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Correlations Between Avocations, Scientific Style, Work Habits, and Professional Impact of Scientists

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ABSTRACT: Forty male scientists (including 4 who eventually won Nobel prizes) were interviewed four times between 1958 and 1978 concerning their work habits, use of time, hobbies, attitudes toward the arts and humanities, scientific attitudes, and related issues. The 38 who were still alive in 1988 then filled out a questionnaire concerning their use of various forms of thinking (e.g., verbal, visual, kinesthetic), their avocations, forms and extent of physical exercise, and when they were most likely to have significant scientific insights (e.g., while working on a problem directly, while working on other problems, while relaxing, on waking). The questionnaire and interview information was then collated and statistically analyzed with regard to the impact of each scientist to determine if any correlations exist between scientific success and avocations, preferred modes of thinking, use of time, energy, or related factors. Significant correlations were found between scientific success and particular modes of thinking (especially visual ones), between success and various hobbies (especially artistic and musical ones), between particular hobbies and use of particular modes of scientific thinking, between success and having a broad range of avocations and forms of physical exercise, and between success and the efficient use of time to manage many competing vocational and avocational demands. We conclude that successful scientists have highly integrated networks of enterprise, whereas less successful colleagues tend to have fewer nonscientific activities that they do not integrate. They develop nonfunctional networks of enterprise in which activities compete against, rather than sustain, each other.

Despite several decades of research into the psychology of scientists, little is known about the influence of particular skills and work habits on an individual's success in science. Most studies have attempted to find correlations between scientific achievement and scores on standard psychological tests

We dedicate the research reported in this article to the memory of the late Bernice T. Eiduson. We thank her husband, Samuel Eiduson, for permission to continue the study.

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such as the Thematic Apperception Test (TAT), the Rorschach, or various measures of intelligence such as the Miller's Analogies Test. The resulting correlations are rarely significant and generally fail to distinguish successful from unsuccessful scientists (Eiduson, 1962; Gardner, 1993; McClelland, 1962; Mitroff, 1974; Root-Bernstein, Bernstein, & Garnier, 1993). In general, previous studies have shown that successful scientists are no more intelligent than their less successful colleagues, and they display just as wide a variation of psychological profiles. Thus, testing for the psychological makeup of individual scientists has proven to be of little practical value to those who might wish to be able to spot emerging talent, hire the most innovative scientists, or better train individuals whose personal qualifications predict success.

We have approached the subject of determinants of scientific success from a different angle. A variety of sources suggest that correlations might exist between such apparently inconsequential factors as an individual's preferred hobbies; his or her verbal, visual, or kinesthetic skills; style of working; degree of physical and mental energy; and ability to invent and solve particular types of problems. Hints of such correlations can be found in the autobiographical and analytical writings of many successful scientists who have had the opportunity of observing hundreds or thousands of students and colleagues. For example, Santiago Ramon y Cajal (1937), a neuroanatomist who was one of the first Nobel Prize winners in Medicine of Biology, asked:

> Are future scientists ... to be found by chance among the most serious students who apply themselves, the winners of prizes and the winners of competitions? At times, yes, but not always. ... A good deal more worthy of preference by the clear-sighted teacher will be 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. (p. 171)

In short, Ramon y Cajal believed that successful scientists were drawn from the ranks of the energetic polymaths. Charles Richet, another Nobel laureate agreed: "Generally those who later become illustrious [in science] have shown from the first, by their aptitude for history, science, literature, languages, that they were superior to their contemporaries" (1927, p. 128). Similar conclusions have been reached by many other eminent scientists such as Paul Bert, Pierre Duhem, David Nachmansohn, Gerald Holton, and Mitchell Wilson, who go on to make the point that the entire complex of skills and experiences that we call personality will be reflected in the specific form that individual scientists's discoveries will take (Bernard, 1927/1957, p. xix; Holton, 1973, 366–374; Duhem quoted in Lowinger, 1941, p. 1, n. 3; Nachmansohn, 1972, p. 1; Wilson, 1972, pp. 12, 316). We might therefore expect that the most eminent scientists will be unusually talented and may learn from literature, art, music, and other hobbies or interests, important mental tools such as mental visualization, pattern forming, modeling, and not least of all playing, that are useful for manipulating and transforming ideas (Koch, 1978; Root-Bernstein, 1984, 1985, 1987, 1989; van't Hoff, 1878/1967; Wilson, 1972). They may also learn from their many activities how to manage their time particularly effectively.

Only a handful of psychological studies have thus far supplemented the anecdotal evidence that specific modes of thinking, styles of research, and hobbies or skills may be related to scientific creativity or success. On the question of research style, Platt and Baker (1931) found in a survey of chemists that the majority reported solving their problems either when working on another problem or while engaged in nonscientific or relaxing activities. This result clearly argues for the notion that scientific work often goes on outside the laboratory and that successful scientists are capable of handling several activities simultaneously. This hypothesis was given further support by Finkelstein, Scott, and Franke (1981), who found a strong positive correlation between the number of different activities (such as multiple research projects, consulting contracts, directorships, and so forth) that engaged a scientist and his or her probability of producing innovative science. Taken together, these two studies suggest that multiple interests combined with excellent time management are crucial to scientific success.

