26

Openness to Scientific Innovation

Frank J. Sulloway

Introduction

Openness to novel experiences, including to new ways of thinking, is a fundamental aspect of human personality. Individual differences in this attribute are also found in lower animals, including other primates, cats, dogs, and hyenas (Bolig, Price, O'Neill, & Suomi, 1992; Gosling, 2001). Over the last several decades, "openness to experience" has become well established as one of the "Big Five" dimensions of personality, ranking alongside conscientiousness, agreeableness, extraversion, and neuroticism within the Five-Factor Model of personality (Costa & McCrae, 1992; John, 1990; John & Srivastava, 1999; McCrae, 1994; McCrae & Costa, 1985). Together, these five dimensions capture the bulk of the variance in personality, and they have been documented in more than 50 different societies (McCrae & Allik, 2002; Schmidt, Allik, McCrae, & Benet-Martínez, 2007).

People who are open to experience are described as being intellectually curious, creative, appreciative of art, unconventional in their beliefs, and liberal in their social attitudes. People who score high on the other end of this personality dimension tend to prefer the familiar to the novel and are muted in their emotional responses, relatively focused in their interests, and conservative in outlook (Costa & McCrae, 1992). Not surprisingly, particularly innovative scientists score higher on this attribute than do their peers (Feist, 1998).[1]

Given this evidence, a potentially fruitful approach to the topic of scientific innovation is to focus on factors that are known to correlate with, and to foster, openness to experience. Although historians and sociologists of science have long investigated the origins and reception of important scientific innovations (e.g., Cohen, 1980; Gillispie, 1951; Glick, 1972, 1987; Kuhn, 1957; Schneider, 1992), few of these studies have engaged in formal hypothesis testing, and none have attempted to approach the topic from the perspective of openness to experience. The usual method of research used by historians and sociologists of science involves "confirmatory hypothesis testing," whereby investigators seek supporting evidence to bolster their arguments. Typically, such studies take the form of a "case history" approach in which a single instance of conceptual innovation is analyzed in an effort to shed light either on the discovery process or on broader patterns in the reception of new ideas (e.g., Brush, 1999; Forman, 1971, 1978; Frank, 1980; Hufbauer, 1982; Rudwick, 1985). More rarely, an effort is made to survey multiple events in the history of science, as Thomas Kuhn (1962) did

---

The Wiley Handbook of Genius, First Edition. Edited by Dean Keith Simonton.

in his highly influential book *The Structure of Scientific Revolutions.* Unfortunately, this method of marshalling evidence is not particularly reliable, and it can lead to spurious conclusions. A good example of confirmatory hypothesis testing gone awry is Desmond and Moore's (2009) book *Darwin's Sacred Cause*, in which the authors argue that Darwin's abhorrence of slavery inspired his evolutionary thinking. Esterson (2013) has provided a compelling demolition of this argument, complete with a litany of carefully demonstrated instances in which facts and texts have been taken out of context and sometimes twisted to suit the authors' intriguing but ultimately groundless thesis. The problem with confirmatory hypothesis testing is simple: Humans are very good at detecting patterns in data, even when no actual patterns exist; and people are also very adept at spinning nonexistent patterns into reasonably compelling stories (Shermer, 2000). As Laudan *et al.* have asserted in the course of a review of various models of scientific change set forth by historians and philosophers of science:

> Nothing resembling the standards of testing that these very authors insist upon within science has ever been met by any of their theories about science. Those of us who claim some modest expertise in the logic of empirical inferences have been notably indifferent about subjecting our own theories to empirical scrutiny, even though our own philosophies of science suggest that without such scrutiny we might well be building castles in the air. (1986, p. 142)

The challenge, then, for understanding the kinds of factors that predispose some scientists to put forward new and better theories, and for other scientists to become the early adopters of such innovations, is for researchers to go beyond confirmatory hypothesis testing and to subject their suppositions to formal testing.

Planck's Principle: Age and Receptivity

One notable exception to the informal approach to historical evidence that is typically used by researchers in science studies has involved what is known as "Planck's principle." As Max Planck asserted, based on his own biographical experience, "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it" (Planck, 1949, pp. 33–34; see also Blackmore, 1978). Although this principle is often associated with Planck's name, other scientists, including Antoine Lavoisier and Charles Darwin, made similar observations before Planck. In *On the Origin of Species*, Darwin remarked:

> Although I am fully convinced of the truth of the views given in this volume…, I by no means expect to convince experienced naturalists whose minds are stocked with a multitude of facts all viewed, during a long course of years, from a point of view directly opposite to mine…. A few naturalists, endowed with much flexibility of mind, and who have already begun to doubt on the immutability of species, may be influenced by this volume; but I look with confidence to the future, to young and rising naturalists, who will be able to view both sides of the question with impartiality. (1859, pp. 481–482)

Thomas Henry Huxley – known as "Darwin's bulldog" because of his spirited support for Darwin's theories – expressed an even stronger opinion on the subject of age and its relationship with openness to innovation. Scientists, he recommended, should be strangled on their 60th birthday "lest age should harden them against the reception of new truths, and make them into clogs upon progress" (Huxley, 1901, vol. 2, p. 117).

Hull, Tessner, and Diamond (1978) subjected Planck's principle to a formal statistical test involving the reception of Darwin's own evolutionary theories. They assembled data on 78 British scientists who spoke out on Darwinian theory during the decade that followed publication of *On the Origin of Species* (Darwin, 1859). These three researchers found a significant trend for older scientists to reject Darwin's theory, but they also noted that the effect was small, explaining less than 10% of the variance. They concluded that the relationship between age and acceptance was not as consequential as scientists such as Max Planck have alleged. Levin, Stephan, and Walker (1995) later replicated the study by Hull *et al.*, using a more rigorous method that takes into account the fact that 11 of the scientists in Hull *et al.*'s sample died before 1869 and therefore did not have the same opportunity as other scientists included in this study to convert to Darwinism. When this methodological problem was resolved by using a hazard rate model, which takes into account the likelihood that scientists who died before 1869 might have converted to Darwinian theory if given more time, they found Planck's principle to be unsupported, as the trend was no longer statistically significant.

Stewart (1986) reached a similarly negative verdict about the supposed relationship between age and openness to innovation in an analysis of supporters and opponents of the theory of continental drift from 1910 to 1950. Messeri (1988) studied the reception of the same theory as it was being transformed into plate tectonic theory from 1963 to 1970. Among early converts – those adopting the theory before 1966 – older and more experienced geologists led the way. In explaining these findings, Messeri argued that older scientists, because they are more established, could afford to take greater intellectual risks than younger scientists, allowing them to support unconventional points of view during the early stages of debates over a new and controversial theory. Although younger geologists did predominate among the converts to plate tectonics after 1966, this trend was not statistically significant once other covariates, such as professional eminence, were included in a hazard model.

