Arts Foster Scientific Success: Avocations of Nobel, National Academy, Royal Society, and Sigma Xi Members

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Various investigators have proposed that "scientific geniuses" are polymaths. To test this hypothesis, autobiographies, biographies, and obituary notices of Nobel Prize winners in the sciences, members of the Royal Society, and the U.S. National Academy of Sciences were read and adult arts and crafts avocations tabulated. Data were compared with a 1936 avocation survey of Sigma Xi members and a 1982 survey of arts avocations among the U.S. public. Nobel laureates were significantly more likely to engage in arts and crafts avocations than Royal Society and National Academy of Sciences members, who were in turn significantly more likely than Sigma Xi members and the U.S. public. Scientists and their biographers often commented on the utility of their avocations as stimuli for their science. The utility of arts and crafts training for scientists may have important public policy and educational implications in light of the marginalization of these subjects in most curricula.

Keywords: hobbies; music; writing; performing; painting; polymaths

What makes some scientists more creative than others? In 1878, J. H. van't Hoff, who would become the first Nobel Prize winner in Chemistry (1901), proposed that scientific imagination is correlated with creative activities outside of science (van't Hoff, 1967). His speculation was later repeated by several other Nobel laureates as well, including Santiago Ramon y Cajal (1951) and Wilhelm Ostwald (1909). Subsequent psychological studies have suggested that "geniuses" in all fields are much more likely to be more broadly talented than the average person. E. L. Thorndike (1911) concluded from his studies that

> Having a large measure of one good quality *increases* the probability that one will have more than the average of any other good quality. He who can learn better than average through his eyes, tends to learn better than the average through his ears also; he who can attend to one thing better than all other men, will be able to attend to many things at once or in rapid succession better than most of them. Artistic ability, as in music, painting, or literary creation, goes *with* scientific ability and matter-of-fact wisdom. The best abstract thinker will be above the average in concrete thought also. (pp. 26–27)

Similarly, White (1931) found that "geniuses" have a wider range of avocations carried out more intensively than the average college graduate, and Milgram and colleagues (1997) found that having at least one persistent and intellectually stimulating hobby is a better predictor for career success in any discipline than IQ, standardized test scores, or grades. It should be noted, however, that precocity in scoring very high on standardized tests such as the SAT also has recently been shown to be predictive of creativity and career success by Benbow and her collaborators (Lubinski & Benbow, 2006; Park, Lubinski, & Benbow, 2007).

While these general studies of successful people lend credence to van't Hoff's speculation, only three previous studies have directly addressed whether the most successful scientists are more likely to be polymaths than are less successful scientists. Cranefield (1966) examined a dozen scientists involved in the founding of biophysics during the mid-19th century and found a positive association between number of avocations and number of major discoveries. In another study of a convenience sample of 40 late 20th-century scientists, it was found that the most successful scientists (which included 4 Nobel laureates and 11 members of the U.S. National Academy of Sciences [NAS]) were significantly more likely to be engaged in a fine arts or a crafts avocation as an adult than were their less successful colleagues (Root-Bernstein, Bernstein, & Garnier, 1995). These results were confirmed in a larger study comparing Nobel Prize winners in Chemistry with the results of a survey of avocations of Sigma Xi (The Research Society) members (Root-Bernstein & Root-Bernstein, 2004).

METHOD

The present article extends the latter study to a comparison of all Nobel laureates between 1901 and 2005; all *Obituary Notices* and *Biographical Memoirs of the Royal Society* between 1932 and 2005; all *National Academy of Sciences (USA) Biographical Memoirs* between 1877 and 2005; a 1936 avocation survey of Sigma Xi members (Ward & Ellery, 1936) and a 1982 survey of arts avocations among the U.S. public (Survey of Public Participation in the Arts [SPPA], 1982). Information on the Nobel laureates was gathered from the *Obituary Notices* and *Biographical Memoirs* just mentioned (which covered only some laureates), as well as from the Nobel Prize Web site biographies and autobiographies (http://nobelprize.se), James (1993), and 45 English-language book-length biographies and autobiographies (covering 9% of the laureates). The average number of pages devoted to Royal Society (RS) obituaries was 17 pages; to National Academy of Sciences biographies, 23 pages; and to non–book-length sources for Nobel laureates, 12 pages. The average *sum* of non–book-length materials used for each Nobel laureate was about 19 pages. It is therefore unlikely that differences in the rates of avocations found among the different groups (see below) are due to more space being devoted to biographical details for one group than another. Even the use of book-length biographies for 9% of the Nobel laureates has no apparent relationship to the varied differences found between laureates and the other groups (see tables and figures).

Nobel laureates, NAS and Royal Society scientists were considered to have an arts or crafts avocation if they described themselves or were described by biographers as being a painter, photographer, actor, performer, composer, poet, dancer, craftsman, glassblower, and so on after entering college; if they took lessons in an art or craft as an adult; or if there was direct evidence of artwork, photographs, sculptures, compositions, poems, performances, and so on. People who were vaguely described in terms such as "having an artistic personality" or "having an avid interest in music" were not counted, and separate codings were made for evidence of collecting art, music, and so on, but were not included in the data analyzed in this article. These criteria may be somewhat stricter than the Sigma Xi data, in which all participants self-identified their avocations merely by categories that are vague enough to have included collectors among artists and avid gallery, theater, and concert-goers among painters and performers.

