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Translational Article

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Translational

Genes, Environments, Personality, and Successful Aging: Toward a Comprehensive Developmental Model in Later Life

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Background. Outcomes in aging and health research, such as longevity, can be conceptualized as reflecting both genetic and environmental (nongenetic) effects. Parsing genetic and environmental influences can be challenging, particularly when taking a life span perspective, but an understanding of how genetic variants and environments relate to successful aging is critical to public health and intervention efforts.

Methods. We review the literature, and survey promising methods, to understand this interplay. We also propose the investigation of personality as a nexus connecting genetics, environments, and health outcomes.

Results. Personality traits may reflect psychological mechanisms by which underlying etiologic (genetic and environmental) effects predispose individuals to broad propensities to engage in (un)healthy *patterns* of behavior across the life span. In terms of methodology, traditional behavior genetic approaches have been used profitably to understand how genetic factors and environments relate to health and personality in somewhat separate literatures; we discuss how other behavior genetic approaches can help connect these literatures and provide new insights.

Conclusions. Co-twin control designs can be employed to help determine causality via a closer approximation of the idealized counterfactual design. Gene-by-environment interaction (G × E) designs can be employed to understand how individual difference characteristics, such as personality, might moderate genetic and environmental influences on successful aging outcomes. Application of such methods can clarify the interplay of genes, environments, personality, and successful aging.

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GIVEN considerations such as increased longevity and rapidly aging populations in the United States and abroad, efforts to understand mechanisms of successful aging are receiving increased attention. Research in this area has identified some apparent predictors of physical, cognitive, and emotional health in later life, which include both genetic and environmental influences. Because environments represent all nongenetic effects, environmental, and quasi-environmental, influences can be conceptualized broadly to encompass protective/risk factors and behavioral patterns in which individuals engage. For instance, they can easily be conceptualized as "purely" environmental influences, such as literal environments (eg, lead exposure). They can also be more complex influences that reflect environmental exposures (eg, a lifetime of smoking) that may arise partly from genetic influences (eg, genes predisposing an individual to develop nicotine dependence). Using this definition, environmental influences affect a wide array of successful aging constructs (ie, constructs associated with improved longevity as well as higher quality of life as individuals age). Environmental influences range from the biological

(eg, longevity) to the psychological (eg, optimism, resilience) to the social (eg, social integration) (1).

Untangling the complex direct causal effects of, and interactions among, genetic and environmental influences will be critical to public health efforts to promote successful aging in the coming years. For instance, although social integration may show positive associations with aspects of successful aging, interventions to improve quality of life by strengthening social ties might fail if these associations reflected reverse causation (eg, continued good health is the cause of increased social integration, as opposed to functioning in the opposite direction) or the presence of a third variable with broad impacts, such as underlying genetic factors. The purpose of the current report is to outline the beginnings of a framework to unravel the complex genetic and environmental influences on successful aging. This framework integrates individual differences in personality as a potential explanatory mechanism and highlights newer behavior genetic methods that can lead to stronger causal inferences due to their novel design features. The wide variability in many outcomes of successful aging suggests numerous opportunities to apply such models toward understanding the sources of this variation.

Genetics and Successful Aging

We will begin our discussion of the relative contributions of genetic factors and environments to successful aging by focusing on the direct effects of genetic factors. It is self-evident that genetic factors relate to human development; just as genes provide the informational framework to build each human embryo, their impacts continue to be felt throughout the life span. Although molecular genetic approaches are now being applied to questions of successful aging—for instance, which genetic variants might be related to the development of dementia of the Alzheimer's type—the majority of our current understanding about the role of genetics in later life has come from behavior genetic studies of twins. In their classic formulations, behavior genetic studies parse variation in an observed phenotype (eg, a trait) into causal components—most typically (i) additive genetic effects (referred to as "A"), (ii) shared environmental effects ("C") that are common within a family, such as the neighborhood in which the twins were raised together, and that act to create greater phenotypic similarity within pairs than would be predicted solely from genetic similarity, and (iii) nonshared environmental effects ("E") that are unique to each family member and that serve to make individuals different, including, eg, stochastic effects (2). Behavior genetic methods, for example, provide estimates of heritability, which is the proportion of phenotypic variance due to genetic effects.