Other studies of the relationship between age and receptivity to innovation have also produced conflicting results. Diamond (1980) found a modest relationship between being younger and becoming an adherent of cliometrics (the application of statistical techniques to economic history). However, when he examined adoption of an innovation during the 1960s that eventually proved to be mistaken (the existence of a supposedly anomalous form of water, called polywater), he found no relationship between age and acceptance of this spurious discovery (Diamond, 1988). By contrast, Perrin (1992) found a trend for younger scientists to be more supportive of the chemical revolution (and of Lavoisier's new oxygen theory of combustion), although he did not provide formal statistics in support of his findings.[2]

As this brief review suffices to show, even such a straightforward claim as Planck's principle has failed to find clear support in a series of previous studies. Some historical findings have supported Planck's claim, other studies have shown no relationship between age and openness to innovation, and yet other studies have indicated that a reversal of Planck's principle occurs under some circumstances. As Messeri (1988) has concluded about such inconsistent findings, "Until a much larger number of case histories has been systematically surveyed, we can only conjecture on the general forms which age-related effects may take in patterning scientific receptivity" (p. 108).

A Meta-Analytic Approach to Scientific Innovation

Given the evidence produced so far, it seems likely that age-related tendencies in openness to new scientific theories are moderated by the nature of the ideas being advocated as well as by the phase of the discovery process associated with each particular innovation. These considerations present what appears to be a classic meta-analytic problem, namely, the search for robust trends across numerous small studies when reported trends vary widely in their effect sizes and may be influenced – sometimes substantially – by unknown moderating factors (Faust & Meehl, 2002; Hunter & Schmidt, 1990). It is for these reasons that I have devoted more than four decades to a research project focused on the antecedents of openness to innovation in science. Toward this end, I have assembled relevant historical data on the reception of 28 different scientific controversies dating from 1543 (the Copernican revolution) to the late 1960s (debates over the theory of plate tectonics; Sulloway, 1996, 2009). These 28 controversies include 16 of the most important scientific revolutions that have occurred during the last five centuries, such as those associated with the names of Nicholas Copernicus, Isaac Newton, Charles Darwin, Albert Einstein, and Niels Bohr. In addition, I have examined a series of less prominent scientific controversies, such as the debates over preformation versus epigenesis in 17th-century embryology, glaciation theory in the 1830s, and germ theory in mid-19th-century biology. I have also considered several scientific controversies involving what subsequently proved to be largely failed theories (e.g., mesmerism, phrenology, and psychoanalysis). What follows are a series of new analyses that use these historical data to address the meta-analytic questions posed by this study.

Age is only one of many factors that may be influencing the acceptance of new theories in science. Historians of science have implicated a variety of other factors, including the role of social attitudes, socioeconomic status, differences in scientific specialization, national differences, and, of course, new discoveries and arguments arising from scientific research itself (Brush, 1999, 2007; Desmond, 1989; Forman, 1971, 1978; Gillispie, 1951; Glick, 1972, 1987; Roazen, 1975; Rudwick, 1985; Shapin, 1975). What previous studies have generally neglected is a systematic consideration of individual attributes that might relate directly or indirectly to variation in openness to experience. This neglect is understandable because historians, given their interests and training, have found it easier to focus on the kinds of individual characteristics that can be documented from the available historical record – such as differences in socioeconomic status, professional training, and nationality – as opposed to the kinds of individual differences studied by psychologists. In attempting to rectify this omission, my own research has included a variety of biographical variables that are known to influence personality and social attitudes – among them, parent–offspring conflict, early parental loss, birth order, sibship size, and religious and political allegiances (including the religious and political attitudes of parents). In assessing individual differences in scientific stance – as well as social attitudes and several other variables in this

Table 26.1 Multivariate model of support for 28 scientific innovations (1543–1970, $N = 3{,}896$).

Predictor	*Zero-order correlation*	*Partial correlation*	N	p
Age (being young)	−.27	−.22	3,265	<.0001
Social attitudes (being liberal)	.25	.20	2,768	<.0001
National differences	.22	.21	3,896	<.0001
Birth order (being laterborn)	.17	.15	2,026	<.0001
Friend of the innovator(s)	.13	.13	3,831	<.0001
Disciplinary differences	.15	.11	3,770	<.0001
Sex (being female)	.10	.06	3,896	<.001
World travel (extensive)	.06	.07	2,516	<.005
High conflict with parents	−.11	−.03	988	.41
Disciplinary breadth	−.04	−.04	3,672	<.02
Disciplinary outsider	.04	.00	3,748	.94
Low socioeconomic status	.02	.02	2,767	.41
Eminence	−.03	−.00	3,874	.84
Extraversion	−.00	−.02	1,111	.46

Note. For the 14-variable model, $R = .48$ ($p < .0001$). All p-values, reported here for the partial correlations, have been adjusted by PROC MIANALYZE in SAS for the variance inflation caused by imputing missing values 100 times (using SAS PROC MI), which achieved 99.7% efficiency in simulating true variance estimates (Schaffer, 1997). Disciplinary and national differences were dummy coded. Where dummy-coded variables exhibited significant differences within controversies, a summary variable was coded −1 or +1 for the relevant cases. Otherwise the summary variable was scored 0. Socioeconomic status is based on father's occupation and social status. Among the bivariate correlations, all are statistically significant at $p < .05$ with the exception of low socioeconomic status, eminence, and extraversion. Controlled for birth order and socioeconomic status, sibship size is also not a significant predictor in the model (partial correlation = .02).

study – I have availed myself of assistance from more than a hundred experts in history and the history of science. These experts, who were all intimately familiar with one or more of the historical episodes being surveyed, served as independent raters of various attributes of the 3,896 participants included in the study. Interrater reliabilities from these independent assessments were respectable. For example, the average correlation between independent judgments about who supported and who opposed a given new theory was .88; and the coefficient alpha, which reflects the additional reliability derived from pooling such ratings, was .94. For ratings of social attitudes, the coefficient alpha was .92. These and other methodological issues are discussed in Sulloway (1996, especially appendices 2–6).

Table 26.1 presents the results of a multiple regression model predicting support for 28 scientific innovations. Allegiance to new theories (the dependent variable) was scored on a seven-step scale for each participant, although the use of multiple raters increased the number of steps on this scale to more than a hundred. The table provides the zero-order correlation (that is, the bivariate relationship between each predictor and support) as well as the partial correlation (the influence exerted by each predictor after controlling for the presence of other variables in the model). In the multivariate model, age and social attitudes are two good predictors of support: Adoption of scientific innovations was most frequent among young scientists and social liberals. As both of these two variables are known to correlate with openness to experience, these findings are not surprising (Costa & McCrae, 1992; Jost, Glaser, Kruglanski, & Sulloway, 2003; McCrae, Martin, & Costa, 2005; Srivastava, John, Gosling, & Potter, 2003).