For purposes of this study, Sigma Xi is considered to be representative of scientists in general since any working scientist can become a member. Beyond membership criteria, three important differences exist between the groups studied. One is that Nobel laureates are international, whereas the Sigma Xi and National Academy of Sciences groups are mainly North American and the Royal Society, British. The current study does not control for cultural differences beyond comparing National Academy of Sciences and Royal Society data. Second, Nobel, National Academy of Sciences, and Royal Society data are scattered over time, whereas Sigma Xi and public arts data capture one time point each. Fortunately, the median age of Nobel laureates would have been 40 in 1936, the Royal Society members 47, and the National Academy members 59, placing this single time point close to the center of the professional life of scientists represented by each distributed data set. In addition, the distribution of avocations prior to and after 1936 was not significantly different in any of the distributed groups. The public arts data were the oldest relevant ones found for the U.S. population and are used despite their temporal inadequacy and the fact that no crafts data were gathered in that study. An extensive search for equivalent data for Great Britain (including contacting the director of census data) yielded nothing, so no appropriate control exists for the Royal Society data. Third, only 4,406 (10.3%) of the 42,525 Sigma Xi members in 1936 reported avocations whereas information was found for 78% of Nobel laureates and about 80% of the Royal Society and National Academy of Sciences members. In analyzing the data, the most conservative approach was therefore taken, assuming that the Royal Society, National Academy of Sciences, and Nobel data sets are complete (i.e., that the 20% of Royal Society and National Academy members and 22% of laureates for whom there is no avocation data had no avocations) and that the distribution of avocations among the 10% of Sigma Xi responders is typical of all Sigma Xi members (Sigma Xi Max in Figure 2). This strategy *minimizes* differences between the groups. The data have also been analyzed assuming that the 10% of Sigma Xi responders were the *only* members who had avocations (Sigma Xi Min in Figure 2). Reality is obviously somewhere between these extremes.

RESULTS

There are various ways to analyze these data, all of which show very significant relationships between success as a scientist and evidence of adult arts and crafts avocations. One measure is the average number of arts and crafts avocations among each group. Sigma Xi respondents had an average of 0.33 arts or crafts avocations (with the other reported hobbies distributed among various sports, numismatics, philately, gardening, etc.); the U.S. public, 0.35; Royal Society members, 0.59; National Academy of Sciences members, 0.56; and Nobel laureates, 0.94 (see Figure 1). In short, the typical Sigma Xi member was about equally likely to have an arts or crafts avocation as a typical member of the public, though the distribution of these avocations was different (see Figure 2). Our data confirm McClelland's (1962) finding that physical scientists enjoyed music but avoided art, poetry, plays, and most other arts, while also validating Terman's (1954) report that scientists' favorite arts-related avocation is photography. Nonscientists appear to enjoy writing poetry, performance arts, and visual arts to a significantly higher degree than the average scientist.

Eminent scientists have a different profile of arts and crafts interests than do typical scientists. The typical Royal Society and National Academy of Sciences member was almost twice as likely to have crafts avocations as the typical Sigma Xi member or the U.S. public. Nobel laureates were almost three times as likely to have arts and crafts avocations as Sigma Xi members and the U.S. public, and about 50% more likely to have such avocations than Royal Society or National Academy of Sciences members. There were no significant differences between the Sigma Xi or U.S. public, or between the Royal Society and the National Academy of Sciences data, but all the other possible

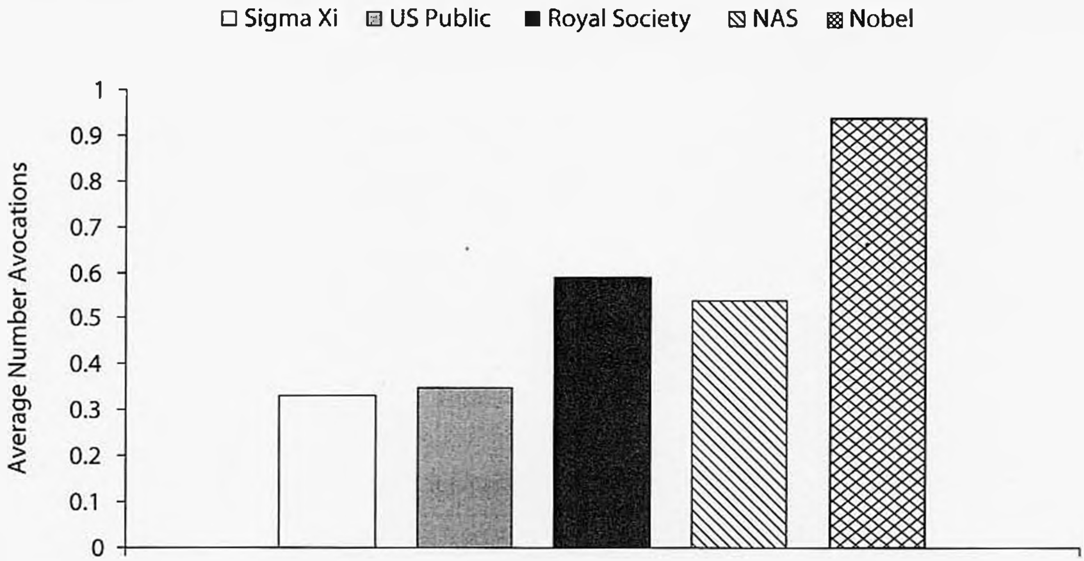

FIGURE 1. Average number of any art and craft avocation per group: Honored scientists, Sigma Xi members, and the U.S. public.