This classic approach has yielded important findings about the relative importance of genetic factors for successful aging. For instance, the heritability of longevity has been estimated to be around 25% or greater and to be stable across birth cohorts (3–5).

Environments and Successful Aging

In accepting a broad definition of "environment"—one that includes all nongenetic sources of variance—we accept a wide variety of possible influences on successful aging. If, for example, 50% of subjective well-being variation were shown to be due to nonshared environmental effects in behavior genetic analyses, the next logical direction would be to ascertain precisely which constructs accounted for this effect. On one hand, we would include literal environmental settings, such as the impact of continuing to live independently in one's own home versus moving to an assisted living community. On the other hand, given our definition, we would include less commonly conceived types of environmental influences as well. These include environmental exposures, such as exposure to health-related behaviors (eg, smoking, exercise), individual differences, social interactions, and so on. Such environmental exposures are not purely environmental in most cases; they are likely most accurately conceptualized as being *partially* environmental exposures because they are also reflections of genetic influence in many cases. For instance, if an individual chooses to expose himself to exercise, this might reflect a genetically influenced predisposition to being energetic and personality traits that might predispose an individual to exercise. Alternatively, if an individual were, say, randomly drafted into the military and was thus exposed to regular physical exercise, this would be a purely environmental manifestation of the same variable. This highlights the relative rarity of identifying a construct that is purely genetically, or environmentally, driven, and any discussion of such "environmental" exposures should be understood as possibly reflecting downstream genetic influences as well. Finally, in behavior genetic analyses, the nonshared environmental variance component typically also includes psychometric error.

Numerous factors that have environmental aspects to them have been linked to successful aging. A recent review has established such behavioral factors as caloric restriction and physical activity, and intervention-based environmental exposures such as cognitive interventions, stress reduction, and social programs, as being associated with cognitive, emotional, and physical health in older adults (1). Of course, health risk behaviors, such as smoking, have also been related to health throughout the life span (6). Constructs such as socioeconomic status—which, in childhood, is a commonly used example of shared environmental effects between twins—are also linked to healthy aging (7).

Personality

Like discrete health behaviors, environmental settings, and genetic factors, personality traits have been associated with important outcomes related to successful aging. For instance, personality traits prospectively predict longevity, divorce, and occupational attainment—and they do so as well as cognitive ability (eg, IQ) and socioeconomic status (8). Personality trait models typically include multiple distinct trait domains.

Examination of these individual domains and the facets subsumed therein has yielded associations with successful aging variables. For instance, the domain of conscientiousness—a key higher-order domain in Big Five models of personality—and some of its facets (eg, responsibility, self-control, traditionalism) are consistent predictors of longevity (eg, an effect size of $r = -.09$ of conscientiousness for mortality, indicating a protective effect; [9,10]). Another trait domain, neuroticism/negative affectivity/internalizing, has been shown to account for the observed comorbidity of many forms of mental disorder at different points across the life span (11). Although beyond the scope of the present chapter, some extreme and maladaptive personality features (12), known clinically as personality disorders, are, by definition, associated with dysfunction and occur throughout the life span, including very late life (13).

Behavior genetic research has consistently demonstrated that individual differences in single-assessment, self-report personality traits, on average, are due approximately 50% to additive genetic effects and 50% to nonshared environmental effects (14); when incorporating multi-rater data and thus assessing personality traits more fully than self-report, genetic factors account for around two-thirds of domain- and facet-level variance (15). However, this literature is typically quite separate from the behavior genetic literature on successful aging and on environmental contributions thereto. Because genetic factors, personality, health-related behaviors, and successful aging appear so closely intertwined, this lack of integration is notable. In the following sections, we lay out some features of a conceptual model of how personality can be used to capture this interplay and how behavior genetic methods can be used to understand the complex etiologic underpinnings of successful aging.