What is also important to note about these predictors in Table 26.1 is the magnitude of the effects. Previous investigators who have studied the influence of age on the acceptance of new scientific theories have sometimes found correlations of similar magnitude (r = .20–.30) but have dismissed them as being unimpressive (e.g., Diamond, 1980; Hull *et al.*, 1978; Rappa & Debackere, 1993). As Diamond (1980) has commented about a correlation of .26 in his study of age and the reception of cliometrics, "Age matters, but it does not matter much" (p. 841). This last conclusion involves a mistaken understanding of effect sizes in behavioral science research. Few effect sizes involving individual behavioral differences and their biographical antecedents are ever greater than r = .20–.30. Such effects, which are generally considered "moderate" in size, are hardly as unimpressive as some researchers have concluded. For example, personality differences between the sexes entail a mean correlation of only .14 (Feingold, 1994); yet research on sex differences in personality is a robust field of research precisely because such individual sex differences have considerable behavioral ramifications. Expressed another way, a correlation of .14 means that women, compared with men, are 1.25 times more likely to score above the mean on a given personality trait. By comparison, a correlation of −.27 between age and acceptance of a new scientific theory (Table 26.1) is nearly twice the size of the average gender difference in personality attributes. A scientist who was younger than the mean age of the sample was 1.6 times more likely to support a new scientific innovation than were scientists who were above the mean; and the odds of a younger scientist doing so were 2.4 times higher. Comparing supporters with opponents, the mean age difference was 14.6 years. Among the most committed supporters and opponents, however, the age disparity was almost twice as large.[3] In this connection, it is worth noting that an influential medical study involving the efficacy of aspirin therapy in preventing heart attacks was discontinued early because it was considered unethical to continue treating the control group with a placebo. The effect size in this particular medical study was $r = .034$ (Rosenthal, Rosnow, & Rubin, 2000). Yet such a seemingly minuscule effect meant that people who had been given the placebo were 1.8 times more likely than treated individuals to experience a heart attack (the relative risk ratio).

Although age would appear to be an important factor in the reception of new scientific theories, the precise mechanism for this relationship remains unclear. In the case of the Darwinian revolution, I tested the hypothesis that age might be a proxy for accrued achievement, and that particularly eminent scientists might have been reluctant to abandon creationist theory because their previous publications were generally predicated on the validity of this theory. I was able to code eminence, as of publication of Darwin's *Origin of Species* in 1859, for 78% of the scientists in the sample, based on the number and general prestige of honors and awards received by that year. I also coded lifetime eminence using the same measures of scientific achievement. Like age, eminence in 1859 proved to be a good predictor of opposition to Darwin's theories ($r = -.28$, $n = 279$, $p < .0001$). In multiple regression models, however, only age – which is substantially correlated with eminence ($r = .43$) – was a significant predictor of acceptance of Darwinism. Eminence did become a significant predictor of opposition to evolution when debates over pre-Darwinian theories of evolution were included in a multivariate analysis, which increased the statistical power of the test.

These results suggest that concern about loss of eminence was not the only reason why older scientists resisted Darwin's evolutionary theories, although it does seem to have been a contributing factor. It is worth noting that scientists who continued to oppose Darwin's theories after 1859 suffered a relative reduction in lifetime eminence compared with scientists who embraced Darwin's theories ($r = -.14$, $n = 262$, $p = .02$). Given these and other considerations, it seems likely that age is a proxy for a series of related considerations. These include (1) a reluctance to admit error; (2) concern about potential loss of reputation if the new theory turns out to be correct; (3) a disinclination to have to retool, conceptually and methodologically; and (4) a modest decline in openness to experience that occurs with age (McCrae *et al.*, 2005; Srivastava *et al.*, 2003).

Also exerting a significant influence on the acceptance of new scientific ideas (Table 26.1) are disciplinary and national differences, which have been widely discussed in the literature on this topic (Brush, 1999; Glick, 1972, 1987; Stewart, 1986; Westman, 1975). As an example, French scientists, steeped in a Cartesian tradition of explaining gravity mechanistically in terms of swirling vortices, were less likely than scientists from other countries to support Isaac Newton's theory of universal gravitation. To Cartesians, Newton's theory appeared to involve a distinctly mystical process of action at a distance. As an example of disciplinary differences in openness to innovation, philosophers were less likely to accept Copernicus's new heliocentric theory than were people in other fields – especially physicists and mathematicians, who appear to have been more impressed by empirical evidence in favor of the new theory.

Three other good predictors of support for scientific innovations include sex, birth order, and being a close friend or relative of the leader(s) of a new scientific theory. Women tended to be more supportive of scientific innovations compared with men, although much of this effect was owing to the fact that women were a very select group in this historical sample ($n = 66$) – more socially liberal than their male counterparts, somewhat younger than other participants, and more likely to be a personal friend of the innovator. Birth order owes its presence in the model to the fact that it is a good proxy for individual differences in sibling strategies and family niches, which in turn exert a small-to-moderate influence on personality – including on openness to experience (Healey & Ellis, 2007; Manaster, Rhodes, Marcus, & Chan, 1998; Paulhus, Trapnell, & Chen, 1999; Rohde *et al.*, 2003; Skinner & Fox-Francoeur, 2010; Sulloway, 1996, 2001, 2010). Because firstborns often serve as surrogate parents within the family, they tend to be more strongly identified with parents and authority compared with their younger siblings. By contrast, in their search for a unique family niche that will impress parents and steer greater parental investment in their direction, laterborns often take greater risks than firstborns and also tend to adopt more unconventional points of view (Courtiol, Raymond, & Faurie, 2009; Sulloway, 1996, 2010; Sulloway & Zweigenhaft, 2010; Zweigenhaft & Von Ammon, 2000).

Several of the variables included in Table 26.1, such as status as a disciplinary outsider and experiencing extensive conflict with a parent, appear to have exerted no influence on the acceptance of new scientific ideas. The same conclusion is true of socioeconomic status, which has been implicated as a major source of support for radical innovations, such as pre-Darwinian evolutionary ideas during the several decades prior to publication of Darwin's *Origin of Species* in 1859 (Desmond, 1989). Even in the case of support for pre-Darwinian evolutionary ideas, however, social class is not a relevant factor when tested in a formal statistical manner (Sulloway, 1996). Finally, it is clear from the results set forth in Table 26.1 that individual differences that are good proxies for openness to experience (e.g., age, social attitudes, birth order, and world travel) collectively explain more about receptivity to scientific innovation than do the kinds of influences that have generally concerned historians of science (e.g., socioeconomic, disciplinary, and national differences).[4]