Note. Nobel Prize winners (1901–2005: 510 individuals); Royal Society biographees (1932–2005: 1,634 individuals); National Academy of Sciences (USA) biographees (1877–2005: 1,266 individuals); Sigma Xi members (1936: 4,406 individuals); and the U.S. public (1982: 4,250 individuals).

permutations were significant to $p < 0.0001$ using a two-tailed chi-squared analysis (Table 1). In addition, analysis of the data showed that Phi (a measure of the size effect that is equivalent to Pearson's r) showed a moderate size effect for overall number of arts and crafts avocations for Nobel laureates compared with all other groups (Table 1). These size effect differences were also confirmed by looking at the odds ratio, which is a measure of the probability that if one randomly chose a member of each of two groups, the two individuals would both be artists/craftspeople. Odds ratios were consistently above 10 for Nobel laureates compared with all other groups.

A more detailed analysis of the incidence of specific avocations yields equally significant differences between the various groups. The results (Figure 2) demonstrate that Nobel laureates are at least as likely (and as much as a factor of 8 more likely) to be photographers than the average scientist; at least a factor of 2 (and as much as 18) more likely to be a practicing musician, composer, or conductor; at least a factor of 7 more likely to be a visual artist, sculptor, or printmaker; at least a factor of 7.5 more likely to be a craftsperson engaged in woodwork, mechanics, electronics, glassblowing, and so on; at least a factor of 12 more likely to write poetry, short stories, plays, essays, novels, or popular books; and at least a factor of 22 more likely to be an amateur actor, dancer, magician, or other performer. These differences are highly statistically significant, in most cases to $p < 0.0001$ using a two-tailed chi-squared analysis. Royal Society and National Academy of Sciences members were significantly more likely ($p < 0.0001$) to have adult arts and crafts avocations than were Sigma Xi members, and Nobel laureates significantly more likely ($p < 0.0001$) than Royal Society and National Academy of Sciences members and the U.S. public (Figure 2).

Analyzing the data for size effects (phi) helped to sort out the most important of the significant differences. Phi values between 1 and 3 are considered to be small; between 3 and 5, moderate; and above 5, large. Moderate size effects were found for eminent musical scientists (Royal Society, National Academy, and Nobelists) as compared with the U.S. public; for eminent artistic scientists compared with Sigma Xi members; and for Nobel craftspeople versus Sigma Xi members. These data suggest that successful scientists accrue a wider range of skills, often including experience with a wide range of patterns, manipulative ability, and hand-eye coordination, than the average person or the average scientist. Such skills might improve experimental ability (see below) since D. W. Taylor (1963) found

TABLE 1. Comparing the Likelihood of Arts and Craft Avocations Among the U.S. Public, Members of Sigma Xi, Royal Society, National Academy of Sciences, and Nobel Laureates

	Ratio	Odds Ratio	Chi-Sq	p-value	Phi (r)
Public vs. Sigma Xi	1.06	1.09	0.18	0.67	.005
Royal Society vs. Sigma Xi	1.79	2.92	30.57	< 0.0001	.010
National Academy vs. Sigma Xi	1.70	2.57	23.93	< 0.0001	.065
Nobelists vs. Sigma XI	2.85	31.79	659.75	< 0.0001	**.366**
Royal Society vs. Public	1.69	2.68	25.30	< 0.0001	.066
National Academy vs. Public	1.60	2.36	19.39	< 0.0001	.059
Nobelists vs. Public	2.69	29.13	617.20	< 0.0001	**.360**
National Academy vs. Royal Soc.	0.95	0.88	0.37	0.55	.014
Nobelists vs. Royal Society	1.59	10.88	217.20	< 0.0001	**.318**
Nobelists vs. National Academy	1.68	12.34	256.03	< 0.0001	**.380**

Note. Ratios are the proportion of members in each group that had at least one avocation or hobby as compared with a corresponding group. Odds ratio is the probability that one would find an artist/craftsperson by randomly selecting a person from the first group as compared with selecting a person at random from the second group. *P*-values are the probability that the difference reported is due to chance. Phi values are a measure of effect size related to Pearson's *r*. In general, effects less than 0.3 are considered small; effects between 0.3 and 0.5 are moderate; and effects greater than 0.5 are large. The Phi values greater than 0.3 are indicated in bold.

that knowledge of tools was correlated with creativity among research physicists. In addition, moderate to large size effects were found for eminent scientific writers and performers compared to most other groups. These data strongly suggest that a critical component of scientific success may be the development of, and enjoyment in using, well-honed communications skills (see below), which is consistent with C. W. Taylor's (1963) observation of a relationship between communication skills and creativity among scientists. The most successful scientists are far more likely to write and perform for the public than are less successful scientists. Presumably, these skills make them better scientific communicators as well, so that their results may be presented in clearer and more compelling ways than those of competitors, and reach a wider audience.

Save for the visual arts, there were no significant differences between the National Academy of Sciences and Royal Society results, suggesting that culture and educational curricula may have little effect on this phenomenon. The set of avocational interests displayed by eminent scientists in the United States and in Great Britain is virtually identical. It would, however, be interesting to compare such data with avocational interests of scientists in non-Western nations.

These data clearly demonstrate the relationship between effective scientific imagination and nonscientific creativity that van't Hoff proposed. Very successful scientists are much more likely to be polymaths than the average scientist. What these data cannot show is the quality of the arts and crafts produced by these scientists. For present purposes it may suffice to list some of the scientists who have had second careers as professional or semiprofessional fine artists, published fiction writers (novelists, short-story writers, playwrights, and poets), or who gave public musical performances (see Table 2; see Appendix for a list of currently available Web sites featuring the art of some of these scientists). (The list of Nobel laureates and National Academy of Sciences and Royal Society members who have published popular science books is so large as to be beyond the scope of this article.) It is worth noting Roald Hoffmann's comment: "It should be said that building a career in poetry is much harder than in science. In the *best* chemical journal in the world the acceptance rate for full articles is 65%, for communications 35%. In a *routine* literary journal, far from the best, the acceptance rate for poems is below 5%" (Hoffmann, n.d.). Similarly, it is worth bearing in mind the constant practice that is required to perform music at even a high amateur level or to produce artwork of sufficient quality to be exhibited publicly. The artistic scientists being described here are not mere dilettantes.

