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Personality Psychology

Finding and Developing the 21st Century Scientific Pioneer

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Research on the personality of creative scientists is revisited using the Neo-Socioanalytic model of personality psychology as an organizing framework. Past research shows that creative scientists, largely from the 20th century, were distinguished by high levels of openness to experience, dominance, ambition, intelligence, and low levels of agreeableness. Contradictory findings for environmental influences highlighted the potential importance of both supportive and adverse diversifying experiences. Developmental trends also run contrary to the likelihood of scientific creativity occurring later in life, which is consistent with the life span models of creativity. Based on this review, we highlight much needed updating to the basic science of scientific creativity, including the need to test these findings in populations other than older white men, and the testing of both environmental experiences and individual differences simultaneously. An agenda for identifying and developing the 21st century creative scientist is provided.

Science shapes culture in a way few institutions do. Much of modern life is a product of the scientific process and its offshoot, technology. In a very real sense, pioneering scientists are the creators of the modern world (Dean K. Simonton, 2004b). But who are these people? What are the characteristics of the scientists whose ideas change science and, ultimately, our lives? And, how do we either identify these characteristics, develop them, or both? In the 20th century, social scientists–and personality psychologists in particular–attempted to answer these questions. Oddly, despite decades of research and apparently coherent findings, the 20th century research on scientific creativity does not appear to be either widely known or to wield much influence over how institutions or societies select and develop scientists so as to maximize the production of creative science.

The goal for this review is to revisit the question of how to identify and foster the creative, pioneering scientist in the 21st century. The importance of science and the ability of scientists to provide answers to pressing societal problems appears to have only grown more important in the intervening decades. As our world manages a worldwide pandemic largely due to the innovative research on mRNA-based vaccines (Sahin et al., 2020), it is apparent that fostering a healthy, creative population of scientists is critical for society's well-being. This task inevitably focuses on scientific creativity—what it is, what factors contribute to it, and how it develops. Accordingly, in this review, we revisit the timeless questions concerning how to identify and develop creative scientists. To help organize and focus our review, we rely on the Neo-Socioanalytic Framework, a personality system that provides a road map for organizing personality constructs related to creativity, as well as an explicit developmental perspective, which has not informed prior reviews (Roberts & Nickel, 2021). Using this framework, we seek to organize prior research, paint a complete portrait of the creative scientist, and identify the developmental patterns and factors that influence whether scien-

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tific creativity is achieved. We then synthesize this information to inform scientific efforts to help identify and develop creative scientists in the 21st century.

What is Scientific Creativity?

Pioneering, creative scientists produce ideas that are recognized by expert opinion as having contributed something of original value to science (Stumpf, 1995). As creativity forms the foundation of pioneering science we start with a synthetic consensus definition of scientific creativity. For a scientific finding to be deemed creative, it would have to be both *original* and *meaningful* (Amabile et al., 2018; Barron & Harrington, 1981; Feist, 2022; Runco & Jaeger, 2012; Sternberg & Lubart, 1999). Indeed, Kant (1790/1987) was the first to argue that originality is not enough: "Nonsense too can be original." (p. 308/175). To be original, an idea must have a low probability of being generated. To be useful, an idea should be able to solve a problem of interest. Simonton (2004a, 2022), added a third criterion, namely surprisingness. To be surprising, an idea must be nonobvious; for instance, if a solution were a simple derivation based on previous expertise, it might be considered original but not surprising. To these three qualities, MacKinnon (1962) added "a sustaining of the original insight" which would presumably reflect the desire and will to persist with an idea even in the face of criticism and skepticism.

As is true in most fields of achievement, scientific productivity is heavily positively skewed, with only a minority of creative scientists producing a disproportionate number of original ideas in science and therefore qualifying as pioneering scientists (Dean K. Simonton, 1988). As far back as 1926 Lotka developed what is now known as the Lotka Law or the inverse square law of productivity. It states that the number of scientists who make T total contributions is inversely proportional to T^2. For example, 100 scientists will have only 1 publication; 25 scientists will have 2, and 11 scientists will have 3. Much empirical research has confirmed this highly skewed law of scientific productivity (Dennis, 1955; Feist, 1993; Lotka, 1926; Murray, 2003; Price, 1963; Dean K. Simonton, 2004b; Dean Keith Simonton, 1998). Price (1963) expanded on Lotka to develop his own "elitist" law: half of a field's total contributions/publications will be produced by the square root of the number of people in the field. For example, if the field has 100 scientists, then 10 of those will publish 50% of all work; if it has 1,000 then 32 scientists will publish 50% of all papers. This makes the identification and fostering of this small group of scientists all the more important.

While pioneering scientists are rare, their influence is anything but small. One optimal way of visualizing the influence of pioneering scientists is a cladogram, which can be used to organize fields of study and help further define scientific creativity (Anderson & Feist, 2017). In a cladogram, the origin of a field has a base stem from which new branches form reflecting distinct moments of peak creativity, insight, and transition. Each new branch is a node. The earlier in a field's development the node is, the bigger the impact on the field it can have. The first node creates the most basic split in the field; in the case of psychology, for example, it was between the clinical and experimental sides of the discipline. Pioneers are those who create new nodes or new fields of study. They transform science.

Operationalization of Scientific Creativity

Scientific creativity, being both a process and an outcome, has been challenging to define and measure (Parkhurst, 1999). Fittingly, research has approached the measurement of scientific creativity from a variety of perspectives and often a combinatorial approach. One consequence of these definitional challenges is that a myriad of operationalizations and metrics of scientific creativity have accumulated in several different literatures, including sociology, psychology, economics, and scientometrics. In this section, we attempt to bring this scattered research together to summarize the different ways in which scientific creativity has been defined and measured in past studies.

Nomination. Nomination was one of the earliest used techniques to study scientific creativity. The technique is simple and appears to have reasonable justifications and assumptions. In particular, the typical approach has been to ask a sample of experts to indicate which scientists from their field of specialty were the most creative. The basic assumptions behind the technique are that the scientists being rated are already successful and that the best judge of creativity comes from subject matter experts from the field itself.

In an early example, Roe (1951), selected a sample of biologists who were members of the National Academy of Science and/or the American Philosophical Society. Then this group of successful biologists was rated by other biologists on the quality (not creativity) of their work. Similarly, peer nominations were used in a study of creative mathematicians (Helson & Crutchfield, 1970). In this study, members of the Mathematics Department at the University of California were asked to nominate the most creative mathematician with whom they had attended graduate school, or to nominate a creative faculty member at their Ph.D. institution. Subsequent work on architects followed a similar approach (Hall & MacKinnin, 1969), where a panel of architecture professors at the University of California, Berkeley, nominated people with unusual creativeness in the practice of architecture. Nominations and ratings can also come from experts and not peers. For example, Helson (1959) had faculty from the Mills College nominate senior students whom they considered to have exceptional potential for creative work in the arts, sciences, or humanities, who were then followed up for many decades (e.g., Helson, 1959, 1965, 1999; Helson et al., 1995).

Although possessing very strong face validity, the nomination approach is not without some drawbacks. For example, by focusing on already established scientists or scientists who have been drawn from prestigious societies, the outcome may be confounded. As noted by Feist (1991a), when drawing from honorific societies, it is difficult to control for idiosyncratic factors that lead to belonging to these groups, such as personal acquaintanceships, topic of study, and university affiliation, among others. This would lead to

Table 1. Scientometric Operationalizations of Scientific Creativity Measures.

Creativity Measure	Operationalization of Measure
Productivity (P_i)	Number of journal articles produced by scientists across their entire career was used as a predictor of productivity of a scientist.
Impact (C_i)	Total number of citations a scientist's work received over his or her entire career.
h-index	Number of papers authored by a scientist with citations each paper receives equal to or greater than *h*.
Soler's Creativity Index	Summing the total number of published papers, total number of citations that each paper receives, total number of references that the paper cites, and then dividing the result by the total number of authors.
Overall creativity score	Standardized and equal weighted sum of P_i, C_i, *h*-index, and creativity index

bias or criterion contamination, such that judgements of creativity would include other types of outcomes, such as the ability to choose popular topics of study, socioeconomic background, and gender (Lerman et al., 2022).