Heterogeneity of Effects

What is of particular interest about the findings set forth in Table 26.1 is an observation that is obscured by the amalgamation of data from multiple historical events. From one historical event to another, most predictors of support for scientific innovation in Table 26.1 display significant heterogeneity in their effect sizes. Statistical heterogeneity occurs when the effect sizes for a predictor such as age differ substantially from one historical event to another. Evidence for heterogeneity generally points the way to important moderator effects. As an example, the correlation between age and acceptance of new theories in science varies from −.50 during the reception of Freud's psychoanalytic ideas ($n = 218$, $p < .001$), with younger people showing greater support for these theories, to +.09 during 19th-century vitalistic efforts to refute the doctrine of spontaneous generation – a conservative stance that generally appealed to older scientists ($n = 43$, $p = .55$). Although a correlation of +.09 is not significantly different from zero (given the small sample size for this particular debate), it *is* significantly different from the correlation associated with debates over Freud's theories ($Z = 3.71$, $n = 261$, $p < .001$). A correlation of +.09 is also significantly different from the mean correlation between age and receptivity observed for all of the controversies in my dataset ($Z = 2.33$, $n = 3{,}265$, $p = .02$). The role of social attitudes varies even more dramatically in the reception of new theories. In debates over pre-Darwinian and Darwinian theories of evolution, the correlation between being socially liberal and accepting any version of evolutionary theory is an impressive .60 ($n = 547$, $p < .0001$). A social liberal was 5.1 times more likely to accept the theory of evolution compared with a social conservative (the relative risk ratio). By contrast, among people who sympathized with early-20th-century theories of eugenics, social conservatives were more likely than social liberals to support these controversial ideas ($r = -.38$, $n = 221$, $p < .0001$).

These and other considerations have led me to divide the 28 scientific innovations in Table 26.1 into four broad categories. As it turns out, most biographical predictors of support for scientific innovation are significantly disparate according to the type of innovation. The following four subgroups capture the bulk of these differences (Sulloway, 1996, 2009):

1. *Radical revolutions* (such as the theories of Copernicus and Darwin): These fiercely debated events involve ideologically controversial ideas that have substantial implications outside scientific circles, especially in the domain of church doctrine. Owing to the heated nature of such controversies, they tend to last longer than most other intellectual transformations in science, and they elicit limited support for innovation during early stages of debate. Radical revolutions are often announced in books, where they can be defended at considerable length, rather

than in technical articles. In addition, such books have often been published anonymously, to protect their authors from social ostracism, and these books have frequently ended up on the Catholic Church's *Index Librorum Prohibitorum.*

2 *Conservative innovations* (among them, eugenics and various vitalistic doctrines): These types of theories may be thought of as the antithesis of radical revolutions. They involve ideas that are supportive, directly or indirectly, of the religious and political status quo as well as of older ways of scientific thinking. Such innovations have tended to occur in the life sciences rather than in the hard sciences, mainly because vitalistic theories have typically supported church doctrine concerning the sanctity of life.

3 *Technical revolutions* (led by scientists such as Newton, Lavoisier, and Einstein): This class of events is largely confined to the physical sciences. The novel ideas set forth during such debates are generally difficult for laypersons to understand, and they are usually announced in technical articles rather than in books. In addition, the debates over this class of scientific innovations are relatively brief compared with other conceptual transformations in science.

4 *Controversial innovations* (such as Semmelweis's theory of puerperal fever and the "Great Devonian" debate in early 19th-century geology): Like conservative innovations, controversial innovations do not rise to the level of what historians and philosophers of science have generally designated as "revolutions" in scientific thought. In addition, this class of events involves a substantial proportion of failed theories, such as mesmerism and phrenology.

Table 26.2 shows the results of formal tests of heterogeneity among the 28 scientific controversies included in this analysis. Ten of the 14 predictors previously reviewed in Table 26.1 exhibit heterogeneity, meaning that effect sizes vary significantly across the four classes of innovation. For social attitudes and birth order, heterogeneity is substantial; for another seven predictors, heterogeneity is moderate but still impressive. Most of these differences in the magnitude of effects, from one scientific debate to another, are driven by where events lie on a scale of ideological radicalism. Radical revolutions such as the Copernican and Darwinian manifest substantial effects in all of the variables that are good proxies for individual differences in openness to experience, including social attitudes, conflict with a parent, birth order, disciplinary breadth, and world travel. During other kinds of scientific debates, the effect sizes for these same five variables tend to be substantially smaller. Conversely, effect sizes for national differences are larger during nonradical innovations, reflecting the fact that – compared with radical revolutions – these other kinds of disputes are less likely to transcend localized allegiances.

Because of heterogeneity, some of the predictors reviewed in Table 26.1 display effect sizes that belie their true influence on openness to scientific innovation. For example, it is surprising that experiencing a high degree of conflict with a parent, which is known to correlate with openness to experience (Sulloway, 2001), is not a significant predictor of support for the 28 scientific innovations. In fact, parental conflict becomes a significant predictor if we confine our analyses to particularly radical or conservative innovations. During radical revolutions, people who previously experienced extensive conflict with a parent have tended to support such innovations. By contrast, during ideologically conservative innovations, people who previously experienced considerable conflict with a parent were more likely to oppose the innovation.

Table 26.2 Tests for heterogeneity of effect sizes among predictors of acceptance of 28 scientific innovations (1543–1970, $N = 3{,}896$).

Predictor	*Chi-square test for heterogeneity of effect sizes*	N	p	*Degree of heterogeneity*
Age (being young)	31.82	3,265	<.0001	Moderate
Social attitudes (being liberal)	212.45	2,768	<.0001	Substantial
National differences	19.87	3,896	<.001	Moderate
Birth order (being laterborn)	69.04	2,026	<.0001	Substantial
Friend of the innovator(s)	0.88	3,831	.83	None
Disciplinary differences	25.24	3,770	<.0001	Moderate
Sex (being female)	0.94	3,896	.82	None
World travel (extensive)	22.53	2,516	<.0001	Moderate
High conflict with parents	11.05	988	.01	Moderate
Disciplinary breadth	44.09	3,672	<.0001	Moderate
Disciplinary outsider	8.99	3,748	.03	Small
Low socioeconomic status	5.77	2,767	.25	None
Eminence	23.63	3,874	<.0001	Moderate
Extraversion	1.27	1,111	.74	None

Note. Chi-square tests for heterogeneity are based on differences in effect sizes, by subgroups, for each of the variables predicting receptivity in Table 26.1. For the purposes of computing these tests, the 28 scientific controversies have been divided into four subgroups ($df = 3$): (1) conservative revolutions and debates (such as eugenics and vitalistic doctrines, including Pasteur's germ theory); (2) controversial innovations (such as Semmelweis's theory of puerperal fever); (3) technical revolutions (e.g., the theories of Lavoisier, Newton, Wegener, and Einstein); and (4) radical revolutions, including those led by Copernicus and Darwin (Sulloway, 1996, pp. 36–48; Sulloway, 2009).

The common denominator in these discrepant findings is that pronounced conflict with a parent is associated with adoption of an ideologically "liberal" position in scientific debates, as defined by the political and religious implications inherent in each new theory. Because of these crisscrossing effects, the influence of parental conflict is cancelled out in the overall analysis of 28 different controversies in the history of science (Table 26.1).