Health Behaviors as Patterns

Studies focusing on health-related behaviors frequently examine how a particular health-related behavior, such as caloric intake or regularity of physical activity, relates to constructs associated with successful aging, such as longevity, subjective well-being, or physical health. This approach has yielded a somewhat piecemeal understanding of the impact of particular behaviors on aging. Numerous seemingly disparate factors are associated with successful aging, such as eating nuts, using sunscreen, and owning a car (16). A different approach—one that focuses on broad longstanding *patterns* of behavior across the life span rather than discrete behaviors—may be a profitable and complementary angle from which to investigate how behaviors are associated with successful aging. For instance, it is probably not solely the frequency of physical exercise in later life that relates to health. Rather, it seems likely that this relation reflects a broad propensity to adopt a healthy lifestyle, in which exercise is but one aspect of an overall approach to living. Other behaviors linked to this propensity perhaps include a combination of high physical energy, focus on physical health, enjoyment of being active versus sedentary, interest in stimulation versus inactivity (eg, watching television), and so on. Studies of physical exercise tap into this propensity, but they fail to capture its breadth and may thereby attenuate its associations with successful aging. The broad propensity is akin to studying general cognitive ability (*g*)—which is a broad construct saturating a variety of performance measures—by assessing only mathematics. On the outcome side, this approach is similar to conceptualizing successful aging solely as one aspect of this broader construct (eg, longevity).

The Role of Personality in Health Patterns

If we accept that specific health behaviors are reflections of broad, underlying propensities to engage in generally stable patterns of related, but distinct, health behaviors, the question becomes how to conceptualize these constructs for further study. We propose that investigations of personality may represent an important first step. The use of personality as a means of framing these health-related behavioral patterns is sensible, given that personality traits confer broad predispositions to behave in a given way within a group of related behaviors. For instance, the trait of extraversion relates to characteristics such as outgoingness, sociability, self-confidence, sensation seeking, energy, and positive emotionality. Clearly, personality traits such as extraversion encompass a broad set of behaviors; although each of these behaviors might relate to successful aging if examined separately, a better understanding of their impacts would require an understanding that they are all manifestations of the same psychological core. By incorporating information about the domain-level trait of extraversion with information about the specific characteristics (facets) it subsumes, researchers can elaborate a model of personality-liked health behaviors that shows both generality and specificity.

To illustrate this point, let us consider a particular personality trait as relating to patterns of specific health-related behaviors. Bogg and Roberts (9) meta-analytically examined trait conscientiousness in tandem with tobacco, drug, and excessive alcohol use; diet and activity patterns; violence, risky sexual, and driving behaviors; and suicide. Results indicated that trait conscientiousness related positively to all beneficial health-related behaviors and negatively to all risky health-related behaviors, thus highlighting how trait conscientiousness can be used to unify our understanding of these superficially different behaviors in a systematic patterned way.

Personality traits are also relatively stable over time, particularly in adulthood (17,18). This is not to say that personality traits are immutable or "set like plaster" as previously thought; indeed, there are patterns of within-individual and between-age cohort mean differences across the life span (19). However, the general rank-order stability of personality traits provides a critical strength for studies of successful aging, which typically take a longitudinal developmental approach. Given recall biases and memory lapses, we can never know

precisely how an individual was in the past by retrospective reporting. Because personality traits show a notable degree of developmental stability, they provide a rough estimate for how individuals have been—and behaved—throughout their life span. In this way, personality traits might be conceptualized as providing a reasonable basis upon which inferences about lifelong health-related behavioral patterns can be drawn. This being said, personality traits can change substantially, even in later life, but this does not change the overarching message. To wit, the factors that concern health and aging investigators may be significantly impacted by latent individual differences constructs that have been excluded from most health research. These latent constructs, including personality traits, likely influence health outcomes, and they do so whether they change across the life span or not. It should also be noted that personality is likely reciprocally influenced by some health outcomes, such as health restrictions being associated with apparent personality changes (eg, decreased mobility resulting in fewer opportunities for, and less interest in, risk taking or sensation seeking).

Integrative Frameworks

Although researchers have demonstrated associations of successful aging and health variables with genetic factors, environmental influences, and personality, these findings have been reported in largely separate literature and remain relatively unsynthesized. The full promise of these separate lines of inquiry likely lies in developing an integrative framework in which the effects of genetics, environmental influences, and personality can be considered simultaneously. We believe that particular behavior genetic approaches can provide a means by which these ends can be realized. As such, we now turn our attention to two methods that hold notable promise for gerontological studies: co-twin control designs and gene-by-environment (G × E) investigations.