Productivity and Eminence. Relatedly, researchers have focused on more objective, yet indirect indicators of scientific creativity, with the most common being productivity, impact, and eminence. Productivity, for example, has included outcomes such as number of inventions, patents, or papers published (e.g., Bergum, 1974; Ikpaahindi, 1987; C. J. Mullins, 1963; Rushton, 1990; Shockley, 1957; Taylor & Ellison, 1967; Van Zelst & Kerr, 1951, 1954). Impact is typically measured by the number of citations received (Reskin, 1977). Because these two measures are correlated, they are often combined (Allison & Stewart, 1974; Busse & Mansfield, 1984; Cole, 1979; Feist, 1993, 1997; Helmreich et al., 1980, 1988; Rushton, 1990; Rushton et al., 1983; Segal et al., 1980). As mentioned above, citation and publication data are inherently positively skewed so they must be log-transformed to partially normalize their distributions.

More recently, publication/citation-based alternatives have been developed and used to codify productivity and influence. The most common one is the *h*-index, which is when an author of *N* number of papers has *h* number of publications cited at least *h* number of times (and all other published articles by that author have received less than *h* number of citations (Hirsch, 2005). For instance, an author has an *h-index* of 20 when she has at least 20 articles cited at least 20 times. As another improvement on straight citation and publication counts, Soler (2007) proposed the creativity index. Soler's creativity index estimates scientific creativity based on the total number of published articles, total number of citations that each article receives, and the total number of references that each article makes to previous articles normalized by the total number of authors per article. Soler's creativity index of a particular scientist can then be calculated by summing the total creativity for every article that an author has written, normalized for the number of coauthors in each case. Finally, Grosul and Feist (2014) created an overall scientific creativity index by standardizing, equal weighting, and then summing publications, citations, *h*-index, and Soler's creativity index into one integrated index (see Table 1).

Although not as widely used in the studies of scientific productivity and eminence, alt-metrics have emerged with the advent of digital publication and open-source data (Brigham, 2014; Priem & Hemminger, 2010). "Alt" stands for alternative to traditional publication and citation count metrics. Alt-metrics include number of times an article has been viewed, tweeted about, discussed, recommended, blogged about, saved (in Mendeley or CiteULike), or downloaded (Brigham, 2014). Two clear advantages to alt-metrics over traditional metrics is they are open-source and their speed: they occur in days, weeks, and months after publication, not a year or more. The validity, however, of alt-metrics for scientific creativity, impact, or even faculty promotion is mixed at best (Bornmann, 2015; Bornmann & Haunschild, 2018; C. H. Mullins et al., 2020).

Similarly, much research has focused on objective indicators of eminence. In these studies, memberships in honorary societies have been used as the primary indicators of eminence, followed by other indicators such as winning highly prestigious awards. Membership in societies such as the National Academy of Sciences, American Philosophical Society, or other professional societies have been common criteria of eminence in past studies (e.g., Azoulay et al., 2011; Chambers, 1964; Clark, 1957; Feist, 1991a, 1993; Wispé, 1965). Other, less common and objective metrics include the number of entries in encyclopedias, biographical books, and archival data (Albert, 1980; Chambers, 1964; Dennis, 1954; Dean K. Simonton, 1991), number of awards received (Feist, 1993; Roe, 1952), and, lastly, receiving especially prized awards such as the Nobel Prize (Albert, 1980; Jones & Weinberg, 2011). Like nominations, these more objective indices provide a complex outcome for the study of scientific creativity, as productivity and eminence can emerge not simply through creative achievement, but through other means such as being prolific or working in the right field.

Science of Science Methods. Science of Science (SoS) is a transdisciplinary field that seeks to understand, quantify, and predict scientific research and the resulting outcomes (Zeng et al., 2017). SoS draws on theories and methods from Network Science, Scientometrics, Sociology of Science, and Econometrics, among other disciplines (Fortunato et al., 2018). Research in the field of Science of Science often focuses on objective details of the published literature, and in so doing relies on massive data that eliminates the subjectivity of nominations or ratings. Many popular performance measures of productivity have emerged from the Science of Science, such as the number of publications, the total number of citations received, the average number of citations per paper, and the *h-index* (Hirsch, 2005).

Beyond quantity measures already described, the SoS has derived numerous indicators that could be used to help identify the creative scientist. For example, the Q index was developed to capture a researchers' ability to enhance the impact of their paper beyond what could be explained by their productivity and status (Sinatra et al., 2016). Similarly, SoS methods have also been developed for identifying rising stars (i.e., researchers with the potential to become influential in the future). For example, researchers have been exploring features of co-authorship networks (e.g., A. Daud et al., 2013, 2015; Ning et al., 2017) and bibliometric networks (e.g., N. N. Daud et al., 2020; Panagopoulos et al., 2017; Zhang et al., 2016). More direct attempts to identify creative research using SoS methods include the atypicality of the citation patterns used by scientists, with the presumption that a scientist who pulls from disparate literatures is more creative than others (Uzzi et al., 2013).

Tests. Another approach that attempts to reduce the subjectivity of approaches like nominations is reflected in "power" tests of creativity. Power tests of creativity require people to do their best on tasks that are thought to be intrinsic to the creative process. The first examples are divergent thinking tests (e.g., Barron, 1955; Erickson et al., 1970; Schaefer, 1969). Divergent thinking (DT) refers to the ability to produce many diverse ideas when presented with an open-ended problem or task (Runco, 1990). Typically, these tests are scored for total ideational output (i.e., fluency), ideational originality, and, sometimes, ideational flexibility (Acar & Runco, 2014). The Guilford Consequences Test (P. R. Christensen et al., 1953), for example, requires participants to list as many consequences as possible of new and unusual situations (e.g., the sudden destruction of all books) in two minutes, and they are scored on ideational fluency and originality. Fluency is scored based on the number of directly connected or obvious consequences, whereas originality is scored based on the number of remotely connected consequences.

Similarly, the Alternate or Unusual Uses Test (P. R. Christensen et al., 1960; Guilford, 1967), involves presenting participants with common objects to which they are asked to list as many creative uses for these objects as possible. For example, alternative uses for a newspaper (commonly used for reading) could include starting a fire, swatting flies, wrapping garbage, etc. Acceptable responses should include conceivable uses that are different from each other and different from common uses. The responses are scored on a set of criteria, including originality, fluency, flexibility, and elaboration. These tests have been used as indicators of creativity among high school students (Schaefer, 1969) and originality among captains of the United States Air Force (Barron, 1955).

Another example of divergent thinking is the AC Test of Creative Ability (R. R. Harris & Simberg, 1954), which was used as an indicator of high-creative performance in a study of scientists and engineers (Erickson et al., 1970). The AC Test of Creative Ability has four parts, which require participants to 1) list as many possible consequences for five common situations as they can (in 20 minutes), 2) list as many reasons as possible to explain the truth of five unusual and not necessarily true statements (in 10 minutes), 3) list any improvements they feel that could be made in five common appliances (in 15 minutes); and 4) give as many possible uses as they can for five common objects. Parts one and four yield scores on both quantity and uniqueness, whereas parts two and three yield scores on uniqueness only.

A different type of test, the Science Test of Pine and Holt (1960), was employed by Feist (1991b) to assess scientific creativity in undergraduate students. In short, students were presented with two hypothetical problems that pose a scientific dilemma (the discovery of a new species similar to humans but having sex organs of both males and females). Students had to provide possible scientific theories to explain the dilemma (context of discovery) and explain how their theories could be tested (context of verification). Scores are based on the quality of theories—calculated based on the specific theories provided and in the general modes of scientific thinking (e.g., questioning attitude, parsimony, use of known facts, etc.). Tests of creativity, like the other modes of assessing scientific creativity have their strengths and weaknesses. Like other power tests, the assumption is that these tests are less biased and influenced by extraneous factors. On the other hand, these tests may not fully capture the qualities necessary to truly be a creative scientist and therefore may be limited in their use.

To summarize, many different methods have been used to identify creative science and creative scientists. While these four domains—nominations, productivity/eminence, Science of Science metrics, and tests are the most common, it is clear from the literature that they are seldom used in isolation. Rather, most efforts to study scientific creativity use multiple approaches depending on the resources and abilities of the researchers themselves. This is less common for the metrics derived from the Science of Science, largely because these approaches are so new. Of course, one technique not often employed is the direct one—simply having experts rate how creative someone's scientific efforts have been and using those ratings as the appropriate outcome (e.g., Dewett & Denisi, 2004; Feist, 1991a). With the definition of scientific creativity and a familiarity of how scientific creativity is measured, we turn now to reviewing the empirical associations of personality and other factors predicting scientific creativity.