Heterogeneity in eminence arises in Table 26.2 because supporters of radical and technical revolutions are judged, retrospectively, as being more eminent than their opponents. By contrast, supporters of conservative innovations, as well as controversial innovations, are generally considered less accomplished than their opponents. This difference in patterns of eminence is due in part to the fact that these two classes of innovation include a higher proportion of failed theories, such as mesmerism and phrenology. Similarly, birth-order effects have sometimes been much larger during the reception of new theories than one would suspect from examining the results reported in Table 26.1, since the table mingles together both positive and negative correlations for this particular variable. During radical revolutions in science, the correlation between birth order and support for scientific innovation is +.33 (more than twice its mean effect for all 28 innovations), indicating that laterborns were strong supporters of ideologically radical doctrines ($n = 583$, $p < .0001$). By contrast, during conservative scientific innovations, firstborns were more favorably disposed than were laterborns ($r = -.17$, $n = 400$, $p < .001$). Because of such person-by-situation interaction effects, variables such as birth order, social attitudes, conflict with a parent, and disciplinary breadth correlate more highly with support for the ideologically liberal position in each debate (by 30–40%) than they do with support for innovation per se.

Initiators of Scientific Innovations

Scientists who have initiated important and sometimes revolutionary theories are not necessarily the same sorts of scientists who have led the way during other revolutionary events. A good example is Louis Agassiz, the Swiss naturalist who championed glaciation theory in the 1830s. Ironically, Charles Darwin, who is one of the greatest revolutionary figures in the history of science, initially resisted arguments about the massive ice sheets that Agassiz claimed to have once covered northern Europe. In addition, some of the strongest supporters of Agassiz's novel theory, including Agassiz himself, were vehemently opposed to Darwin's theory of evolution by natural selection – and to all other forms of evolutionary theory, for that matter.

The reason why Louis Agassiz and other geologists could support glaciation theory but reject Darwinism lies in the disparate nature of the theories. Many geologists initially perceived glaciation theory to be a throwback to a catastrophist position in geology, which in turn harked back to a geological tradition that was heavily influenced by religious doctrine, including the historical reality of the biblical flood (Boylan, 1998; Carozzi, 1966; Gillispie, 1951). The scientific liberals of the day, including Charles Lyell and young Charles Darwin, were engaged in a concerted effort to rid geology of its previous religious and catastrophist ties by supporting the doctrine of uniformitarianism. This novel geological perspective maintained that the only causal factors that should be evoked in geology were those drawing on currently observable causes – ruling out catastrophic processes like the biblical flood. This and other examples drawn from the history of science clearly show that there is no such thing as a single "revolutionary" disposition in science. Rather, individual scientists appear to be preadapted, in differing ways, to initiating and supporting different kinds of theories.

This last conclusion is borne out by an analysis of scientists who have been the primary instigators of new and revolutionary ways of thinking. Among the 3,896 participants included in the 28 scientific innovations I have surveyed, it is possible to identify 114 individuals who were the chief initiators of these new ideas. I have coded these 114 instigators on a three-step scale according to the contributions each scientist made during the period of innovation. For example, Darwin and Alfred Russel Wallace, who both independently developed the theory of natural selection, were given a score of 3 for their intellectual contributions to the Darwinian revolution. Other important pre-Darwinian evolutionists, such as Jean-Baptiste Lamarck and Robert Chambers, were assigned a 2 on this same scale. A number of scientists who played more minor roles in the advocacy of evolutionary ideas prior to publication of Darwin's (1859) *Origin of Species*, including Leopold von Buch and Bory de Saint-Vincent, received a score of 1. Everyone else in the study who did not contribute in a significant manner to a phase of scientific innovation was assigned a score of 0.

Although subjective to a degree, this four-step scale for the initiators of major scientific innovations exhibits considerable predictive validity. For example, the creators of new theories were substantially more eminent than their contemporaries, based on 19 retrospective measures of eminence (Sulloway, 2009). In addition, this same scale correlates .50 with the number of times Bernard Cohen mentioned each scientist in his 711-page review of the most prominent revolutions in the history of science (Cohen, 1985). This correlation is all the more impressive given that Cohen's book also discusses many of the foremost opponents of revolutions in science, which attenuates the correlation. These 114 scientific innovators differ from their scientific contemporaries in other telltale ways. They were more liberal in their social attitudes and broader in their scientific interests, and traveled more extensively – all good proxies for openness to experience. In addition, innovators were more likely than noninnovators to be disciplinary insiders rather than mavericks interloping from other fields of science.[5]

Regarding the role of age, the issue is more complicated. When they first developed their new ideas, innovators were 3.5 years younger than the scientists who subsequently made public pronouncements about their theories. At the same time, innovators were 4.9 years older than their opponents and 19.5 years older than their supporters. These differences occur, in part, because innovators often developed their ideas many years before the ideas were finally published and became widely debated within the scientific community. The 21 years that elapsed between Darwin's conversion to the theory of evolution, which occurred in 1837, and his brief account of the theory of natural selection, published in the *Biological Journal of the Linnean Society* in 1858, is a good example. What seems reasonably clear from these findings is that being young was less critical for innovators than it was for subsequent adopters of the same theories.

These generalizations about scientific innovators are potentially misleading without considerable qualification, because they fail to take into account the substantial heterogeneity in effect sizes for various biographical predictors that is observed from one class of scientific advances to another. Table 26.3 presents formal tests of heterogeneity for the 14 predictors of openness to scientific innovation previously analyzed in Table 26.1 and Table 26.2. Six of the 14 predictors exhibit significant heterogeneity, with the greatest degree of heterogeneity being for social attitudes, birth order, conflict with a parent, and professional eminence. Not surprisingly, a major source of heterogeneity is the distinction between having been involved in a radical revolution and not. Those scientists who were intellectual leaders of radical revolutions were more likely than other types of innovators to be socially liberal, to have experienced extensive conflict with a parent, to be laterborn, to have broad scientific interests, and to be judged retrospectively as especially eminent figures in the history of science. Both Darwin and Wallace, who codiscovered the theory of natural selection, fit this general pattern (although neither scientist experienced particularly pronounced conflict with a parent). In sum, these biographical proxies for openness to experience, which generally provide sources of inspiration among all innovative scientists, supplied even more stimulus to those scientists such as Darwin and Wallace who have led the way during radical revolutions in the history of science.[6]

The distinction between technical revolutions – such as those instigated by Newton, Lavoisier, and Einstein – and other types of scientific innovation is also critical to

Table 26.3 Tests for heterogeneity of effect sizes among predictors of the 114 initiators of 28 scientific innovations (1543–1970, $N = 3,896$).