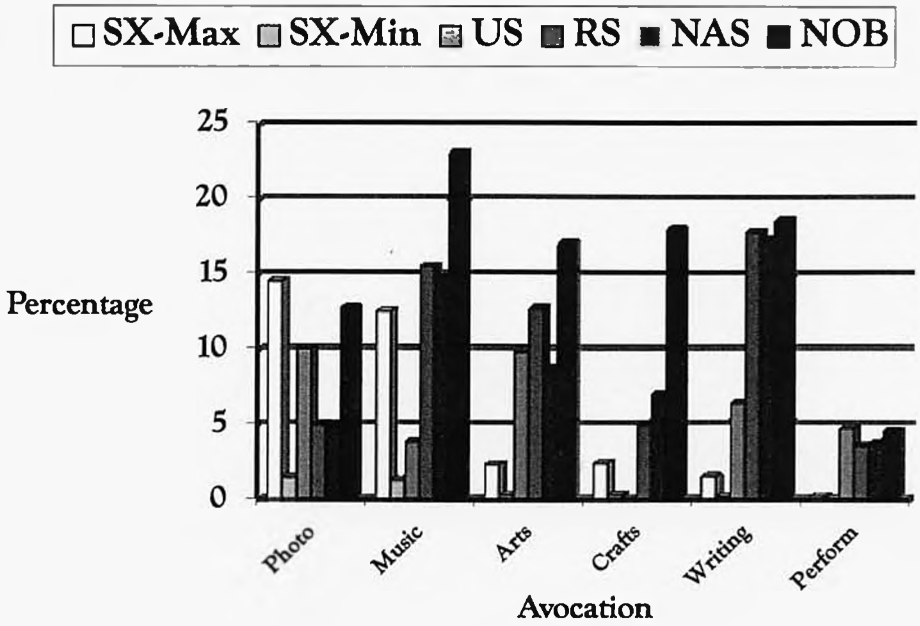

FIGURE 2. Percentages of adults in specific arts and crafts avocations: Honored scientists, Sigma Xi members, and the U.S. public.

Note. SX = Sigma Xi; Max = Maximum; Min = Minimum; US = U.S. Public; RS = Royal Society; NAS = National Academy of Science; NOB = Nobel Laureate.
All differences between Nobel laureates and Sigma Xi Max data were significant to $p < 0.0001$ save for the photography category, which was not significantly different ($p = 0.26$). All differences between laureates and Sigma Xi Min data were significant to $p < 0.0001$. All differences between laureates and the U.S. public were significant to $p < 0.0001$ save for the photography and performing categories ($p = 0.04$ for both). The corresponding author will be happy to provide the statistical analyses of all the possible combinations of the data in the table to anyone who requests it.

DISCUSSION

These data can help to address the issue of whether very successful scientists are simply genetically endowed with an unusually broad range of unrelated talents; whether they are imbued with extraordinary energy and the drive to excel at everything they do; whether their arts and crafts avocations are simply reflections of their scientific skills; or whether avocations develop skills and knowledge of use to them as scientists. Undoubtedly, each of these factors plays some role in the phenomenon described by our data, but probabilistically speaking, it is noteworthy that increasing success in science is accompanied by developed ability in other fields such as the fine arts. If one were to assume that talent in individual fields or domains segregates independently, then the greater the degree of talent exhibited in one field, the less probable it would be to find developed talent in any other discipline. Our data show the reverse. Similarly, if the development of talent in one discipline or domain is independent of the development of talents in other disciplines or domains, then it would seem logical that the degree of energy and persistence required to gain ever-higher levels of success in science would be inversely proportional to the amount of energy left over to explore avocational talents in arts and crafts. Again, our data show the opposite. If, however, there exist functional connections between scientific talent and arts, crafts, and communications talents so that inheriting or developing one fosters the other(s), then it would make sense that very talented scientists would exploit their talents through related avocations. The existence of such a connection is consistent with our data.

Previous research is also consistent with the idea that vocational and avocational skills and knowledge interact positively among the most eminent scientists. It has been shown that innovative scientists develop "correlative talents" (Root-Bernstein, 1989) that combine their vocations and avocations into what have been variously called "integrated activity sets" (Dewey, 1934) or "networks of enterprise" (Gruber, 1984, 1988). These terms describe the ability of creative scientists to explore a wide range of apparently unrelated activities and to connect the knowledge and skills gained thereby into integrated networks

TABLE 2. Scientists Who Publicly Exhibited and/or Sold Visual Art or Sculpture, Published Works of Fiction, or Publicly Performed Musical Pieces

