controls based on vacuum tube technology; and there were several generations of computer-based control systems. *All these systems were being used to control processes at the plant.* (p. 40)

This overlay of functional mechanisms existed because it was too expensive to shut the plant down, even briefly. Like the old power plant, the brain is made up of redundantly interrelated parts, and they provide the crucial property of robustness.

Robustness refers to the ability to retain core properties in the face of environmental perturbations. It is a familiar concept in design of engineering systems, where relevant principles have been worked out, and their implications can be measured. Increasingly, however, it is being applied to the study of biological systems. Like genius, it is a system-level phenomenon that cannot be understood by looking at the individual components of the system (Kitano, 2004). It is the property that allows the system to function in unpredictable environments using unreliable components. The successful hopeful monster, the turtle, is very robust, and the striking property of Slijper's diagrams of the morphology of his goat is the robustness of its developmental adaptations, despite its ultimate evolutionary failure. For all their extreme outlier status, much of the behavior of geniuses is similarly robust: Despite often Sisyphean obstacles, they persisted in the work for which they are known.

One property of robustness may be particularly relevant to this aspect of genius. A system with little sensitivity to some kinds of disturbance necessarily has greater sensitivity to other kinds of disturbance. This can be demonstrated using a formula known as Bode's sensitivity integral, and its necessity can be proven (Kitano, 2004). The genius who persists in their work despite physical illness, debt, persecution, imprisonment, and so forth, may just be in danger of being tipped into madness by some other, perhaps superficially more minor, upheaval such as romantic rejection.

Geniuses as dragon-kings emerging through cosmobia?

Robustness could be the property, studied in an old, almost forgotten line of research, that may be relevant to understanding genius. This research was based on the idea that studying the abnormal can lead to better understanding of the development of the normal. Wilder (1908) made a distinction between highly unusual morphological forms resulting from what he termed “primary” deformity and equally unusual, even sometimes identical, forms that result from conditions Wilder termed “secondary.” Examples of Wilder’s primary deformity might be the phocomelia, or truncated limbs, that developed in offspring when pregnant women were prescribed thalidomide in the 1950s and 1960s, as well as those resulting from rare genetic variants, such as those causing phenylketonuria, that substantially disrupt normal basic metabolic function, leaving it defective. The most common examples of the secondary forms were, to Wilder, variations in the “germ” that cause variations from the normal patterns of timing of development of various characteristics. These variations can lead to often substantial deviations from normal phenotype that are nonetheless stable and show no evidence of any kind of malfunction. He was particularly interested in the rare cases of conjoined twins and people born with either one or three eyes, and worked out that there was a continuous progression of abnormality from individuals with just one eye and no nose in the middle of their faces; to people with two pupils on “figure 8” irises and noses above the single-but-double eye; to people with very narrowly spaced eyes and very thin noses in the usual position; to people with very widely spaced eyes and thick noses; to people with three eyes and two noses; and all the way through to people with two heads, four eyes, and two noses on a single neck. The disorder is called holoprosencephaly and is one of the most common brain deformities in humans (Roessler *et al.*, 1996). Wilder (1908) coined the term “cosmobia” (meaning “ordinary beings”) to describe individuals with abnormalities that form such progressions on either side of normality, when the abnormalities are not associated with any kind of disruption of function (beyond the obvious clumsiness of walking around, for example, with two heads on one neck). He documented the presence and details of several examples in humans and other animals, and demonstrated that his cosmobia were robust in exactly the way that his primary deformities were not.

Wilder (1908) reasoned that such orderly, robust, and symmetrical phenotypic variation must result from genetic variation, and that kind of assumption about the sources of orderly variation is common. But Stockard (1921) challenged this explicitly deterministic genetic interpretation. He carried out an extensive series of experiments with model organisms that demonstrated clearly that the same kinds of progressions of stable abnormalities could be generated in genetically identical embryos by environmental manipulations such as cooling them at particular points of gestation, and worked out the resulting differences in developmental sequences of gene expression that brought them about. It is becoming increasingly clear in the field of genetics that any one genotype can generally display not just one but some range of phenotypes, depending on environmental conditions, and that the phenotype that is displayed in any one environment depends importantly on particular timings of gene expression during development as well as on actual genotypic variation, making cosmobia in all likelihood common but its viable extremes rare as extremes generally are. This makes traditional attempts to tote up genetic and environmental “causes” separately all but ridiculous. Theories of the emergence of genius are going to have to take into

consideration the newly emerging understanding that structural variation in the human genome is vastly greater than previously realized, and its roles in both disease and “normal” variation during lifespan development remain to be explicated (Stankiewicz & Lupinski, 2010).

Could the dragon-king genius be one end of a “cosmobian” progression in the brain?

Note

- 1 It is not widely recognized that every experiment requires assumptions. When an experimenter compares a treatment group with a control group they assume that the treatment represents the causal mechanism. For example, shocking rats is seen as a form of stress. To test the hypothesis that stress causes ulcers, experimenters shocked rats. The stressed rats got ulcers, and the unshocked control group did not get ulcers. Does stress cause ulcers? Actually, about 60% of ulcers are caused by *Helicobacter pylori* (curable with antibiotics) and about 20% are caused by aspirin and ibuprofen. Stress is involved, by making the rats more vulnerable to the bacteria and side-effects of the painkillers, but it is not actually the cause. The clincher in this instance is that one can get an ulcer by ingesting bacteria and one can cure it by taking antibiotics. In the case of quantitative genetic models, the clincher is one can breed other mammals for behavioral traits, increasing and decreasing their frequencies over generations to reliable degrees. It is essentially impossible to imagine how human genetics could operate differently.

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