Predictor	*Chi-square test for heterogeneity of effect sizes*	N	p	*Degree of heterogeneity*
Age (being young)	1.63	3,265	<.65	None
Social attitudes (being liberal)	17.55	2,768	<.001	Substantial
National differences	0.05	3,896	1.00	None
Birth order (being laterborn)	14.27	2,026	<.005	Substantial
Friend of the innovator(s)	5.06	3,831	.17	None
Disciplinary differences	10.49	3,770	.01	Moderate
Sex (being female)	3.44	3,896	.33	None
World travel (extensive)	4.43	2,516	.22	None
High conflict with parents	8.50	988	.04	Substantial
Disciplinary breadth	16.15	3,672	<.0001	Moderate
Disciplinary outsider	0.61	3,748	.89	None
Low socioeconomic status	4.35	2,767	.23	None
Eminence	129.93	3,874	<.0001	Substantial
Extraversion	3.68	1,111	.30	None

Note. Chi-square tests for heterogeneity are based on differences in effect sizes among four subgroups of scientific controversies ($df = 3$; see Table 6.2, note).

predicting who might initiate such celebrated historical events. During this particular class of scientific innovations, firstborns rather than laterborns have generally led the way, reflecting the degree to which intellectual ability – as opposed to openness to experience – appears to have been a particularly critical factor in the innovation process. Although laterborns tend to be more open to experience than firstborns, firstborns have slightly higher IQs, and they have been 2.0 times more likely to win a Nobel Prize in science than laterborns (Clark & Rice, 1982; Kristensen & Bjerkedal, 2007; Sulloway, 2007; Zajonc & Sulloway, 2007). This difference in professional eminence by birth order is strongly reflected among the leaders of technical revolutions. During the 11 different historical disputes belonging to this class of innovations, firstborns such as Galileo, Newton, Lavoisier, and Einstein were the primary instigators in eight of the events; and they played important supporting roles in the remaining three. Overall, firstborns were 3.7 times more likely than laterborns to lead this class of scientific events (the relative risk ratio). Although firstborns were more likely than laterborns to lead technical revolutions, laterborns were quicker than firstborns to accept the new ideas proposed during these same historical events. This discrepancy shows that it is easier to be enthusiastic about one's own novel ideas than it is to accept the novel ideas of another person. Another interesting feature of technical revolutions is the fact that the scientific leaders were more narrowly focused in their professional interests than innovators in other classes of scientific events. This difference reflects the kind of specialization that is often a prerequisite for success in highly technical science.

Conclusion

Individual differences in openness to experience (and biographical influences that tend to nurture it) are substantially responsible for which scientists adopt, and which ones reject, new and revolutionary theories. This conclusion is particularly true during the most ideologically radical revolutions, such as those pioneered by Copernicus and Darwin. Among the best predictors of support for radical scientific innovations are being young, espousing liberal social attitudes, being laterborn, having experienced substantial conflict with a parent, exhibiting broad scientific interests, and having traveled extensively.

In many ways, the best indicator of who is likely to propose or accept new ideas in science is the nature of the ideas themselves. Scientific innovations vary substantially in their conceptual, ideological, and technical features. These disparate characteristics of new theories in turn dictate the kinds of intellectual preadaptations that allow one scientist rather than another to propose, or later to endorse, such ideas. During conservative scientific innovations – that is, events involving new ideas that have conservative ideological implications or that are allied to historically older ways of thinking – the best predictors of acceptance are typically the opposite of those predicting adoption during radical innovations. Similarly, technical revolutions, such as those led by Newton and Einstein, have their own unique features that affect the biographical calculus of who is most likely to initiate and support them. For these reasons, there is no such thing as a "revolutionary personality" in science, and there is accordingly no single biographical formula for scientific creativity. Rather, the scientific community appears to be preadapted in diverse ways to nurturing a multiplicity of new ways of thinking, and individual scientists often solve important scientific problems in different ways. If we are to advance our understanding of the process of scientific innovation, future research needs to focus on essential features of the innovations themselves as much as it does on the scientists who propose and support them.

Notes

1 Here and elsewhere in this essay, I draw on data involving the reception of scientific innovations that were previously analyzed in Sulloway (1996, 2009). Among 3,896 participants who lived during the last five centuries and who are included in these earlier studies, the primary instigators of major scientific innovations scored higher than other scientists on openness to experience, which was assessed using a composite measure of this psychological attribute ($r = .17$, $n = 1{,}250$, $p < .0001$). This composite measure entailed (1) breadth of scientific interests, (2) social attitudes (coded on a conservative-to-liberal scale), and (3) world travel. This same measure also correlates with whether a scientist is considered to be a "revolutionary" figure in the history of science ($r = .20$, $n = 1{,}250$, $p < .0001$). Being judged a scientific "revolutionary" is based on the number of times a person is mentioned in I. Bernard Cohen's (1985) *Revolution in Science* and in Thomas Kuhn's (1962) *Structure of Scientific Revolutions.*

2 From Perrin's (1992) published data, it is possible to compute a formal statistical test of the relationship between age and acceptance of Lavoisier's theory. Using binary logistic regression, the trend is significant (Wald $\chi^2_1 = 8.49$, $N = 76$, $p < .005$, Cox & Snell pseudo $r = .37$). Perrin's findings extend and confirm those of McCann (1978), who analyzed publications by chemists between 1760 and 1795, which he classified by age of author

(dichotomized at age 40). Because McCann's data involve multiple publications by the same scientists, the data do not permit a formal test because they are not statistically independent.

3 Strong commitment among supporters and opponents is defined here as having a mean rating for the acceptance of new theories that is in the lowest or highest deciles. The age difference between these two subgroups was 28.2 years ($n = 535$).

4 Although I have used linear regression models in Table 26.1 to assess receptivity to new theories in science, one can analyze these same data with a proportion hazards model, assessing time to event (in this case, time to conversion to a new theory). If censored cases (people who have failed to convert before the end of the survey period for each debate) involve statistical bias, Cox regression models will correct for this bias. However, these models require a binary outcome for receptivity, which disregards useful information contained in a continuous measure of attitudes toward new theories. This having been said, with one exception (sex differences), all of the variables that are significant predictors of receptivity within a linear regression model (Table 26.1) are also significant predictors in a Cox regression model. More important, effect sizes are very similar in the two kinds of models ($r = .90$, $n = 14$, $p < .0001$), indicating little or no bias owing to censoring. In addition, all significant predictors in Table 26.1 are also significant predictors if the data on scientific stance are dichotomized in a logistic regression model, with effect sizes correlating .99 with the partial correlations reported in Table 26.1.

5 Significant correlates with status as a scientific innovator are as follows: retrospective eminence, $r = .26$, $n = 3{,}874$, $p < .0001$; breadth of scientific interests, $r = .12$, $n = 3{,}831$, $p < .0001$; close ties with a fellow innovator, $r = .09$, $n = 3{,}831$, $p < .0001$; world travel, $r = .06$, $n = 2{,}516$, $p = .001$; being a disciplinary insider, $r = .05$, $n = 3{,}748$, $p = .001$; age, $r = .05$, $n = 3{,}265$, $p = .003$; liberal social attitudes, $r = .05$, $n = 2{,}768$, $p = .01$; and national differences, $r = .04$, $n = 3{,}896$, $p = .01$. Although statistically significant, these correlations are mostly small because the sample contains few innovators (2.9%). Relative risk ratios and odds ratios help to correct for this imbalance and provide a better indication of effect sizes. For example, a scientific innovator was 1.9 times more likely than a noninnovator to be socially liberal (that is, above the population mean on this attribute); and the odds of an innovator being socially liberal were 3.6 times greater than for a noninnovator. Nonsignificant predictors of status as a scientific innovator include birth order, conflict with parents, sex, extraversion, and social class – all having $r < .03$ and $p > .37$.