Visual Art/Sculpture	Published Fiction	Performed Musical Pieces
Frederick Banting (NP)	Hannes Alfen (NP)	Walter Cannon (NAS)
Charles Best (RS)	Fritz Haber (NP)	Ernst Chain (NP)
Homi Bhabha (RS)	J. B. S. Haldane (RS)	Manfred Eigen (NP)
William Henry Bragg (NP)	Archibald Hill (RS)	Albert Einstein (NP)
Harold ("Doc") Edgerton (NAS)	Roald Hoffmann (NP)	Stephen Jay Gould (NAS)
Richard Feynman (NP)	Fred Hoyle (RS)	Werner Heisenberg (NP)
Alexander Fleming (NP)	Arthur A. Noyes (NAS)	Martin Kamen (NAS)
Henry Kendall (NP)	J. Robert Oppenheimer (NAS)	Jacques Monod (NP)
Walter Gilbert (NP)	Wilder Penfield (NAS)	Wilhelm Ostwald (NP)
Roger Guillemin (NP)	J. R. Pierce (NAS)	Max Planck (NP)
Alister Hardy (RS)	Santiago Ramon y Cajal (NP)	Edmund Wilson (NAS)
Sir Cyril Hinshelwood (NP)	W. J. M. Rankine (RS)	
Johannes Holtfreter (NAS)	Charles Richet (NP)	
Francois Jacob (NP)	Ronald Ross (NP)	
Harold Kroto (NP)	Charles Sherrington (NP)	
Andre Lwoff (NP)	Carl Sagan (NAS)	
Albert Michelson (NP)	C. P. Snow (RS)	
C. H. Waddington (RS)	Leo Szilard (NAS)	
Robert R. Wilson (NAS)	Niko Tinbergen (NP)	
Robert W. Wood (NAS)	Gordon Willey (NAS)	
	Robert W. Wood (NAS)	

Note. NP = Noble Prize; NAS = National Academy of Sciences; RS = Royal Society.

that can be brought effectively to bear in raising and solving important scientific problems. Gruber (1984, 1988) has provided a classic example of how such networks of enterprise were used by Charles Darwin when he drew together his interests in hunting, collecting, travel, paleontology, geology, geography, zoology, botany, agriculture, breeding, and economics to generate the integrative concept of evolution by natural selection. Cranefield made a similar argument regarding cultural influences on the number, quality, and integrative nature of discoveries made by early biophysicists such as Hermann von Helmholtz and Emil du Bois Reymond (Cranefield, 1966).

This phenomenon of exploring diverse interests and talents that are subsequently integrated into one's scientific creativity is common enough that Ramon y Cajal argued its necessity. Rather than preferring monomaniacally dedicated specialists, he therefore advised those trying to identify scientific talent to choose, "those students who are somewhat headstrong, contemptuous of first place, insensible to the inducements of vanity, and who being endowed with an abundance of restless imagination, spend their energy in the pursuit of literature, art, philosophy, and all the recreations of mind and body. To him who observes them from afar, it appears as though they are scattering and dissipating their energies, while in reality, they are channeling and strengthening them. . . . The investigator would possess something of this happy combination of attributes: an artistic temperament which impels him to search for, and have the admiration of, the number, beauty, and harmony of things" (Ramon y Cajal, 1951, pp. 170–171).

Following Ramon y Cajal's lead, many Nobel Prize winners (NP) and members of the RS and NAS have explicitly commented on how avocations develop useful skills: hand-eye coordination; knowledge of tools and processes; better visual imagination; improved ability to communicate using words, images, and models; the stage presence of the practiced performer; and a refined scientific aesthetic sensibility

(Root-Bernstein, 1989, 2000, 2001, 2003; Root-Bernstein & Root-Bernstein, 2004; Root-Bernstein, Bernstein, & Garnier, 1995; van't Hoff, 1967). A brief survey of relevant comments follows.

Peter Mitchell (NP) noted that, "Most [scientists] who try to be creative, I think, have found that they've got to become craftspeople as well as art people" (Wolpert & Richards, 1997). This was certainly true of artist-craftsman Charles Minot, whose "mechanical ability aided him greatly in his delicate work with the microscope."[1] Carl Weiman (NP) attributed some of his success to similar talents: "I think that much of my talent and enjoyment at improvising solutions to experimental problems goes back to those homebuilt projects. . . . Carrying out these individual projects also developed in me a good sense of self-reliance and a sense when a piece of improvised apparatus was likely (or unlikely) to be adequate. This sense is one that I often see missing in students whose education has been confined to formal instruction." Similarly, Robert Laughlin (NAS) recounts that,

> I, for example, used to take appliances apart when they broke in an attempt to fix them, which I rarely did successfully, being a kid. I am better at this now. It was through such creative play that I first learned about pump impellers, refrigerant cycles, material strength, corrosion, and the rudiments of electricity, and more importantly the idea that real understanding of a thing comes from taking it apart oneself, not reading about it in a book or hearing about it in a classroom. To this day I always insist on working out a problem from the beginning without reading up on it first, a habit that sometimes gets me into trouble but just as often helps me see things my predecessors have missed.

Henry Kendell (NP), a pioneer of underwater salvaging and photography, noted that, "These activities, mostly self-taught, were a good introduction to two skills very helpful in later experimental work: seeing projects through to successful conclusions and doing them safely." W. H. Bragg (NP), W. L. Bragg (NP), Maurice Wilkins (NP), Luis Alvarez (NP), Walter Hess (NP), Bruce Merrifield (NP), Steven Chu (NP), Martin Perl (NP), and Barry Marshall (NP) are among the many others who attributed their scientific success to crafts avocations.