Co-twin Control Analysis

The first behavior genetic method we will discuss is the co-twin control design. Traditional behavior genetic approaches parse variance in a phenotype (or set of phenotypes) of interest into genetic, shared, and nonshared environmental components. This can be helpful for ascertaining the heritability of a phenotype and determining where, for instance, research and intervention efforts should be directed. For instance, a phenotype with a very high heritability—say, 80%—would suggest that the phenotype arises primarily from genetic influences (eg, stature is an example of this type of highly heritable phenotype, [20]). The picture here is complicated in a sense because, although various phenotypes may differ in the degree to which their variance is heritable, all human phenotypes are mediated through genes. In other words, environmental exposures, such as carcinogen exposure in the workplace, will interact with the genetically driven biological substrates within each individual, and thus gene-environment interplay will account for whether an individual develops cancer.

The co-twin control design yields different information than these traditional approaches. Rather than parsing phenotypic variance in a single phenotype into its etiologic components, co-twin control analyses support causal inferences about the relations between specific constructs and aging outcomes of interest. The illustration of causation is a contested and complex issue in general (21). Drawing strong causal inferences is even more problematic for gerontological research because the causal inference gold standard—the randomized controlled experiment—can rarely be conducted given the constructs of interest, the life-span perspective, potential selection effects, and other confounding factors. To understand better the strengths of the co-twin control design for causal inference, we must first discuss the counterfactual briefly.

In simplified experimental terms, we can think of the counterfactual as being the result of a given individual receiving and not receiving the experimental treatment. (For an excellent discussion of the counterfactual and co-twin control designs, see McGue and colleagues [22]). If a researcher is interested in the impact of a cognitive intervention (treatment) versus no intervention (control) for a successful aging outcome like memory performance, what she would like to know is how her sample of *N* individuals would react if they received the treatment compared with if they had received the control. In other words, she seeks a difference score for each individual (δ_i) between his or her memory performance after receiving the treatment (Y_i^T) and after receiving the control (Y_i^C), which can be represented as $\delta_i = Y_i^T - Y_i^C$ (22,23). However, this counterfactual approach—where one knows the outcome of simultaneously exposing, and not exposing, each individual to both treatment and control—is not feasible. Instead, the researcher relies on a randomized experiment. Because she cannot assign each individual to both conditions simultaneously, she will instead assign individuals to the treatment or control group. By use of random assignment and a reasonable sample size, she hopes that individual differences will cancel each other out and the groups will differ meaningfully only with regard to treatment condition. As such, she is attempting to approximate the idealized counterfactual model.

Nonexperimental designs, and particularly the observational and quasi-experimental designs used in much gerontology research, typically approximate the idealized counterfactual model less well than randomized experiments; however, close attention to observational study design can mitigate some of these issues (23). (In some instances, due to factors such as selection effects, it may indeed even be the case that broad observational studies can provide better estimates of causality than potentially biased experimental designs; [22]). One study design that can approximate the idealized counterfactual model is co-twin control, wherein twins who are discordant for a given X (ie, a treatment, exposure, behavior, individual difference, etc.) are compared on an

outcome of interest Y. The use of twins reared together to compare the impact of one potential cause on the outcome capitalizes on the understanding that monozygotic (identical, MZ) twins have in common 100% of their segregating DNA and 100% of their shared rearing environments. Dizygotic (fraternal, DZ) twins, on the other hand, have in common, on average, only 50% of their segregating DNA in addition to 100% of their shared rearing environments. Neither MZ nor DZ twins have any nonshared environmental effects in common because, by definition, these effects are unique to each twin.