6 Computed using a logistic regression model (note 4), Charles Darwin's probability of accepting the theory of evolution was 0.96. For Alfred Russsel Wallace, the predicted probability was 0.97. Besides Wallace, only six of the 353 scientists in this Darwinian revolution sample had higher predicted probabilities of accepting Darwin's theories than did Darwin himself, and all of them had accepted the theory by 1863. These six people include Thomas Henry Huxley ("Darwin's bulldog"), Clémence Royer (who translated Darwin's *Origin of Species* into French), and Darwin's cousin Francis Galton. The other three people were Alexander Bain, Harriett Martineau, and Charles Eliot Norton.

References

Blackmore, J. T. (1978). Is Planck's "principle" true? *British Journal of Philosophy of Science*, *29*, 347–349.

Bolig, R., Price, C. S., O'Neill, P. L., & Suomi, S. J. (1992). Subjective assessment of reactivity level and personality traits of rhesus monkeys. *International Journal of Primatology*, *13*, 287–306.

Boylan, P. J. (1998). Lyell and the dilemma of Quaternary glaciation. *Geological Society, London, Special Publications*, *143*, 145–159.

Brush, S. G. (1999). Why was relativity accepted? *Physics in Perspective*, *1*, 184–214.

Brush, S. G. (2007). How ideas became knowledge: The light-quantum hypothesis 1905–1935. *Historical Studies in the Physical and Biological Sciences*, *37*, 205–246.

Carozzi, A. V. (1966). Agassiz's amazing geological speculation: The Ice-Age. *Studies in Romanticism*, *5*, 57–83.

Clark, R. D., & Rice, G. A. (1982). Family constellations and eminence: The birth orders of Nobel Prize winners. *Journal of Psychology*, *110*, 281–287.

Cohen, I. B. (1980). *The Newtonian revolution: With illustrations of the transformation of scientific ideas.* Cambridge, UK: Cambridge University Press.

Cohen, I. B. (1985). *Revolution in science.* Cambridge, MA: The Belknap Press of Harvard University Press.

Costa, P. T., Jr., & McCrae, R. R. (1992). *Revised NEO personality inventory (NEO PI-R) and NEO five-factor inventory (NEO-FFI): Professional manual.* Lutz, FL: Psychological Assessment Resources.

Courtiol, A., Raymond, M., & Faurie, C. (2009). Birth order affects behaviour in the investment game: firstborns are less trustful and reciprocate less. *Animal Behaviour*, *78*, 1405–1411.

Darwin, C. R. (1859). *On the origin of species by means of natural selection, or The preservation of favoured races in the struggle for life.* London, UK: John Murray.

Desmond, A. (1989). *The politics of evolution: Morphology, medicine, and reform in radical London.* Chicago, IL: University of Chicago Press.

Desmond, A., & Moore, J. (2009). *Darwin's sacred cause: Race, slavery and the quest for human origins.* London, UK: Michael Joseph.

Diamond, A. M., Jr. (1980). Age and the acceptance of cliometrics. *The Journal of Economic History*, *40*, 838–841.

Diamond, A. M., Jr. (1988). The polywater episode and the appraisal of theories. In A. Donovan, L. Laudan, & R. Laudan (Eds.), *Scrutinizing science: Empirical studies of scientific change* (pp. 181–198). Dordrecht, Netherlands: Kluwer Academic.

Esterson, A. (2013). Desmond and Moore's *Darwin's Sacred Cause*: A misreading of the historical record. *Sage Open*, *April–June*, 1–7.

Faust, D., & Meehl, P. E. (2002). Using meta-scientific studies to clarify or resolve questions in the philosophy and history of science. *Philosophy of Science*, *69*, S185–S196.

Feingold, A. (1994). Gender differences in personality: A meta-analysis. *Psychological Bulletin*, *116*, 429–456.

Feist, G. J. (1998). A meta-analysis of personality in scientific and artistic creativity. *Personality and Social Psychology Review*, *2*, 290–309.

Forman, P. (1971). Weimar culture, causality, and quantum theory, 1918–1927: Adaptation by German physicists and mathematicians to a hostile intellectual environment. *Historical Studies in the Physical Sciences*, *3*, 1–115.

Forman, P. (1978). The reception of an acausal quantum mechanics in Germany and Britain. In S. H. Mauskopf (Ed.), *The reception of unconventional science* (pp. 11–50). Boulder, CO: Westview.

Frank, R. G., Jr. (1980). *Harvey and the Oxford physiologists: A study of scientific ideas.* Berkeley, CA: University of California Press.

Gillispie, C. C. (1951). *Genesis and geology: A study in the relations of scientific thought, natural theology, and social opinion in Great Britain, 1790–1850.* Cambridge, MA: Harvard University Press.

Glick, T. F. (Ed.). (1972). *The comparative reception of Darwinism.* Austin, TX: University of Texas Press.

Glick, T. F. (Ed.). (1987). *The comparative reception of relativity.* Dordrecht, Netherlands: D. Reidel.

Gosling, S. D. (2001). From mice to men: What can we learn about personality from animal research? *Psychological Bulletin*, *127*, 45–86.

Healey, M. D., & Ellis, B. J. (2007). Birth order, conscientiousness, and openness to experience: Tests of the family-niche model of personality using a within-family methodology. *Evolution and Human Behavior*, *28*, 55–59.

Hufbauer, K. (1982). *The formation of the German chemical community (1720–1795)*. Berkeley, CA: University of California Press.

Hull, D. L., Tessner, P. D., & Diamond, A. M. (1978). Planck's principle. *Science*, *202*, 717–723.

Hunter, J. E., & Schmidt, F. L. (1990). *Methods of meta-analysis: Correcting error and bias in research findings.* Newbury Park, CA: Sage.

Huxley, L. (1901). *Life and letters of Thomas Henry Huxley.* 2 vols. New York, NY: Appleton.

John, O. P. (1990). The "Big Five" factor taxonomy: Dimensions of personality in the natural language and in questionnaires. In L. A. Pervin (Ed.), *Handbook of personality: Theory and research* (pp. 66–100). New York, NY: Guilford Press.

John, O. P., & Srivastava, S. (1999). The Big Five trait taxonomy: History, measurement, and theoretical perspective. In L. A. Pervin & O. P. John (Eds.), *Handbook of personality: Theory and research*, 2nd ed. (pp. 102–138). New York, NY: Guilford Press.