The Neo-Socioanalytic Framework

What are the qualities that characterize pioneering scientists and have they changed over time? The Neo-Socioanalytic model of personality provides a useful framework to revisit this question and to better understand the research on scientific creativity largely conducted in the 20th century (Roberts & Nickel, 2021). One of the challenges in reviewing prior research on scientific creativity is the variety of perspectives and measures investigated. For example, many of the investigations happened well before the advent of the Big Five framework for personality traits. Or, they used concepts that confounded different aspects of personality, like motivation and traits. The Neo-Socioanalytic framework is useful in this regard because it organizes the field of personality and the units of analysis therein. Rather than arguing for the primacy of any one domain of personality, the Neo-Socioanalytic model delineates the existence of at least four domains of personality that should be kept distinct in coming to understand how personality might impact an outcome such as scientific creativity. Those four domains are, first, personality traits, or the characteristic and automatic patterns of thoughts, feelings, and behaviors captured most often with a personality inventory focused on the Big Five and its facets. The second domain is motivation, which encompass a wide range of constructs such as intrinsic and extrinsic motivation, interests, and vocational aspirations. The third domain is abilities, which are most often manifest in the assessment of cognitive abilities, but could also include social, emotional, and behavioral skills. Finally, the fourth domain refers to the life experiences and story about which the person tells—their narrative identity. These historically bound, contextualized narratives bring into focus the unique features of a person's life that capture the larger societal context and zeitgeist of their time. We can use these four domains to help organize and integrate prior work on scientific creativity.

The second helpful feature of the Neo-Socioanalytic framework is the explicit inclusion of life contexts which include experiences that may shape a person's development. The primary focus for life context within the Neo-Socioanalytic framework is the social role (Roberts, 2007), which organizes the social environment into relevant organizational systems that capture the major domains of human functioning. Work roles, such as being a researcher or a professor, are critical constellations of environments for realizing scientific creativity. Roles such as being a leader, a follower, or a contributor, provide structure that calls upon traits like extraversion and conscientiousness and socializes people to gain more of those qualities (Hudson & Roberts, 2014). These types of roles are afforded to a limited set of individuals and bring with them conditions that further shape, develop, and even inhibit psychological changes that may help or hinder scientific creativity.

The key reason for including social roles is the third feature of the Neo-Socioanalytic model, which is that it assumes personality is a developmental phenomenon. None of the four domains of functioning are fixed. And, in fact, most show a blend of continuity and change at all stages of the life course (Roberts & Yoon, 2022). Moreover, empirical research shows that qualities like traits, motives, and abilities are shaped by experiences in social contexts and social roles, often throughout the life course (Roberts & Nickel, 2021). The fact that personality differences linked to scientific creativity are developmental phenomena invites the question of whether and how they might be fostered.

While there are other components to the Neo-Socioanalytic framework not covered here, these are the main features that are most useful for organizing a review of the factors associated with scientific creativity. We focus on these four domains of functioning, reviewing each separately to better understand prior findings. We also review relevant social roles and experiences and how they might contribute to scientific creativity. Finally, we will discuss developmental issues relevant to the qualities and characteristics that are most strongly linked to becoming a creative scientist.

Personality Traits and Scientific Creativity

The dominant focus of past research on scientific creativity has been on personality traits, which reflect characteristic, automatic patterns of thoughts, feelings, and behaviors elicited in affording circumstances. One of the key features of modern personality science is the discovery of a workable taxonomy of personality traits that had yet to be widely accepted and used by 20th century creativity researchers. This system, described as the Big Five, organizes personality traits into five domains: extraversion, agreeableness, conscientiousness, emotional stability, and openness to experience. Each of these domains can be further divided into facets that reflect lower-order, narrower features of the trait domain that are themselves better tools for understanding phenomena like creative scientific achievement (e.g. Kaufman et al., 2016).

Using the Big Five taxonomy as a lens to reinterpret personality research of creative scientists from the 20th century, the personality domain most clearly associated with pioneering science is openness to experience (Feist, 1993, 1998; Jauk et al., 2014). Openness, like the remaining Big Five, is best thought of as a collection of related subtraits, or facets, that include dimensions such as curiosity, creativity, intellectualism, and openness to ideas (A. P. Christensen et al., 2019; Schwaba, 2019). Of these facets, we would expect dimensions like intellectualism and imaginativeness to be key elements in producing creative scientific breakthroughs (Kaufman et al., 2016). Consistent with this hypothesis, several studies have shown that the intellectual facet was more strongly correlated with scientific creativity, and the openness facet was more strongly related to creative achievement in the arts (Kaufman, 2013; Kaufman et al., 2016). It is unclear whether facets like variety seeking and non-traditionalism are also important. To date, research questions focusing on the facets of the Big Five and scientific creativity have not been systematically addressed.

The second trait domain that is consistently related to scientific creativity is extraversion (Kaufman et al., 2016). In particular, the assertiveness-dominance facet appears most strongly linked to creative science (Feist, 1998; Kaufman et al., 2016). As well, dominance predicted higher achievement in STEM-related careers in a group of STEM graduate students followed for 25 years (McCabe et al., 2020). Further, extraversion was linked to self-perceptions of creative achievement (Batey & Hughes, 2017). As assertiveness and dominance can sometimes drift into more negative social interactions, it is not surprising to find that narcissism is linked to scientific achievement (Guo et al., 2021; Lebuda et al., 2021). Narcissism correlates most strongly with high extraversion and low agreeableness in the Big Five (Paulhus & Williams, 2002). Not too surprisingly, narcissism is more strongly related to self-reported creative achievement than objective indices of creativity (Lebuda et al., 2021; Lemaitre, 2020). Alternatively, extraversion might influence creativity through the novelty or sensation seeking facet (Gocłowska et al., 2019). These findings are partially consistent with Cattell's psychometric study of 140 notable scientists (1963, p. 121), where he found that, compared to the general population, eminent scientists were more dominant; Cattel also found that eminent scientists were more "schizothymic" ("withdrawn, skeptical, internally preoccupied, precise, and critical"), which would be indicative of lower levels on the sociability facet of extraversion. Cattell (1963) complemented this psychometric study of contemporary scientists with a historiometric study of luminaries and found that great scientists of the past were introverted, serious, contemplative, and autonomous. This is consistent with findings by Roe (1952) who found that eminent scientists preferred individual rather than social activities for recreation. Overall, with respect to extraversion, it appears that great scientists tend to be dominant (which is one facet of extraversion) but, overall, introverted, which is consistent with prior meta-analytic results and reviews (Feist, 1998; Feist & Gorman, 1998). Nevertheless, there are notable deviations from this dispositional profile, where social scientists may be much more extraverted than natural scientists (Roe, 1953), an issue that we revisit later.

The third trait domain that appears relevant to creative achievement is agreeableness and in particular low agreeableness. Studies of eminent scientists as well as creative achievers in other domains have shown that creative achievers demonstrate a consistent pattern of low agreeableness (Feist, 1993; Zabelina et al., 2022). This again becomes a question of facets. Agreeableness contains up to five facets: Compassion, Morality, Trust, Affability, and Modesty (Crowe et al., 2018). The lack of modesty facet of agreeableness appears to be the critical component for predicting creative scientific achievement (Silvia et al., 2011). Creative scientists are described as lacking humility and even, with more colorful terminology, as arrogant and hostile (Feist, 1993). To start, one would focus on affability (warmth) and modesty as the key components of agreeableness that might differentiate pioneering scientists from their peers.

The remaining two Big Five personality trait domains are less clearly and consistently associated with creative scientific accomplishment, but there are hints that reliable patterns may be found at the level of facets rather than domains. For example, in a meta-analytic review of the literature, creative scientists scored high on both positive and negative aspects of conscientiousness and yet scientists compared to non-scientists scored higher on conscientiousness (Feist, 1998). Similarly, self-reported grit was unrelated to creative achievement while teacher-rated grit was positively related to creativity (Grohman et al., 2017). This could reflect the possibility that creative scientists have to be simultaneously driven and hardworking (e.g., the industriousness facet of conscientiousness) while prone to question norms and be unconventional. Alternatively, some have argued that the tendency for scientists to persist is rooted more in their ambition than their conscientiousness and that they will apply themselves to the tasks necessary to achieve greatness because of their drive to succeed (Hogan et al., 2021). In the latter case, the hard work that emerges from motivation is mistaken for the personality trait of high conscientiousness. The idea that eminent scientists are ambitious and hard-working (similar to the industriousness facet of conscientiousness) but lower on other aspects of conscientiousness that are closer linked to traditionalism and rule-following is consistent with findings from biographical studies of genius-level creators (Dean K. Simonton, 2002).