Fine arts also develop skills of value to scientists. J. H. van't Hoff (NP) (1967), Wilhelm Ostwald (NP) (1909), Santiago Ramon y Cajal (NP) (1951), and Max Planck (NP) all argued in Planck's words that, "The pioneer scientist must have . . . [an] *artistically* creative imagination" (Planck, 1949, p. 8). For example, in her book *The Mind and the Eye,* Agnes Arber (RS) maintained that drawing is as important as words for learning about and communicating scientific knowledge. Like Arber, William Brooks (NAS), Santiago Ramon y Cajal (NP), and Howard Florey (NP) were among many who believed that that which had not been drawn had not been seen. Artist-dancer-poet C. H. Waddington (RS) expanded on this theme in his book *Behind Appearance: A Study of the Relations Between Painting and the Natural Sciences in the 20th Century.* He advocated David Bohm's (RS) philosophy that creative process is a transdisciplinary link between the sciences and arts (cf., Bohm & Peat, 1987). For Waddington, understanding how art was made was a way to understand his own field of embryology, because, "An art object is always an *instruction,* to do or to experience, not a piece of information; and living things are organized instructions, not organized information" (Waddington, 1972, p. 37). For similar reasons, artistic processes and themes pervaded the way in which Robert R. Wilson (NAS) designed and invented cyclotrons: "In designing an accelerator I proceed very much as I do in making a sculpture. I felt that just as a theory is beautiful, so, too, is a scientific instrument—or that it should be. The lines should be graceful, the volumes balanced. I hoped that the chain of accelerators, the experiments, too, and the utilities would all be strongly but simply expressed as objects of intrinsic beauty" (Wilson, 1992). "One thing is clear," Wilson once wrote, "it is that there is much in common between what the creative artist does and what the scientist does" (Wilson, 1978).

Some artistic scientists also found connections between the content of their arts and their scientific research. Ostwald (NP), a painter, invented a widely employed color theory and taught at the Bauhaus design school in Germany. Similarly, Ogden Rood (NAS) focused his vocation and avocation on the "numerous themes that lie in the middle ground between physics and painting." His book *Modern Chromatics* influenced both physicists and impressionist painters. Gabriel Lippmann (NP), Dennis Gabor (NP), and Harold ("Doc") Edgerton (NAS) combined their love of photography and physics to revolutionize both by developing novel photographic techniques that were simultaneously used for artistic purposes.

Musician-scientists have found similar conjunctions. James Jeans (RS) translated his musical proclivity into studies of how different musical instruments produce their characteristic sounds, resulting in his classic book *Science and Music,* while Georg von Bekesy (NP) translated his musical talent into studies of how the human ear functions. Walther Nernst (NP) invented some of the first electronic instruments while J. R. Pierce (NAS) combined his electronics expertise with his musical ability to develop the first computers capable of making music. Pierce eventually became a professor of music at Stanford University's Center for Computer Research in Music and Acoustics. Victor Benioff (NAS) combined his interests in music and crafts to design electronic violins, cellos, and pianos, the latter produced by the Baldwin Piano Company.

As with the visual arts, the connections between music and science are not always so direct. Jesse Greenstein (NAS) believed that musical problems could inform scientific ones, "[Suppose] someone is getting interested in musical problems. He may then apply what he finds there back to his scientific research. That's something which may affect very much the result. I think it's good" (Root-Bernstein, Bernstein, & Garnier, 1995, p. 126). Indeed, Boris Chain (NP), and Charles Martin Hall each found playing piano a source of scientific inspiration (Root-Bernstein, 2001) and Albert Einstein (NP) not only played whenever he came to a mathematical dead end (Suzuki, 1969, p. 90), but also asserted that, "The theory of relativity occurred to me by intuition, and music is the driving force behind this intuition. . . . My new discovery is the result of musical perception" (Curtin, 1982, p. 84). Richard Feynman (NP), a talented drummer, may have used similar perceptions, since he reported solving scientific problems using "acoustic images" (Root-Bernstein, Bernstein, & Garnier, 1995).

Words, too, are scientific tools. William Phillips (NP) writes that "in retrospect, I can see that the classes that emphasized language and writing skills were just as important for the development of my scientific career as were science and math." Roald Hoffmann (NP) elaborates: "I write poetry to penetrate the world around me, and to comprehend my reactions to it. . . . By being a natural language under tension, the language of science is inherently poetic" (Hoffmann, 1988, p. 10). James Swinburne (NAS)—a "polymath if there ever was one"—illustrated Hoffmann's point when naming a lacquer *Damard* because it was "Damn Hard" and inventing the words *rotor* and *stator* to describe two of his most important inventions. Swinburne reminds us that scientific inventors often add to language as well as to science. And the literary creative process, like that in the visual arts and music, is also viewed by some scientists, such as Peter Medawar (NP), as being transdisciplinary: "the kind of creative process that generates on the one hand poetry as ordinarily understood is also that which operates in the context of science, generating laws and explanations and all else that we recognize as the furniture of scientific thought" (Medawar, 1990, p. 90). Medawar believed that to master one creative process is to have insight into all.

Given such creative connections, it is not surprising to find that many scientists use aesthetic considerations to inform their science (Chandrasekhar, 1987; Curtin, 1982; Medawar, 1990; Root-Bernstein, 1999). Albert Michelson (NP) wrote that he was drawn to physics by the beauty of light: "The aesthetic side of the subject is, I confess, by no means the least attractive to me. Especially is its fascination felt in the branch which deals with light. And I hope the day may be near when a Ruskin will be found equal to the description of the beauties of coloring, the exquisite graduations of light and shade, and the intricate wonders of symmetrical form" (Michelson, 1903, pp. 162–163). Similarly, for organic chemist Robert Woodward (NP), the sensual aspects of the subject were its primary draw: "It is the *sensuous* elements which play so large a role in my attraction to chemistry. I love crystals, the beauty of their form—and their formation; liquids, dormant, distilling, sloshing!; swirling, the fumes; the odors—good and bad; the rainbow of colors; the gleaming vessels of every size, shape, and purpose. Much as I might *think* about chemistry, it would not exist for me without these physical, visual, tangible, sensuous things" (Woodward, 1984, p. 137). C. T. R. Wilson (NP) invented his cloud chamber in order to reproduce the beauty of the coronas and glories he witnessed while mountain climbing. William Lipscomb (NP) comments that such beauty also drew him into science: "I have seen the glory effect, and have made a Wilson cloud chamber when I was a youth. Both effects are beautiful indeed" (Curtin, 1982, p. 1). He went on to say of his Nobel Prize–winning work: "I would certainly not separate aesthetics from science . . . the processes that I used and the responses that I felt were more like those of an artist [than a scientist]" (Curtin, 1982, p. 20) Robert R. Wilson (NAS) agreed, arguing that, "most of the effort of [cyclotron] design is intuitive, that aesthetics are indeed a valuable and necessary guide in any design process, that these very human qualities are an important part of physics and give to physics a quality of humanness" (Wilson, 1978). And for very similar reasons, Georg von Békésy (NP), "a true Renaissance man . . . studied art not only for the great pleasure it gave him, but also for an effect that he believed it would have on his mind. Comparing one art object with another to determine quality and authenticity, he thought, greatly improved his ability to make judgments about the quality of scientific work too . . . there is no question that art pervaded all of Békésy's science."