The understanding that MZ and DZ co-twins have different profiles of genetic, shared environmental, and nonshared environmental overlap, formulated in quantitative terms, allows for co-twin control behavior genetic modeling and bolsters causal inferences (22). For example, if one can identify identical twins who differ, within pairs, on exposure to a risk environment and those twins differ in a corresponding way on an outcome, this *suggests*, but does not definitively demonstrate, that the risk exposure is causal. The risk-outcome association in this case would likely not be a function of, for example, the same genetic variation causing both the risk exposure and the outcome because these MZ twins share 100% of their segregating DNA. Thus, the co-twin control design can be particularly helpful for testing and rejecting some causal hypotheses. The design is comparatively less strong in rejecting third variable explanations (eg, third variable X causes the investigated risk exposure as well as the outcome, giving the appearance of a direct exposure-outcome link that is instead mediated through the third variable X; third variable X causes the one twin to be exposed while the other is not, and thus the measured risk variable might not actually be in the causal chain of exposure-outcome events). One limitation of the co-twin control design—particularly for studies of aging—relates to potentially varying ages of onset of disorders within twin pairs, which may give the appearance of true discordance while actually representing only a temporary discordance.

Co-twin control studies can be conducted with different levels of analytical sophistication. For instance, some co-twin control studies take a relatively straightforward approach: they approximate the idealized counterfactual by comparing outcome measures of MZ twins who are discordant for a potential causal factor. Although we cannot assess individual *i* after he or she has been exposed to a potential causal factor and after not having been exposed to the factor, we can treat a pair of MZ twins as being highly similar individuals who are nearly perfectly matched on many potential confounders (eg, gender, age, childhood environment, genetic code, etc.). Now, if $Twin_1$ has engaged in, say, regular physical exercise, whereas $Twin_2$ has not, our comparison of these two highly similar individuals on an outcome (subjective well-being) will help clarify the role regular physical exercise plays with regard to subjective well-being (24). Basic co-twin control designs of this nature are not perfect analogs of the counterfactual, of course, and they do not definitively demonstrate causation in and of themselves; however, these designs do approximate the comparison of the same person after exposure and nonexposure to a potential causal influence in a closer way than individual-level analysis (22).

Given its analytic and inferential strengths, the co-twin control design is being increasingly applied to gerontological questions. Historically, co-twin control designs were applied to the evaluation of interventions by giving one MZ twin the treatment while leaving the other as a control, which is a more efficient design than the standardized case–control randomized-controlled trial (25). This method is equally applicable to nonexperimental observational designs as well, making it a particularly promising approach to test hypotheses in aging research. Co-twin control designs of this nature require little in the way of analytic complexity and several registries of mid- to later-life twins exist (eg, the Midlife in the United States sample and the Longitudinal Study of Aging Danish Twins).

Discussion of a nongerontological co-twin control study of this nature would be informative for the purposes of illustration. One excellent application of this sort of co-twin control was done to examine the potentially causal relations between childhood sexual abuse (CSA) and later development of psychopathology (26). By examining a population-based sample of 1,411 female adult twins (MZ and DZ analyzed as a group), the researchers brought to bear the power of basic co-twin control designs to test hypotheses. After they established a link between CSA and later psychopathology, the researchers were able to infer whether this link was causal by examining co-twins discordant for CSA. It is possible, for instance, that some characteristic of the individual (eg, a personality-related third variable confounder) would predispose her to CSA and independently to psychopathology. Because twins (and particularly MZ twins) are likely to share this characteristic with their co-twins, within each pair of twins, there should be a relatively low association between CSA and psychopathology; the third variable hypothesis here would suggest that, since the twins have similar levels of the characteristic, they should both develop psychopathology regardless of whether or not they experienced CSA. The authors did not find this pattern; rather, their results showed clear links between CSA status and psychopathology within discordant twin pairs, with the abused twin significantly more frequently experiencing psychopathology. This bolsters the inference that CSA causes psychopathology. In this way, a relatively basic comparison of twins—and particularly those discordant on a potential influence of interest—can rule out confounding factors and provide support for causal links. Causal inferences are further strengthened by study design factors and the nature of the research question. For instance, the temporal sequencing of the variables in this study (26)—onset of psychopathology temporally followed CSA—bolstered the inference that CSA's link to psychopathology was causal.