Finally, while it has been quite common to believe that psychopathology, and thus variants of neuroticism, to be relevant to creativity (MacKinnon, 1962), the findings for scientific creativity appear to be less consistent or systematic (Feist, 1998; Feist et al., 2021). These prior inconsistent findings may be resolved by further considering the domain of achievement because different domains (arts vs. science or even different scientific fields) may "permit" different degrees of psychopathology to successfully operate within that field (we revisit this issue in the later section on "Domains of Scientific Creativity"). Consistent with this idea, in a study of 204 eminent scientists, thinkers, writers, artists, and composers, *positive monotonic* functions were found between psychopathology and eminent creativity for writers and artists, whereas *nonmonotonic single-peak* functions were found for scientists, composers, and thinkers (Dean K. Simonton, 2014a). Notably, the peak for the eminent scientists occurred in the low psychopathology range (i.e., mild symptoms), unlike for the peaks of composers and thinkers, who were in the middle and high ranges of psychopathology, respectively. Furthermore, Simonton (2014b) showed in a mathematical simulation that it is possible that two apparently conflicting propositions may be simultaneously true. Namely, it is possible that (1) among creative people, the most creative show more psychopathology than the less creative, and (2) among all people, creative people show better mental health than do non-creative individuals. This phenomenon follows from the fact that creative productivity is approximated by Lotka's law (described above), where an extremely small number of people are responsible for the highest number of creative products. In sum, the jury is still out on how emotionally stable pioneering scientists might be and this may differ based on their scientific domain.

It should be noted that along with narcissism, there have been a number of dimensions not typically organized in the Big Five that have been identified with creativity and scientific creativity. Of these, two stand out. First, is the independence of thought and autonomy associated with creative achievement (Cattell, 1963). Individuals who succeed in creative careers have been described as energetic, original, unique, and odd (Tang & Kaufman, 2017). Like narcissism, these qualities either fail to load on any of the Big Five directly or cut across more than 2 of the Big Five. These types of descriptions invite questions about the utility of focusing exclusively on the Big Five only for sources of differences between creative and non-creative scientists.

In summary, prior research on personality traits links greater openness, and especially the facets found in intellectualism, to be unambiguously and positively related to scientific creativity. Similarly, the dominance facet of extraversion and possibly the lack of humility facet of agreeableness appear relevant to creativity in scientific fields. The evidence for emotional stability and conscientiousness is mixed. It is possible that clarity on these domains might be gained by examining patterns at the level of the facets. It is also possible that their importance will be revealed when separate fields of scientific achievement are examined. Finally, several predictors that are probably best thought of as composites of various facets of the big five, such as narcissism and originality, have also been linked to scientific creativity. It is yet unclear whether these are unique predictors or simply convenient composites of various Big Five domains.

Motivation and Scientific Creativity

Motivational factors, or a person's desires, goals, and interests in certain topics, have also been implicated in scientific creativity—in short, there is a "drive to create". Most prominently, people who leave a mark on history almost always exhibit high levels of ambition, a profound desire to excel, coupled with drive and persistence (Devogler & Ebersole, 1980; Ebersole & DeVogler-Ebersole, 1986). Cox (1926) found the first empirical evidence for the importance of this motivational disposition based on biographical data from 100 eminent creators and concluded that drive and persistence may even be more important than intelligence in achieving greatness. Moreover, among scientists, more eminent scientists were more ambitious and driven than their less accomplished colleagues (Feist & Gorman, 1998). Importantly, the ambition and hard work that characterize eminent scientists do not seem to stem from unhealthy workaholism but more from a genuine absorption with and enjoyment of their work, and needs for achievement and mastery, as well as job involvement and self-efficacy (Roe, 1952; Dean K. Simonton, 2002). This is consistent with prior work showing that creative scientists demonstrate robust intrinsic motivation for the topic they study as well as the process of science. Creative scientists are thought to want to work on their topics regardless of any personal profit or extrinsic factor (Rubenson & Runco, 1992). Working on their preferred topic is rewarding as it brings with it a sense of flow and immersion that is itself rewarding (Csikszentmihalyi, 1996). Subsequent research has shown that acts of creativity bring on a sense of flow associated with intrinsic motivation and that offering extrinsic rewards can undermine creativity (Amabile et al., 1990; Feist, 1993, 2006).

Consistent with the idea that creative scientists are intrinsically motivated for their work is the fact that investigative vocational interests are the strongest positive predictor of success in scientific careers while enterprising interests are the strongest negative predictor (McCabe et al., 2020). People who are scientists or who achieve some form of scientific creativity show early signs of being interested in analytical and scientific activities (Zabelina et al., 2022). Investigative interests reflect the desire to play with ideas, test hypotheses, and work with experimental processes to answer scientific questions. In contrast, enterprising interests are almost exclusively extrinsically focused on money, power, and status. It appears that liking the trappings of science—playing and testing ideas and related technological questions—lends itself to scientific creativity.

In contrast to the stereotypes that creative scientists are single-minded in their intrinsic motivation to seek truth, research has pointed to the importance of extrinsic factors, such as the desire for professional recognition (Mansfield & Busse, 1981). Feist (1998) identified the role of extrinsic motivation and the rationale for its importance. Although intrinsic motivation is critical for creating ideas, the extrinsically motivated desire to make one's mark in society is also a driving force behind scientific achievement. So, compared to the personality trait literature, the motivation research is less coherent, albeit clearly indicative of the importance of motivational concepts to creative scientific achievement.

In summary, the role of motivation is less clear than for personality traits. It appears that creative scientists must be simultaneously intrinsically and extrinsically motivated to succeed. An alternative interpretation arises from the range of outcomes used to document scientific creativity. Some of the outcomes weigh more heavily the role of being a scientist than the act of creative science, for example (e.g., eminence). It might be that to stay in and succeed at being a creative scientist, it helps to love what you are doing. It may also be important to pursue the trappings of status in the role of being a scientist (endowed chairs, external funding, etc.) as these factors help one to focus on the work that is so intrinsically rewarding (Dean K. Simonton, 2002).

Intelligence and Scientific Creativity

Scientists in general have high IQs, with means ranging from 2 to 4 standard deviations above the population mean (Cox, 1926; Gibson & Light, 1967; Harmon, 1961; Lubinski et al., 2014; Roe, 1953). The role of intelligence in scientific creativity, however, is fraught due to several complexities. One issue is the extent to which intelligence measures, or their proxies, are used to select and identify creative scientists. It is often the case that the groups being examined are selected, in part, on intelligence. This makes the examination of the role of intelligence problematic because the range of intelligence will be restricted, attenuating any potential relationship (Lubinski, 2004; Wai & Lakin, 2000). Setting these complexities aside, and keeping in mind that the link between intelligence and creativity in the general population is a heavily debated topic (for a review claiming that creativity and intelligence are highly similar see Silvia, 2015; but see Sternberg's 1985 triarchic theory of intelligence, whereby creative intelligence is distinct from other forms of intelligence), the preponderance of evidence shows a small, positive relation between cognitive ability scores and creativity, broadly construed (Karwowski et al., 2021).

Of course, cognitive abilities, while presumed to be dominated by a g-factor, can also be successfully differentiated into more specific components (Roe, 1953). In particular, when it comes to science adjacent research focused on intellectually precocious youth and STEM PhD students, different aspects of intelligence appear to lead to success in different occupations (Bernstein et al., 2019). For example, mathematical abilities are more strongly linked to success in STEM related fields and in medicine. Conversely, verbal skills are more strongly associated with achievement in the social sciences. While not directly focused on scientific creativity, these studies do point to the importance of assessing a full complement of cognitive abilities as fields that lean more heavily on verbal or mathematical skills might dictate which abilities are more important for creative achievement.