Some of these scientists and their biographers have even made explicit the concept of integrated networks of enterprise. Harry Hess's (NAS) biographer wrote that, "These [apparently] separate activities intermeshed and complemented each other . . . every thread of activity and research interest . . . imperceptively interwoven with time into a pattern of increasing breadth, color, and complexity." William Dalby's (NAS) biographer similarly commented, "hobbies were barely distinguishable from scientific research" and Karl Ziegler's (NP) that his avocations "undoubtedly contributed to his success" (James, 1993, p. 454). For these scientists, science is only part of being human, not the end-all and be-all of their existence. Thus, we find Roald Hoffmann (NP) saying that, "Writing, 'the message that abandons,' has become increasingly important to me. I expect to publish four books for a general or literary audience in the next few years. Science will figure in these, but only as a part, a vital part, of the risky enterprise of being human" (Hoffmann, n.d.).

The relationship between scientific success and arts and crafts talents documented here, combined with the evidence of functional integration between disciplines, suggest that current science curricula may need to be broadened. As several of the scientists noted above, purely academic skills are not sufficient to train a person for creative scientific work. Such creative work requires the entire range of abilities subsumed in the arts and crafts, integrated and focused on specific scientific problems and techniques. To train the best scientists may therefore require what is often called a "liberal arts education." This is not a new conclusion. W. H. Bragg (NP) argued in the first half of the 20th century that arts and crafts stimulate scientific development (e.g., *Old Trades and New Knowledge*) and his son, W. L. Bragg (NP), concluded in a 1942 report for the Royal Society that, "The training of our physicists is literally too academic" (Bragg, 1942, p. 79).

In a 1947 poll, the starred scientists in *American Men of Science* agreed: while 74% reported little (35%) or no (39%) fine arts training, 80% strongly recommended fine arts training as an essential component of scientific education (Visher, 1947). Our data provide the first rigorous basis for their opinions.

Notably, the results and interpretation provided above are consonant with the trend of psychological research into personality factors that are associated with creativity in general. One of the best correlates of demonstrated creativity is openness to experience (Chamorro-Premuzic & Furnham, 2005; McCrae, 1987). Openness to experience is one of the major domains defined within the Five-Factor Model (Goldberg, 1993; McCrae & John, 1992), and it is characterized by an unusual degree of curiosity, desire for learning, puzzle solving, and a desire to think carefully about ideas. Having a diversity of avocations and hobbies is often related to openness to experience (reviewed in Chamorro-Premuzic & Furnham, 2005). It follows that avocations and hobbies should be related to creativity as we have demonstrated here.

One can go on to ask why successful scientists are more likely to be open to novel experiences than the average scientist. One possibility, as Simonton has conjectured (Simonton, 1988), is that successful scientists were exposed to a wider range of cultural experiences as children and adolescents, and that these early experiences helped to create their desire for wide intellectual experiences later in life. Certainly, the Goertzels (1962, 1978) have shown that successful people often grow up in families that provide access to an unusually broad range of intellectually stimulating activities to their children. Simonton (1988) has gone on to conjecture that such openness-seeking families are economically more well-to-do than average, but there appears to be no hard evidence on this matter at present. It seems possible that cultural *values* may play at least as large a role in avocational availability as socioeconomic factors, given the extraordinarily small proportion of Catholic Nobel laureates compared with population, and extraordinarily large proportion of Jewish laureates (e.g., Zuckerman, 1977).

Finally, one might ask whether broad avocational interests, openness to novel experiences, and creativity are simply functions of general intelligence. This is almost certainly not the case. Eminent scientists do not differ in IQ (as measured by various tests) from their less-successful colleagues (e.g., Cole & Cole, 1973; MacKinnon & Hall, 1972; Roe, 1966; Root-Bernstein, Bernstein, & Garnier, 1993). MacKinnon (1962) argued from his studies that above an IQ of about 120, creative ability is determined by nonintellective factors, and Terman (1954) found no relationship between high IQ and creativity in his longitudinal studies of people with IQs above 135. Indeed, among Nobel laureates who have revealed their IQ test scores, Richard Feynman reported that his IQ was 126 (Gleick, 1992); James Watson, 124 (Watson, 1968); William Shockley, 125 (Shurkin, 2007); and Luis Alverez's was below 135 (he did not qualify for Terman's "genius" study [Alvarez, 1987]). Similarly, Hudson found that the vast majority of the high IQ boys whom he studied showed very distinct preferences to either sciences or arts and humanities, but rarely both (see also Park et al., 2007). Notably, however, Hudson (1966, pp. 135 ff) found that there were a small group of what he called "hybrids" or "well adjusted all-rounders" who had the ability to be both scientists and artist-humanists and who were often the most creative boys in his study. These "hybrids" did not differ in IQ or standard scholastic test scores from the other boys in his study. They differed simply in the unusually balanced nature of their abilities. Maslow (1959) has described such adults as "self-actualizing" and attributes their high degree of creativity to their ability to integrate the fullest range of their talents, a conclusion in line with the discussion of "integrated networks of enterprise" above. Thus, for people with normal or above normal intelligence, polymathy (M. Root-Bernstein, 2008; R. Root-Bernstein, 2008; Root-Bernstein & Root-Bernstein, 1999, 2004)—which is to say, a balance of abilities, as indicated by a range of avocations practiced at an intensive level, or high scores on both the verbal and mathematical portions of SAT tests, or a range of well-developed "multiple intelligences"—might be a better indicator of potential creativity than IQ per se.