More complex co-twin control designs are available, and these designs can be even more informative. By examining

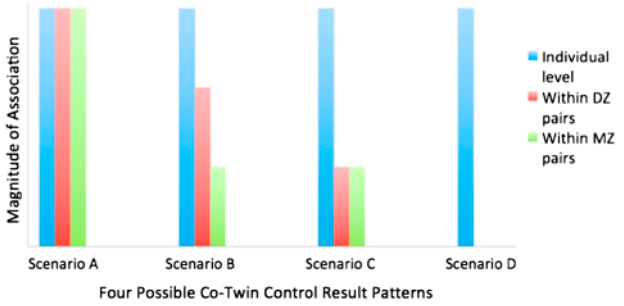

Figure 1. Possible co-twin control result patterns. Scenario A suggests a causal link between influence and outcome. Scenario B suggests a genetic third variable may account for the influence-outcome association. Scenario C suggests a shared environmental third variable may account for the influence-outcome association. Scenario D suggests genetic and shared environmental third variables may account for the influence-outcome association. These scenarios are intended to be heuristic sketches of possible observations, as opposed to involving model-derived precise point values corresponding with the exact heights of the lines in the figure.

within- and between-pair associations between the potential influence and the outcome, separately in MZ and DZ twins, a researcher can statistically estimate the outcome level of an affected twin had he not been affected and vice versa (27). Perhaps more importantly, these approaches also can test causal hypotheses about the association between a potentially causal influence and an outcome rather clearly. Like traditional behavior genetic analyses, the co-twin control design relies on what we know about the differences and similarities between MZ and DZ twins in terms of shared genes, shared rearing environments, and unique environments, as discussed above.

Co-twin control analyses estimate the magnitude of the relationship between influence and outcome within individuals in the general population (R_{WI}), within discordant MZ twin pairs (R_{MZ}), and within discordant DZ twin pairs (R_{DZ}). Four possible resulting scenarios for comparing the magnitudes of these relationships are shown in Figure 1. Scenario A: If the influence is truly causal (ie, exposure to the influence directly contributes liability to the outcome), then R_{WI}, R_{MZ}, and R_{DZ} will be equivalent—regardless of one's genetic and shared environmental status, exposure to the influence increases the risk for the outcome. Scenario B: If the influence-outcome association is not causal but is due to a genetic third variable that causes both the influence and outcome, one would expect R_{WI} to be large, R_{DZ} to be smaller, and R_{MZ} to be smaller still. Scenario C: If the influence-outcome association is not causal but is due to a third variable residing in shared family environment (eg, childhood socioeconomic status conferring risk to CSA as well as psychopathology) causing both influence and outcome, one would expect R_{WI} to be large and R_{MZ} and R_{DZ} to be equivalently lower. This is because both MZ and DZ twins experience the same shared rearing family environments, and, regardless of whether or not they were exposed to the influence, their shared environment predisposes them equally to the outcome. Scenario D: Finally, if the influence-outcome association is not causal but is due entirely to some mix of both genetic and/or shared environmental effects, one would expect R_{WI} to be large while R_{MZ} and R_{DZ} would similarly be near zero because the influence-outcome association would be seen only at the individual level (27,28). Importantly, Figure 1 is intended to be heuristic, as opposed to involving precise point values corresponding with the exact heights of the lines in the figure. For example, the "within MZ pair" bar in scenario B is not precisely zero as drawn, and hence, there may be a partial causal effect if those bars corresponded with precise numerical values along the y-axis. In actual empirical application of these approaches, formal quantitative models can be fit that yield precise quantitative statements of the degree to which the data fit with the different kind of scenarios portrayed heuristically in the Figure (eg, McArdle and Prescott [29]).

This sort of co-twin control design is increasingly being applied in gerontological research, given its ability to parse out cause and effect (30,31). A recent review of the co-twin control studies in successful aging research highlights this method's versatility (22). Co-twin control designs—often examining discordant MZ and DZ twins grouped together—have tested the impacts of potential influences on outcomes, such as physical exercise and job complexity on dementia; physical activity, smoking, and heavy alcohol use on mortality; social class on cognitive performance; physical exercise on life satisfaction; and so on. Some of these studies have suggested causation by exposure to a potential influence, whereas others have suggested genetic and/or environmental confounding.