One of the longstanding assumptions was that there is a non-linear relationship between intelligence and scientific creativity, such that above a certain threshold there are few gains to be made from higher intelligence (Stumpf, 1995). Subsequent work has found mixed support for, or not supported the non-linear model, with most studies finding a small, linear relation between cognitive ability and scientific creativity even at higher levels of intelligence (Brown et al., 2021; Jauk et al., 2013; Karwowski & Gralewski, 2013). Few studies have examined the relationship between intelligence and scientific creativity, and yet the threshold effect does not appear to hold (Zabelina et al., 2022). Others have suggested that there is no threshold for cognitive ability, but that its realization in creative output depends on also being high on the personality trait of openness to experience (A. M. Harris et al., 2019). Similarly, when examining 100 eminent creators Cox (1926, p. 187) concluded that "high but not the highest intelligence, combined with the greatest degree of persistence, will achieve greater eminence than the highest degree of intelligence with somewhat less persistence".

The best guess at this juncture would be that scientific creativity is a multidetermined phenomenon, and some form of cognitive ability helps bolster scientific creativity. Like with other life outcomes, cognitive abilities and other attributes like personality traits and motivations might all act independently of each other when contributing to scientific creativity (de Manzano & Ullén, 2018), or less likely but still a possibility is that these qualities interact with one another to predict scientific creativity.

Narrative Identity

We move now away from the more psychometric assessment of personality and scientific creativity to the more qualitative aspects found in narratives, interviews, and life stories. The narrative content of a life reflects the experiences of the individual in their immediate environments, in their relationships, in their community, and in their society (McAdams, 2013). Unlike the other content domains of personality, narrative identity is much more concrete, time bound, qualitative, and grounded in individual experience. The content of narrative identity reflects the particularities of the person's experiences and their propensity to integrate those experiences into their personality and/or identity (McAdams, 2013). These are the stories of a person's life, with particular characters and actions that reflect one's actual lived experiences, rather than some extrapolation from those experiences as is common in assessments of personality traits and motivations. Narrative identity potentially can be useful for the study of creativity in two ways. First, it is possible to identify previously unidentified patterns or associations using this type of qualitative material. Second, studies in other domains of personality have shown that dimensions of narrative identity provide incremental validity above and beyond traditional personality constructs (Adler et al., 2016).

Although highly creative scientists have often been the focus of psychobiographies, they have not been the primary focus of those studying narrative identity. Many writers have focused on individual stories, such as that of Albert Einstein, but less work has attempted to glean regularities in the life stories of multiple creative scientists. There are a few early examples of studies that interviewed eminent scientists to identify some commonalities in their life stories. For example, Roe (1952) interviewed 64 eminent scientists and found a common theme of persistence and personal satisfaction derived from work, fueled by curiosity. Further, Eiduson (1962) examined 40 eminent scientists (including Nobel laureates and National Academy of Sciences members) and found a pattern of early recognition of intellectual ability reinforced by both intrinsic and extrinsic rewards for scientific activity during youth, openness to the new and unfamiliar, an "impersonal" early family environment, and a single-minded focus on science in adulthood. In a study of eminent creators, Csikszentmihalyi (1996) used interview data and found that eminent scientists showed a keen interest and curiosity for their domains of achievement, as well as flexible capacities for both energy and quietude; divergent and convergent thinking; playfulness and discipline; selflessness and ambition; iconoclasm and tradition. These findings reinforce the perspective that scientific creativity is the result of a complex set of attributes and experiences.

Going beyond these early studies, McAdams and Logan (2006) dug deeper into narrative identity by interviewing 15 professors, many of whom were successful scientists. Building on the insights provided by Gardner (1993) who examined seven highly regarded creative geniuses, McAdams and Logan (2005) identified distinctive features of the creative genius' life story. In particular, creative geniuses appeared to have four distinct features in their narrative identity. First, the inspiration for their work that they later became famous for often started in childhood. An encounter, often seemingly random, with a person, idea, or phenomenon captured their imagination and became a primary obsession for the rest of their lives. Second, the idea often afforded some idealized and grand achievement, such as creating the first autonomous robot, or discovering a cure for cancer. Third, these successful creative types brought a strong personal aesthetic to their work. They did not just want to create robots, for example, but robots that had style. Or, in the case of more abstract pursuits, they had insights that were elegant and had a beauty all their own. Finally, these successful scientists often created strong dualities that manifested as conflicts within their narratives. The classic duality was between love and work, with the creative scientists' focus and passion for their ideas competing with their romantic lives.

These insights, like many from the narrative identity research, provide a deeper, richer portrait of the potential creative scientist and some of the features of their lives. One of the accepted components of creativity is that the author of a creative idea often needs ample time to dwell on an idea in order to arrive at a creative insight. Clearly, coming upon one's passion early in life affords more of that critical time that may be necessary to crystalize new discoveries. Also, it is clear that much of what is deemed creative happens in the context of one's historical and cultural context. Inventing high functioning robots could be imagined in prior centuries, but could only be realized in the late 20th and early 21st century. Discovering the role of microRNA and how it could be applied to issues like vaccinations could only happen after the discovery of DNA and the genetic system surrounding it. The strong aesthetic brought to bear on the chosen topic of the creative scientist resonates with the trait profile of high openness. It is highly likely that these individuals have a heightened aesthetic sensitivity across many issues and therefore also apply this sensitivity to their work. Finally, the focus and passion that leads to discovery reflects a level of motivation that might come at a cost, as is seen in those conflict laden dualities. Like other work in personality psychology, it is incumbent that we discover which aspects of the narrative identity are distinct from the remaining components of personality and the extent to which a fuller picture afforded by narrative identity is also an informative picture.

To summarize, using the Neo-Socioanalytic model to interpret past research on scientific creativity points to the importance of traits from the domains of openness to experience, agreeableness, and extraversion with the possibility of specific factors from other domains also playing a role. Research also supports the importance of motivation, with scientists showing high levels of ambition and complex combinations of intrinsic and extrinsic motivational patterns. Additionally, cognitive abilities clearly play some role in scientific creativity, but are most likely best considered one of many components of a broad portfolio of attributes rather than the sole focus, which is often the case. Finally, the story that is idiosyncratic to the scientist's life and times, especially the germination of their creative spark, may reflect a necessary ingredient for future scientific creativity.

Several unanswered research questions emerge from this review. First, we still do not know whether facets of the Big Five trait domains can maximize our ability to predict scientific creativity. We simply do not know whether the components of these domains are differentially linked to creativity in science. Second, few (if any) studies have attempted to use more than one domain (traits, motives, abilities, and narratives) simultaneously to predict scientific creativity. Some of the contradictory findings in past research may be clarified by the inclusion of multiple predictors from a comprehensive model of personality (Roberts & Nickel, 2021). Finally, there have been few attempts to systematically integrate the focus on individual differences with the social conditions that either afford or inhibit scientific creativity, a topic we turn to next (c.f., Dean K. Simonton, 2004b).

Social Conditions That Promote Scientific Creativity

Another feature of modern personality science is the explicit incorporation of a developmental perspective that includes the influence of context, environments, and life experiences on the development of personality (Roberts & Yoon, 2022). Similarly, pioneering science does not occur in a vacuum, and personality qualities associated with scientific creativity are enhanced or afforded due to social conditions. By social conditions, we mean the broad environments and experiences that creative scientists experience as children, as well as the conditions of their work that support or undermine their creative potential. Broadly, the arguments range from the need to expose and stretch the capacities of the future pioneering scientist (Damian & Simonton, 2015) to the need to protect pioneering researchers from organizational structures and barriers that can be present in many research environments (Griffin et al., 2012).

In terms of being exposed to challenging environments and conditions, one argument is that diversifying experiences facilitate the development of creative potential. Diversifying experiences are "highly unusual and unexpected events or situations that push individuals outside the realm of 'normality,' enabling them to conceive ideas that are less bounded by conventional constraints" (Damian & Simonton, 2015, p. 623). Specifically, experiences such as being an immigrant, being from an underrepresented group, unconventional educational settings (e.g., studying abroad), being orphaned, sickly, or having grown up in poverty, are thought to challenge pioneering scientists to see the world in a wider, less traditional way, making it possible for them to make unusual and more creative connections between ideas (Feist, 2006). In fact, these types of diversifying experiences were positively related to creative achievement across many occupations in a sample of eminent African Americans (Damian & Simonton, 2015).