Jost, J. T., Glaser, J. T., Kruglanski, A. W., & Sulloway, F. J. (2003). Political conservatism as motivated social cognition. *Psychological Bulletin*, *129*, 339–375.

Kristensen, P., & Bjerkedal, T. (2007). Explaining the relation between birth order and intelligence. *Science*, *316*, 1717.

Kuhn, T. S. (1957). *The Copernican revolution: Planetary astronomy in the development of western thought.* Cambridge, MA: Harvard University Press.

Kuhn, T. S. (1962). *The structure of scientific revolutions.* Chicago, IL: University of Chicago Press.

Laudan, L., Donovan, A., Laudan, R., Barker, P., Brown, H., Leplin, J., Wykstra, S. (1986). Scientific change: Philosophical models and historical research. *Synthese*, *69*, 141–223.

Levin, S. G., Stephan, P. E., & Walker, M. B. (1995). Planck's principle revisited: A note. *Social Studies of Science*, *25*, 275–283.

Manaster, G. J., Rhodes, C., Marcus, M. B., & Chan, J. C. (1998). The role of birth order in the acculturation of Japanese Americans. *Psychologia*, *41*, 155–170.

McCann, H. G. (1978). *Chemistry transformed: The paradigmatic shift from phlogiston to oxygen.* Norwood, NJ: Ablex.

McCrae, R. R. (1994). Openness to experience: Expanding the boundaries of Factor V. *European Journal of Personality*, *8*, 251–272.

McCrae, R. R., & Allik, J. (Eds.). (2002). *The five-factor model of personality across cultures.* New York, NY: Kluwer Academic/Plenum.

McCrae, R. R., & Costa, P. T., Jr. (1985). Openness to experience. In R. Hogan & W. H. Jones (Eds.), *Perspectives in personality* (Vol. 1, pp. 145–172). Greenwich, CT: JAI Press.

McCrae, R. R., Martin, T. A., & Costa, P. T., Jr. (2005). Age trends and age norms for the NEO Personality Inventory-3 in adolescents and adults. *Assessment*, *12*, 363–373.

Messeri, P. (1988). Age differences in the reception of new scientific theories: The case of plate tectonic theory. *Social Studies of Science*, *18*, 91–112.

Paulhus, D. L., Trapnell, P. D., & Chen, D. (1999). Birth order and personality within families. *Psychological Science*, *10*, 482–488.

Perrin, C. E. (1992). The chemical revolution: Shifts in guiding assumptions. In A. Donovan, L. Laudan, & R. Laudan (Eds.), *Scrutinizing science: Empirical studies of scientific change* (pp. 105–124). Baltimore, MD: Johns Hopkins University Press.

Planck, M. (1949). *Scientific autobiography and other papers.* With a memorial address on Max Planck, by M. von Laue. Translated by F. Gaynor. New York, NY: Philosophical Library.

Rappa, M., & Debackere, K. (1993). Youth and scientific innovation: The role of young scientists in the development of a new field. *Minerva*, *31*, 1–20.

Roazen, P. (1975). *Freud and his followers.* New York, NY: Alfred A. Knopf.

Rohde, P. A., Atzwanger, K., Butovskaya, M., Lampert, A., Mysterud, I., Sanchez-Andres, A., & Sulloway, F. J. (2003). Perceived parental favoritism, closeness to kin, and the rebel of the family: The effects of birth order and sex. *Evolution and Human Behavior*, *24*, 261–276.

Rosenthal, R., Rosnow, R., & Rubin, D. B. (2000). *Contrasts and effect sizes in behavioral research: A correlational approach.* Cambridge, UK: Cambridge University Press.

Rudwick, M. J. S. (1985). *The great Devonian controversy: The shaping of scientific knowledge among gentlemanly specialists.* Chicago, IL: University of Chicago Press.

Schafer, J. L. (1997). *Analysis of incomplete multivariate data*. Boca Raton, FL: Chapman & Hall.

Schmidt, D. P., Allik, J., McCrae, R. R., Benet-Martínez, V. (2007). The geographic distribution of Big Five personality traits: Patterns and profiles of human self-description across 56 nations. *Journal of Cross-Cultural Psychology*, *38*, 173–212.

Schneider, H.-G. (1992). *Paradigmenwechsel und generationenkonflict: Eine fallstudie zur struktur wissenschaftlicher revolutionen: Die revolution der chemie des späten 18. jahrhunderts.* Frankfurt am Main, Germany: Peter Lang.

Shapin, S. (1975). Phrenological knowledge and the social structure of early nineteenth-century Edinburgh. *Annals of Science*, *32*, 219–243.

Shermer, M. (2000). *How we believe: The search for God in an age of science.* New York, NY: W. H. Freeman.

Skinner, N. F., & Fox-Francoeur, C. A. (2010). Personality implications of adaption-innovation: V. Birth order as a determinant of cognitive style. *Social Behavior and Personality*, *38*, 237–240.

Srivastava, S., John, O. P., Gosling, S. D., & Potter, J. (2003). Development of personality in early and middle adulthood: Set like plaster or persistent change? *Journal of Personality and Social Psychology*, *84*, 1041–1053.

Stewart, J. A. (1986) Drifting continents and colliding interests: A quantitative application of the interests perspective. *Social Studies of Science*, *16*, 261–279.

Sulloway, F. J. (1996). *Born to rebel: Birth order, family dynamics, and revolutionary genius.* New York, NY: Pantheon.

Sulloway, F. J. (2001). Birth order, sibling competition, and human behavior. In H. R. Holcomb II (Ed.), *Conceptual challenges in evolutionary psychology: Innovative research strategies* (pp. 39–83). Dordrecht, Netherlands: Kluwer Academic.

Sulloway, F. J. (2007). Birth order and intelligence. *Science*, *317*, 1711–1712.

Sulloway, F. J. (2009). Sources of scientific innovation: A meta-analytic approach. *Perspectives on Psychological Science*, *4*, 455–459.

Sulloway, F. J. (2010). Why siblings are like Darwin's Finches: Birth order, sibling competition, and adaptive divergence within the family. In D. M. Buss & P. H. Hawley (Eds.), *The evolution of personality and individual differences* (pp. 86–119). Oxford, UK: Oxford University Press.

Sulloway, F J., & Zweigenhaft, R. L. (2010). Birth order and risk taking in athletics: A meta-analysis and study of major league baseball players. *Personality and Social Psychology Review*, *14*, 402–416.

Westman, R. S. (Ed.). (1975). *The Copernican Achievement.* Berkeley, CA: University of California Press.

Zajonc, R. B., & Sulloway, F. J. (2007). The confluence model: Birth order as a within-family or between-family dynamic? *Personality and Social Psychology Bulletin*, *33*, 1187–1194.

Zweigenhaft, R. L., & Von Ammon, J. (2000). Birth order and civil disobedience: A test of Sulloway's "born to rebel" hypothesis. *Journal of Social Psychology*, *140*, 624–627.