Given the wealth of constructs of interest—both as potential influences and important outcomes for successful aging—these studies represent only a preliminary step toward a comprehensive developmental model of successful aging in later life. How can we best proceed to test the myriad possible combinations of influences and outcomes, particularly given that it is likely patterns of behavior over the life span rather than short-term exposures, that will have the strongest impacts on successful aging? Again, we suggest the unifying role of personality. It seems likely that the analysis of twins discordant for personality traits, which have broad impacts on a range of behaviors and other influences, would clarify influence-outcome relationships and provide researchers with useful constructs for further study. For instance, analyses of twins discordant for the personality trait disinhibition might show associations with successful aging. Researchers could then examine particular aspects of disinhibition (eg, medication noncompliance, risk taking, alcohol and substance use, etc.) likely to be associated with different types of health outcomes.

Gene-by-Environment Analysis

Traditional behavior genetic methods assume that the effects of genetics, shared environments, and nonshared environments are relatively set at a given level. For instance,

an approximate 50% heritability for a phenotype (a common finding) is interpreted as 50% of the trait's variation across individuals is due to additive genetic factors; we emphasize that it is not, and should not be interpreted as, that 50% of the "cause" of a disorder in an individual is due to genetic influences. Indeed, heritability is a *population* statistic that tells us about the variation of a phenotype among people not about an individual person. However, some compelling behavior genetic models also have the power to get closer to influences on individuals within the population, by examining interactions between genetic factors and environments. In other words, the impact of genetic factors (or environments) might be moderated by some other variable—perhaps heritability of a phenotype differs as a function of another construct. While such interactions have long been considered theoretically, recent statistical advances (32) have made examining them more empirically tractable, and it has become clear that the effects of genetic factors are not static as once believed. We now turn our attention to these models, focusing on what is commonly referred to as gene-by-environment (G × E) analyses (albeit these techniques rely on genetic variation discerned from family data, as opposed to specific measured genetic polymorphisms). While other methods of investigating the associations between genetic factors and environments exist (eg, the gene–environment correlation), we believe G × E will provide a particularly important tool for gerontological researchers. For information on other models, see Johnson (33).

The mathematics behind gene–environment interactions is complex and beyond the scope of the present report, but both algebraic derivations and theoretical descriptions have been reported elsewhere for interested readers (32–34). For our purposes, it is sufficient to think about gene by environment analyses as being conceptually analogous to interactions in multiple regressions, and we will discuss these methods by example rather than design. To use an example of relevance to successful aging, we will review a study of the genetic and environmental contributions to two indicators of physical health (number of chronic illnesses and body mass index; [35]). Although one can think of an aspect of physical health as having a set level of heritability, it is perhaps optimal to think of this level of heritability as representing the *mean* genetic influence on physical health when the effect of all other influences are removed. For instance, the authors noted that, while physical health has been shown to have a genetic component in previous studies, there is also a robust association between income level and physical health, such that individuals with higher incomes tend to have better physical health. Clearly, genetic factors and environments both potentially play a role in physical health outcomes.

There are several ways to reconcile the genetic- and income-related findings regarding physical health—among the most statistically elegant is the analysis of G × E interaction. Rather than assuming that genetic and environmental contributions were steady across the full range of income, we (35) tested whether these contributions might differ as a function of income. Indeed, this was the case. When individuals earned 1 *SD* above the income mean, the genetic variance associated with number of chronic illnesses (after controlling for insurance coverage and education) was .33; for individuals 1 *SD* below the mean, the associated genetic variance was 1.7 times greater (.55). Similar results were reported for body mass index. These trends, which became even more pronounced toward the tails of income distribution, indicated that the impact of genetic factors on physical health was moderated by income. At low levels of income, genetic effects are associated strongly with physical health; at high levels of income, variance in physical health is due much less to genetic effects. Why? One hypothesis is that genetic factors provide a diathesis for health problems, and, at lower income levels, individuals face higher levels of stress (eg, financial, physical stress due to manual labor, etc.) that can activate this diathesis. Importantly, modern methods can also model gene–environment correlations in the same framework as gene–environment interactions, and examination of these correlations can also enrich our understanding. For example, in an extension of our first study on income and health (36), higher gene–environment correlations were observed between income and the personality characteristic of sense of control, in relatively higher income environments. This may reflect a tendency for similar (eg, personality and ability) tendencies to affect both an individual's perception of control and that individual's income level.