On the opposite end of the spectrum is the necessity of having explicitly supportive conditions for scientific creativity to occur. The broad sociocultural context, under the rubric of "zeitgeist" is often invoked as a necessary ingredient to the emergence of scientific ideas (Dean K. Simonton, 2004a). In particular, sociocultural zeitgeist in the form of political, economic, or social conditions promoting specific types of science or scientific ideas appears instrumental in fostering scientific creativity. For example, wartime appears to be a condition in which the respective societal pressures and rewards focus on certain types of discoveries that are subsequently financially supported by political entities. In turn, this support leads to an increase in the number of scientists in specific fields and the sheer number of discoveries (Dean K. Simonton, 2004a). At a more immediate level, organizations, like businesses or universities, can create conditions in which scientific creativity is fostered. In particular, providing creative scientists access to the broad sweep of information necessary to apply their skills, as well as freeing them from the typical bureaucratic burdens most employees face so that they have the freedom to play with ideas, and take risks not typically afforded to others, appears critical to the creation of innovative ideas (Griffin et al., 2012).

The most conspicuous issue about the role of experience, development, and social-environmental conditions and scientific creativity is the lack of research integrating these factors with the study of individual differences. To our knowledge, there are few (Ko & Kim, 2008) studies that have combined systematic assessments of the known personality factors and known environmental conditions considered relevant to the creative scientific process. While some have posited that factors such as the revolutionary nature of the scientific field (Ko & Kim, 2008), or whether scientific fields are conservative would moderate individual differences, there are few if any systematic empirical tests of these ideas. Thus, we do not yet know whether these two broad classes of factors contribute independently, synergistically, or redundantly to scientific creativity.

Personality Development and Scientific Creativity

The question of development and scientific creativity is reflected in two broad questions. First, how do the qualities associated with scientific creativity grow and develop across the life course? That is, are qualities like cognitive ability, openness to experience, confidence, and investigative interests best considered as developmental constructs that show changes during different periods of the life course? Second, if these qualities do change, the natural question is can these qualities be actively changed? Under what circumstances can these qualities be enhanced and thus provide an avenue for increasing the likelihood of producing creative scientific findings? To the extent that these qualities are malleable, it would be possible to maximize individual and societal outputs of creativity in science.

The prevailing perspective is that personality traits are developmental concepts because they show continuity, change, and the ability to be changed throughout the life course (Roberts & Yoon, 2022). The traits most strongly associated with scientific creativity show quite differential life course patterns of development. Traits like openness, dominance, and agreeableness show little systematic gains or losses in childhood and adolescence. In contrast, the transition to young adulthood is the key period during which people show gains in openness, dominance, and agreeableness (Bleidorn et al., 2022; Roberts et al., 2006; Schwaba, 2019). Interestingly, the gains made in openness in adolescence appear to be lost in old age, during which time there is a general decrease (Schwaba, 2019). Overall, the life course patterns of change in creativity-related personality traits would indicate that adolescence and young adulthood are key periods for making gains in some of the most important predictors of scientific creativity. Yet, the normative, longitudinal changes in agreeableness would appear to diminish the likelihood of scientific creativity, as gaining agreeableness would putatively undermine the creative scientists' progress in their career (given the negative association between agreeableness and creativity).

Mean level changes in creativity-related abilities and motives also exist. Fluid abilities tend to peak early in the life course and then decline thereafter, while crystalized abilities tend to peak in midlife and then drop off (Schaie & Strother, 1968). These developmental trends could be the source of life course differences in scientific contributions across different fields. For example, mathematicians are known to make their breakthroughs earlier in the life course and this may reflect the fact that fluid abilities are more important for that field. Alternatively, the age of first major contribution might vary based on when and how many constraints each field imposes. More paradigmatic fields, where contributions are more easily recognized, may see a corresponding peak of scientific achievement earlier in the life course (Dean K. Simonton, 2004a). Conversely, fields that lean more heavily on accrued knowledge and skills show contributions occurring later in the life course, consistent with the pattern of development for crystalized intelligence and with the fact that less paradigmatic sciences require more time and more context for contributions to be recognized (Dean K. Simonton, 2004a).

Motivations also show systematic changes across the life course. Measures of motivation, when assessed as the importance or salience of a goal show a very consistent pattern of no mean-level change or decreasing across the life course (Atherton et al., 2021; Stoll et al., 2021). Feist (2006), for instance, found that most members of the National Academy of Science knew they were scientifically talented by age 16 and that they wanted to be a professional scientist by age 18—a goal that remained for the rest of their lives. When measured as interests, the picture for motivation grows more complex. Those that do exist show heterogeneous patterns, with creativity-related interest domains, like Realistic and Investigative, showing declines in young adulthood and increases later in life (Hoff et al., 2018).

The existence of change in creativity-related constructs invites the question of what type of experiences might be associated with these changes. In terms of the typical experiences of adulthood, some work experiences have been linked to changes in openness, including promotions (Nieß & Zacher, 2015) and short-term unemployment followed by re-employment in a new job (Anger et al., 2017). In contrast, marriage was associated with decreases in openness while divorce was associated with subsequent increases, at least in men (Specht et al., 2011). Particular experiences, especially those focused on expanding one's experiences, are also associated with changes in openness. In particular, travel abroad is associated with changes in openness. In one study, Germans who traveled to another country were more likely to increase in openness, as well as agreeableness and decrease in neuroticism (Lüdtke et al., 2011). A second study of German "sojourners" (students who study abroad) found strikingly similar results. Sojourners grew more open and agreeable and less neurotic the longer they stayed abroad (Zimmermann & Neyer, 2013). Furthermore, participating in cultural activities, such as going to concerts, museums, and art galleries is associated with increases in openness across the life course (Bleidorn & Schwaba, 2017). Additionally, there have been reports that consuming psychedelics is associated with increases in openness (Erritzoe et al., 2019).

The obvious follow up question is whether the personality traits associated with scientific creativity could be changed through intervention. Although it is still widely thought that personality is not changeable, recent research has contradicted that notion. A review of over 200 intervention studies found that the personality trait of neuroticism was modifiable through clinical intervention, with changes on average being half of a standard deviation over periods as short as 6 weeks (Roberts et al., 2017). Moreover, changes that resulted from therapy not only happened quickly but also remained in place well after patients left therapy. Subsequent research has shown that the other trait domains, including openness and agreeableness, can also be changed through intervention even if the population or intervention is not clinical in nature (Stieger et al., 2021).

Another relevant question would be whether the amount of change that happens naturally or through intervention would be enough to affect scientific creativity. Naturalistically, people change between ½ and 1 standard deviation on traits like openness with age (Bleidorn et al., 2022). Intervention studies have consistently found changes in the order of ½ of a standard deviation that happen over relatively short time frames. Although ½ of a standard deviation is a large effect size for psychology it is not evidence that change in personality relevant constructs would improve our ability to foster scientific creativity, which remains an untested idea. However, we might take inspiration from intervention studies in economics, in which it has been shown that investments in personality-adjacent constructs result in returns on investment that are large enough to be policy relevant (Zhou et al., 2021).

In summary, many of the qualities associated with scientific creativity are changing and changeable. The life course patterns of development would appear to undermine the probability of scientific creativity with age, as with age come declines in openness, cognitive abilities, and increases in agreeableness. Nonetheless, these same qualities show optimal levels earlier in the life course, which also happens to be when most scientists choose their career, invest in their work, and make their creative breakthroughs. There are two caveats to this generalization: (a) scientists in more paradigmatic sciences peak in their careers at an earlier chronological age, presumably because those fields can recognize contributions faster and are faster to master because of their clearer-cut rules, and (b) some people start their scientific careers later in the life course. Therefore, it would be appropriate to focus on "career age" in addition to chronological age in understanding these developmental patterns (Dean K. Simonton, 2004b). Finally, the fact that qualities long thought to be unchangeable can be changed through intervention invites compelling policy questions such as whether societies should invest in maximizing openness through intervention, for example, especially in childhood, adolescence, and young adulthood.

Social Roles and Scientific Creativity

The Neo-Socioanalytic model argues for a focus on social roles as an ideal level of analysis to better understand the social contexts and environments that would confront persons pursuing careers in this domain. It also affords the opportunity to engage in issues that have been overlooked or not explicitly examined in prior research on scientific creativity, especially issues related to gender, race & ethnicity, and class.