It follows from these general psychological considerations that the equation between sciences and the arts and crafts appears to be commutative among very creative people. An informal and incomplete study of Nobel laureates in Literature shows that at least 20% had formal training in science or engineering and some worked professionally in these fields (Root-Bernstein & Root-Bernstein, 2004). The pioneers of kinetic sculpture, Naum Gabo, George Rickey, and Alexander Calder, were all trained as engineers, and although their colleague, Jean Tinguely, lacked such formal training, he had begun inventing mechanical devices as a teenager (R. Root-Bernstein, 2008). Similarly, an unexpectedly large number of modern composers have science and engineering backgrounds, including four of the great Russian "Mighty Five"—Aleksandr Borodin, Modest Mussorgsky, M. A. Balikirev, and Cesar Cui (the fifth being Rimsky-Korsakov). Other scientifically and mathematically trained composers who revolutionized 20th-century music include George Antheil, Lajaren Hiller, Iannes Xenakis, Ernest Ansermet, and Joseph Schillinger. Edward Elgar had several chemical patents. Camille Saint-Saens was an amateur astronomer (Root-Bernstein, 2001). Further exploration of such cases may reveal that the deep divide that C. P. Snow described in his influential book *The Two Cultures* may not exist for the most creative people in any discipline and such a finding might, in turn, transform how we educate for creativity and our potential to reach E. O. Wilson's *Consilience: The Unity of Knowledge* (1998).

NOTE

1. Unless otherwise cited, information on Nobel laureates can be found at http://nobelprize.org and all quotes for NAS and RS members are from the respective *Biographical Memoirs*, which are online at http://www.nasonline.org/site/PageServer?pagename=MEMOIRS_A and http://www.journals.royalsoc.ac.uk/content/120177/

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APPENDIX

Biographical Memoirs (available on JSTOR) and some currently available Web sites featuring art and photographs by Nobel laureates, and National Academy and Royal Society members mentioned in this article:

Frederick Banting (Noble Prize): http://www.ntpl.ca/ws_par/banting/main.html

Walter Gilbert (Noble Prize): http://wallygilbert.artspan.com http://wallygilbert.30art.com http://www.wallygilbert.co.uk

Roger Guillemin (Noble Prize): http://www.holborngallery.com/guillemin-main.html http://www.duganne.com/gallery.html

Sir Cyril Hinshelwood (Noble Prize): Hartley, H. The Exhibition of Sir Cyril Hinshelwood's Paintings at Goldsmiths' Hall on 20 March, 1968. *Notes and Records of the Royal Society of London*, 23(1) (June 1968), 23–28.

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An Appreciation on His Retirement from the Editorship of 'Notes and Records'. *Notes and Records of the Royal Society of London*, 26(1) (June 1971), 1–2.

Henry Kendall (Noble Prize): http://library.stanford.edu/depts/ssrg/misc/sac2-ntb.htm

Harold Kroto (Noble Prize): http://www.kroto.info/Graphics/index.html

Albert Michelson (Noble Prize): http://www.usna.edu/LibExhibits/Michelson/Michelson_personal.html

Wilhelm Ostwald (Noble Prize): http://home.arcor.de/wilhelm-ostwald/ostweng/engener2.htm http://hometown.aol.de/ostwaldenergie/index.htm?f=fs http://www.nature.com/nature/journal/v425/n6961/full/425904a.html

Charles Best (Royal Society): http://www.ntpl.ca/ws_par/banting/database/000167e.html

George E. Briggs (Royal Society): Robertson, R. George Edward Briggs. 25 June 1893–7 February 1985. *Biographical Memoirs of Fellows of the Royal Society*, Vol. 32 (December 1986), p. 59.

Alister C. Hardy (Royal Society): http://www.sahfos.ac.uk/parables/start1.htm http://www.sahfos.ac.uk/parables/start14.htm

Herbert M. Powell (Royal Society): McLauchlan, K. A. Herbert Marcus Powell. 7 August 1906–10 March 1991. *Biographical Memoirs of Fellows of the Royal Society*, Vol. 46 (November 2000), p. 426.

Charles Piazzi Smyth (Royal Society): http;//www.nmm.ac.uk/collections/search/listResults.cfm?maker=Charles%20Piazzi%20Smyth&sortBy=maker

Robert R. Wilson (National Academy of Sciences): http://history.fnal.gov/sculpture.html http://www fnal.gov/pub/about/campus/sculptures.html http://www.fnal.gov/pub/ferminews/ferminews00-01-28/sculpture.html http://upload.wikimedia.org/wikipedia/en/8/82/Topological_III_by_Robert_R._Wilson%2C_at_Harvard_University.JPGhttp://www.sciencenews.org/articles/20000902/mathtrek.asp