Physical health variables aside, how could G × E analyses be meaningfully applied to research on successful aging? Again, we return our focus to personality and the supposition that personality traits represent reasonable proxies for relatively stable lifelong patterns of behaviors of interest to gerontologists. By examining broadband constructs such as personality traits, gerontology researchers can (i) ascertain the genetic and environmental contributions to personality, (ii) determine how these contributions are moderated by relevant environmental variables, and (iii) test the effects of potentially worthwhile environmental variables as they relate to successful aging. Questions of this sort have already begun to be addressed. For instance, one study examined G × E with regard to the origins of higher-order personality domains of positive emotionality (a tendency to view life as pleasurable; including facets of achievement, social closeness, social potency, and well-being), negative emotionality (a tendency to experience psychological distress, akin to neuroticism; including facets of aggression, alienation, and stress reactivity), and constraint (a tendency to act cautiously and endorse traditional beliefs; including facets of control, harm avoidance, and traditionalism; [34]). Clearly, these domains are broad constructs, and they comprise theoretically interesting and important facets related to successful aging (eg, well-being, social factors, risk avoidance, etc.). Although it had previously been established that the variance of personality traits such as these is due approximately 50% to additive genetic effects and 50% to nonshared

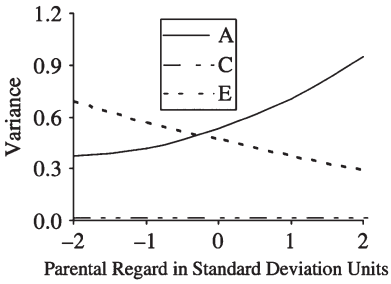

Figure 2. Sources of variance in the positive emotionality personality trait across different levels of parental regard from Krueger and colleagues (34). A = additive genetic variance. C = shared environmental variance. E = nonshared environmental variance. This figure was previously published in Krueger and colleagues (34). Copyright 2008 John Wiley and Sons. Reprinted by permission.

environments in single self-report assessments, the authors questioned whether the origins of these traits might differ somewhat based on parent–child relationships during youth. When using two measures of the parent–child relationship—parental regard and parental conflict—as moderators of the variance components of personality traits, the effects of genetic factors and environments were altered. For instance, as depicted in Figure 2, genetic factors accounted for 35% of the variance in positive emotionality when parental regard for their children was 2 *SD*s below the mean; at the mean of parental regard, genetic factors accounted for 52% of the variance in positive emotionality; at 2 *SD*s above the mean, genetic factors accounted for 76% of the variance in positive emotionality. This finding appears to indicate that increasing levels of parental regard provide a stable "canvas" upon which genetic factors can demonstrate their predisposing effects. The directionality of these links can alternatively be reversed, highlighting how personality can moderate the genetic and environmental etiologies of the parent–child relationship. Indeed, a separate study taking this perspective demonstrated that the genetic and environmental influences on parent–child relationship variables were significantly moderated by the child's personality traits, suggesting that the child's personality also had an evocative impact on the quality of the parent–child relationship (37).

Summary

Studies of successful aging must move beyond traditional frameworks and apply sophisticated methods to understand causality and etiology. Behavior genetic approaches such as co-twin control and G × E analysis can provide a framework for such analyses. Further, refinement of constructs, beyond specific influences, to relatively stable, lifelong constructs that can pervade multiple aspects of life and account for longstanding patterns of behavior, may be of particular importance. We believe personality traits are worthwhile constructs for study toward these ends. The integration of personality traits with novel analytic methods may provide compelling findings, and help frame new hypotheses, about how and why some individuals age successfully, while others do not. In addition, the merging of traditional tools (such as the twin study) with novel biological technologies (eg, the ability to study epigenetic variation at the genomic level) is likely to provide novel insights about the mechanisms underlying individual differences in aging outcomes (38).

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