The role of being a creative scientist largely entails holding jobs in higher education with pockets of similar activities in science-based industries, such as biochemical, pharmaceutical, petrochemical, consulting, government, and even social media companies. Who then, occupies the role of academic researcher or scientist? The answer to that question has changed over time, which is an important consideration when trying to understand the role of personality in scientific creativity. A preponderance of the research determining the personality qualities of creative scientists was conducted in the 20th century (e.g., Feist, 1998). This means that in addition to potentially being outdated, the scientific findings have been largely drawn from the study of older, white men. In Feist's 1998 meta-analytic review of personality and scientific creativity only 3% of the samples studied were of women scientists. There was no attempt to document scientists of color because too few were recorded in the research conducted in the 20th century. The resulting portrait of the creative scientist, albeit clear in the features painted, is potentially flawed as wide swaths of scientists were not included in this research.

Of course, the role of scientist and researcher has changed markedly since the middle of the 20th century. Since the turn of the 21st century, institutional changes in the scientist role have invited more women and scientists of color into the field and have changed the nature of the scientific process (Ward, 2006). In particular, the tendency to work in teams (whether interdisciplinary or not) has also increased (Wuchty et al., 2007). Thus, what was once a role embodied by the lone researcher gleaning insights about their scientific enterprise populated mostly by other white men, has now become an enterprise increasingly carried out in larger, diverse groups.

These changes raise a number of pressing questions for the role of personality in facilitating scientific creativity. First, are the personality predictors of scientific creativity the same for women and scientists of color as they were for white men in the 20th century? We would expect, for instance, that openness to experience would still be the strongest personality predictor of scientific interest and creativity in women and scientists of color, but cannot hazard any other predictions (Sokić et al., 2021). There is a surprising paucity of research addressing these questions. One recent study would appear to show strong similarities for men and women in the predictors of occupational success in science (not the same thing as creativity; McCabe et al., 2020). Unfortunately, a formal examination of whether gender moderated the predictors of occupational attainment in science was not presented. In addition, there is little evidence that men and women differ in terms of levels of creativity (Baer & Kaufman, 2008). On the other hand, despite the seeming similarities in the personality antecedents to creativity and success in science, women still achieve success at a far lower rate than men (McCabe et al., 2020) and win far fewer awards per capita than men (Lerman et al., 2022).

Some argue that the disparities that remain between men and women in attained scientific creativity can be attributed to differences like those seen on social vocational interests (Stewart-Williams & Halsey, 2021). While the differences are large between men and women on social interests, for example, it is not the most important predictor of scientific creativity and thus begs the question of why women might not achieve at a similar rate as men. Alternatively, the obvious answers are that women and scientists of color experience less supportive environments in their careers. For example, STEM culture has been noted for its lack of support for women (Ranganathan et al., 2021). The STEM culture can undermine careers of underrepresented groups through factors such as (1) misconduct, (2) lack of representation, (3) racism/sexism, and (4) lack of support (including but not limited to inadequate compensation, untenable demands, and poor work-life balance). To the extent that women and scientists of color experience these factors disproportionately, it is likely that these factors diminish the probability of these groups realizing their full potential as creative scientists. It also invites untapped research questions such as whether certain aspects of personality contribute to or buffer women and scientists of color from the negative consequences of these types of experiences.

Domain of Creative Achievement

One of the key role distinctions related to scientific creativity is what kind of scientific role is being pursued. When considering the dispositions of creative scientists, it is important to recognize that not all scientific fields impose the same opportunities or restrictions on creative thinking. Therefore, the dispositions required to be creative within a specific field may differ across fields. The idea that scientific fields can be organized in a hierarchy based on the theoretical, methodological, and substantive restrictions they impose on their scientific communities was first proposed by Auguste Comte (1855). Thomas Kuhn (1970) extended this idea by suggesting that the variation in disciplinary constraints may reflect differences in paradigmatic structure or coherence. An empirical investigation supported the proposed hierarchy of sciences, finding that highly paradigmatic disciplines exhibited (a) faster rates of research impact and obsolescence, (b) higher theories-to-laws ratios, (c) greater disciplinary consensus, (d) a lower age at recognition, and (e) even lower lecture disfluency when teaching (Dean K. Simonton, 2004a). Moreover, critical reviews of extensive studies conducted on highly creative scientists support the idea that the dispositional traits and developmental experiences of scientists operating in different fields may differ based on where in the hierarchy of sciences their fields may fall (Dean K. Simonton, 2002, 2004a, 2015). More specifically, this hierarchy of sciences places physics at the top of the paradigmatic fields, followed by chemistry, biology, psychology, and sociology. Mathematics can be placed even above physics and the arts can be placed further down the line under sociology.

Dispositions and developmental experiences appear to vary by field of achievement as follows: more paradigmatic (vs. less paradigmatic) fields require (a) more constrained, logical, and deliberate thinking (vs. more unpredictable, illogical, intuitive, and versatile thinking), (b) lower openness to experience, (c) lower rates of psychopathology, (d) more conventional, stable, and homogenous home environments, (e) fewer and more homogenous role models and mentors, and (f) more politically stable and culturally uniform sociocultural Zeitgeist. Even within each domain, more revolutionary scientists are said to be closer to the scientists operating in fields lower down the hierarchy (e.g., the most creative biologist might be more similar to a psychologist). The idea behind these propositions is that dispositions and developmental experiences must be matched to afford the best functioning within the level of constraint imposed by each field (e.g., more openness should go with less constrained fields where high levels on this trait might be more beneficial; for instance, psychologists should show more openness on average than chemists, though revolutionary chemists should be more open than normative chemists). There is indeed empirical evidence for each of these assertions (Dean K. Simonton, 2002, 2004a, 2015), though the evidence is fragmentary (i.e., patched together from many different studies of piecemeal comparisons across disciplines on only a few traits), and no study to date has examined this model in a unified fashion. In sum, the dispositions and developmental experiences presented earlier, though they are likely to be characteristic of creative scientists compared to the general population, may show some variation across scientific domains.

Synthesis

The picture of the creative, scientific pioneer that emerges from prior research is of an ambitious, confident, iconoclastic person, who grew up loving science and having experiences that taught them the world was dynamic and unpredictable, who is immersed in, and open to, a sea of ideas, and who works in a supportive environment that allows them the time and space to focus and create. To help clarify and integrate this review, we have provided a conceptual model (Figure 1) to help delineate what is seemingly known about identifying pioneering scientists and what has yet to be empirically determined.

Consistent with the delineation of the Neo-Socioanalytic model, there are four main factors that contribute to pioneering science: personality traits, motives, abilities, and narrative identity. These qualities predict, and thus select for both facilitating and challenging environments which emerge from adopting the role of the scientist or researcher. In turn, these experiences predict changes in the four domains of personality. Finally, this entire set of factors has the potential to contribute to the outcome of interest: scientific creativity.

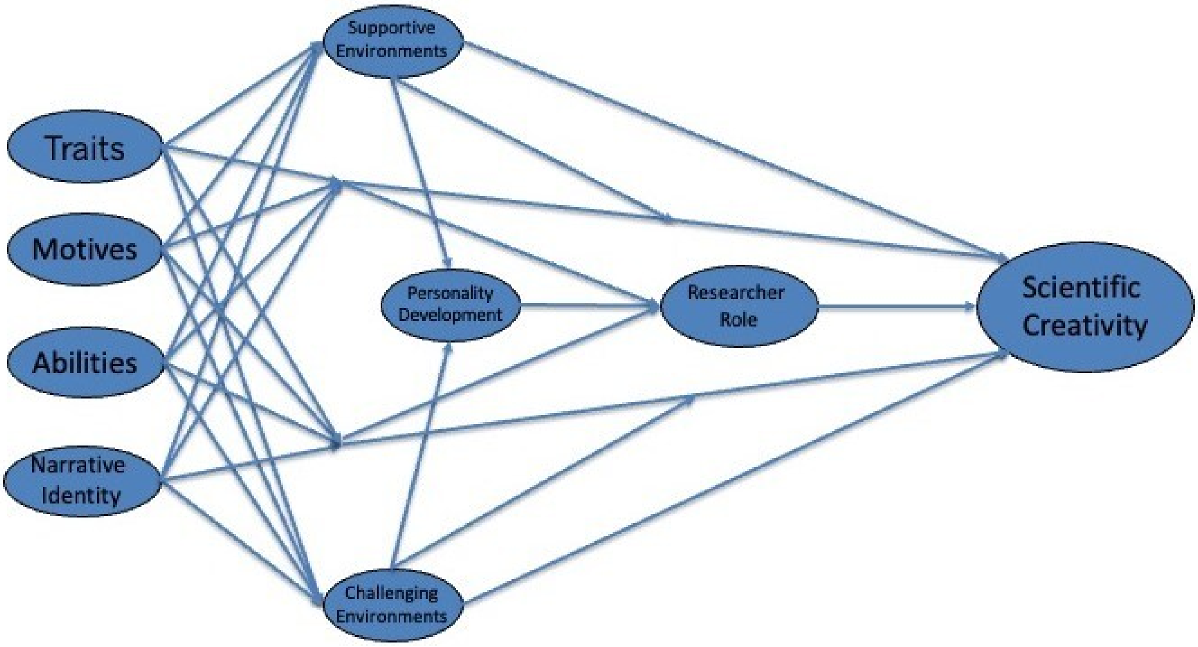

Figure 1. Integrative conceptual model of scientific creatvity

Within and across these large categories lie unanswered research questions delineated earlier that we have compiled and expanded on in Table 2. The purpose of the questions in Table 2 is to present an outline and encouragement of a research program on the pioneering scientist in the 21st century. As we see it, these are the questions that most require empirical investigation.

In terms of personality traits, higher openness and extraversion, and lower agreeableness appear to be critical predictors of scientific creativity. The distinction between the role of scientist and the outcome of scientific creativity highlights unaddressed questions. For example, is extraversion, in the form of confidence, or disagreeableness in the form of lack of humility, direct causes of scientific creativity? Or, could it be that these factors are more important for survival and success in the role of the historical and modern scientist than they are for scientific creativity? Or, could it be that these distinctions are driven by the type of measure used to capture scientific creativity? It might be that outcomes more strongly associated with status and prestige, rather than directly reflecting creativity, might pull for different qualities. Furthermore, are these qualities as important now, in this current climate in which science is performed differently and done by different people than in the 20th century? Despite the examination of gender in relation to achievement in sciences, there is little or no empirical work addressing whether the qualities that predicted scientific creativity in the past for men work the same way for women or scientists of color in current times.

Many of the questions about the relevance of the personality traits thought to be predictive for all scientists are made even more salient by the inclusion of facilitating and challenging environments that come along with the scientific role. Many scientific environments are characterized by challenging climates where the expectation is that the scientist needs to weather pointed criticism if not the typical rejection that comes with the review process in science. It makes sense then, that for a creative scientist to succeed, it may be that lacking humility and possessing above average levels of confidence might help a creative scientist survive the challenges of the career and the withering criticism that new ideas receive. This invites an uncomfortable follow up question. Are we needlessly winnowing scientists who have the skills to contribute new and exciting ideas to society simply because we make the road to success needlessly and arbitrarily difficult? Or is the difficult pathway part of the necessary process to achieve scientific creativity? Likewise, other dispositions may come into play in the winnowing process in ways that have not been revealed to date. On the negative side of the ledger, graduate students who may lack entitlement or competitiveness may find the culture not to their liking and simply leave the career. On the positive side, it may be that other graduate students evoke more positive reactions from the system or are buffered from the negative climate. Thus, another salient research question is whether personality, broadly construed, is selected for by the career or leads to deselection for those who do not find the path appealing.

In turn, the experiences that come along with being a scientist, either successful or not, might contribute to changes in the dispositions known to predict scientific creativity. Getting the opportunity to dive deep into the pool of ideas in a field and be exposed to the breadth of ideas found in graduate education may foster new and different ways of thinking, which in turn may contribute to better creativity. Time spent focused on topics and the expertise that comes along with this type of effort and experience may also be foundational to scientific creativity. The changes in commensurate personality features, such as increased ideational fluidity and increased crystalized intelligence may then contribute to achieving scientific creativity

Table 2. Unanswered research questions to help identify the 21st century pioneering scientist.

Domain	Research Question
Traits	1. Do patterns from the 20th century replicate in the 21st century?
	2. What added insight do we get from a facet-level analysis of the Big Five?
	3. Are dominance and disagreeableness related to creativity or to success in the role?
Motives	4. Does motivation account for the apparent role of conscientiousness?
	5. Are both intrinsic and extrinsic motivation necessary for scientific creativity?
	6. Like traits, do motives predict the role or scientific creativity?
Abilities	7. Should spatial abilities be better incorporated into the model of scientific creativity?
Narrative Identity	8. Is it necessary to success in creative science to come to one's interest early in the life course? 9. Does being a successful creative scientist create conflict with other social roles?
Scientific Role	10. Do the personality predictors of creative science generalize to women?
	11. Do the personality predictors generalize to scientists of color?
	12. Do the personality predictors generalize to different cultures?
Personality development	13. Do changes in traits, motives, abilities, and narratives contribute to scientific creativity above and beyond where people stand on these attributes when they are young?
	14. Do the supportive and challenging environments contribute to personality change that is relevant to scientific creativity?
General	15. What are the relative contributions of each domain of personality to scientific creativity?
	16. Do the patterns of associations vary depending on the type of outcome used to characterize scientific creativity or by the sub-domain of scientific creativity?
	17. Do environmental and role factors account for or contribute independently of the personality factors associated with scientific creativity?
	18. Do environmental factors work synergistically with personality to predict scientific creativity?

above and beyond where a person stood on these qualities as a graduate student, for example.

Issues concerning motivations and narrative identity also remain to be resolved. The contradictory portrait of the successful scientist being both intrinsically and extrinsically motivated needs further clarification. Again, the distinction between the role of being a scientist and the achievement of being a creative scientist might help in answering this question. It makes sense that those who achieve higher status in the role are afforded greater support to realize their creative potential. Conversely, it may also be the case that scientists who are not extrinsically motivated face barriers to success that would help make their ideas more influential. The limited work on the narrative identity of creative scientists invites the developmental question of whether the crystallizing experience is by necessity something that happens early in the life course, or whether creative potential can be realized with a later start on one's creative activities. Also, the dualities identified in the narrative identity research would appear to indicate tensions in the lives of the creative scientist, especially in their other roles, such as family roles. It remains an open question whether creative scientists are faced with more complications such as these.

Finally, cutting across these factors are combinatorial questions. Do factors from each domain—traits, motives, abilities, and narrative identity play independent roles in predicting scientific creativity? Or, are some of the factors redundant? Do the patterns of prediction vary systematically depending on the type of outcome measure used to quantify scientific creativity? This is especially relevant to the newer indices drawn from the Science of Science, as these outcomes have not been the focus of personality research yet. Or, as has been proposed, will the qualities that contribute to scientific creativity differ depending on the field of study? Furthermore, do the environments and experiences act independently of personality to facilitate scientific creativity or does one set of factors supersede the other? And, do personality and environmental factors work synergistically? It is possible that personality factors may moderate the relation between facilitating and challenging environments and scientific creativity. Or, in turn, that facilitating and challenging experiences may moderate the effect of personality factors on scientific creativity. For example, the role of dominance and disagreeableness may only develop in hostile research environments. In contrast, the importance of facilitating environments may be enhanced by researchers being more open to ideas, which would make them more likely to respond to the zeitgeist of their time.

Conclusion

Identifying and fostering creative scientists is one of the most important issues facing modern society. There are more scientists now than at any time in the history of humankind, and their influence can be felt in our arms (vaccines), in our hands (our smartphones), and in the ways we travel and work (driverless vehicles). Looking back at the decades of research on the personality factors linked to scientific creativity through the lens of the Neo-Socioanalytic model is gratifying, as it is clear that much knowledge has been gained about scientific creativity. However, the reliability, generalizability, and utility of that knowledge to present day scientific careers is unknown. Times and careers have changed, and it is important to determine if the scientific findings have also changed. Finally, given the importance of fostering breakthrough science to society, one of the most salient conclusions is that our accumulated knowledge about the predictors of scientific creativity play almost no role in how society selects, trains, or supports scientists. One only has to examine the typical screening materials for Ph.D. programs (e.g., the GRE as a proxy for intelligence; GPA, and letters of recommendation) to see that modern selection processes do not leverage the findings on scientific creativity to identify the most promising students. Moreover, few of these findings are used to inform the design of research systems or concrete training programs focused on scientists. With such a clear profile of the creative scientist, how is it possible that we do not use these scientific findings to better foster the future generations of scientists and scientific breakthroughs? We hope this review sparks the imagination of a future scientist who might bring new insights to their field and apply their findings to society's betterment.

Contributions

Contributed to conception and design: BWR, RD, GF, NK, CC, GC, EF

Drafted and/or revised the article: BWR, RD, GF, RF, CC, GC, EF

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To the best of our knowledge, no authors have competing interests.

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