Other studies, when taken together, suggest that successful scientists are also unusual in their energy, range of hobbies, and modes of thinking. Surveys of broad groups of scientists and engineers have shown that they generally dislike and avoid the arts, poetry, and music (Deutsch & Shea, Inc., 1957; McClelland, 1962). On the other hand, Francis Galton (1874, 1892) found that the majority of Fellows of the Royal Society (London) whom he surveyed had a multitude of mechanical and musical skills and avocations, took great interest in literary and dramatic arts, and were unusually energetic both mentally and physically. Möbius (1900) and Ostwald (1909) corroborated Galton's findings in subsequent studies of eminent mathematicians and physical scientists. R. K. White (1931) reviewed the lives of 300 historical "geniuses" (including 38 mathematicians and scientists) and found that the scientists in the study, like "the typical genius surpasses the typical college graduate in range of interests and ... He surpasses him in range of ability" (p. 482). Jacques Hadamard (1945) and Anne Roe (1951, 1953) found that successful scientists use an unusually wide range of mental skills, including verbal, mathematical, visual, kinesthetic, and other nonverbal forms of thought. Eugene Ferguson, Winston Koch, and Brook Hindle argued similarly that visual and other nonverbal forms of thought are critical for success as an inventor (Ferguson, 1977, 1993; Hindle, 1981, 1984; Koch, 1978). Although Hadamard and Roe did not address the origins of these mental skills, both Hindle and Ferguson related them directly to experience with artistic and mechanical training. Thus, it is not surprising to find that D. W. Taylor (1963) reported that one of the few correlates to success as a physical scientist in an industrial setting is prior skill using tools. C. W. Taylor (1963) argued, on the other hand, that a relation between verbal communications skills and creativity seems to exist. In sum, the hypothesis that styles of thinking are related to hobbies and skills, and that these aptitudes are in turn related to scientific success, seems plausible but is far from being demonstrated.

Method

To test whether hobbies, habits of thinking, or other skills correlate with scientific style and success, data collected by the late

Bernice T. Eiduson on a group of 40 scientists were reexamined. Eiduson began collecting data, interviewing, and testing the scientists in 1958 and completed her study in 1978 (Eiduson, 1960, 1966a, 1966b; Eiduson & Beckman, 1973). The scientists, all men, were fairly evenly spread among physics, chemistry, biochemistry, and biology, and no particular a priori criteria were used in their choice other than willingness to participate in the study. Personal interviews were conducted by Eiduson with each individual in 1958, 1964, and 1969; and by Eiduson or Maurine Bernstein in 1978. The Rorschach and the TAT were administered at each interview in 1959, 1969, and 1978; and the Miller Analogies Test in 1969 and 1978. Bibliographies were compiled for each scientist and publication rates and citation data collected. The mean age of the scientists in 1958 was 41.7 (range, 29–59) and in 1978, 60.9 (range, 50–79) (two of the scientists died during the course of the study). Four of the scientists have been awarded Nobel prizes. Two others repeatedly were nominated for Nobel Prizes and appear in lists of scientists holding the so-called "41st chair" (those generally considered to have deserved a Nobel Prize but not receiving one; Zuckerman, 1977). An additional scientist became a member of a President's Science Advisory Committee. Eleven became members of the National Academy of Sciences, including all those receiving Nobel Prizes or nominations for that award. Some scientists have achieved varying degrees of eminence in their fields as researchers, others as administrators and governmental advisors. A few produced only a handful of papers and never established significant reputations. In short, the group is heterogeneous.

We previously reported that a retrospective analysis of Eiduson's data has yielded two predictors of long-term, high-impact scientific creativity among this group (Root-Bernstein et al., 1993). One was the production of four or more high-impact publications by the age of 45 and the other was investigation of an unusual diversity of concurrent research topics. To determine "impact," two criteria were essayed. One was to define a measure called "impact ratio," which was the total number of citations an author received in the Science Citation Index between 1964 and 1978 divided by the author's total number of publications over the same period of time (Ashton & Oppenheim, 1978; Garfield, 1970a, 1970b, 1973). A qualitative analysis of the publications and citations data also produced four distinct categories of analytical utility. We again relied on peer evaluation to rank the scientists from low to high on their impact on the scientific community: (a) scientists having one or more papers cited 100 times or more in the Science Citation Index in the period 1964 to 1978 inclusive (this group included all of the Nobel laureates and those known to be nominated for this award); (b) those having at least one paper cited 10 times in one year (but not meeting Category 1 criteria); (c) those not meeting Category 1 or 2 criteria, but having at least one paper cited 10 times during the period 1964 to 1978 inclusive; and (d) those scientists meeting none of the previous criteria. In other words, the impact of a scientist's work on his colleagues determined his achievement ranking. The one drawback to this approach is that it assumes that an equal pool of colleagues exists for each scientist so that there is an equal probability of their being cited. That is obviously not the case. Some fields are very large; other very small. On the other hand, one of the criteria for success in science is the ability to choose a field in which one can have a significant impact, so that scientists choosing small fields are also telling us something about their problem preferences and perhaps their personalities. In the event, the scientists were approximately evenly distributed among the four categories: 12 in Category 1, 11 in Category 2, 8 in Category 3, and 9 in Category 4. The four groups that resulted from this analysis are referred to throughout this study as *publication citation clusters*.

The data were analyzed with respect to both the impact ratio of the scientists and with respect to their citation cluster. For reasons to be discussed shortly, we believe that the citation cluster approach is the more useful in the present context, but both types of analyses are provided.

Information on hobbies, skills, preferred modes of working, physical activity, and general mental energy were acquired in part from the four sets of interviews performed in 1958, 1964, 1969, and 1978. Because these interviews were not sufficiently detailed or did not address certain issues of interest to the present study, Eiduson's work was supplemented by sending out a confidential questionnaire concerning hobbies, styles of thinking, and physical activities to the 38 members of the group who were still alive in 1988. Each of the scientists was given a code number (#11 to #50) to insure confidentiality, and these code numbers have been used both in the present article and in our previous article (Root-Bernstein et al., 1993) for identification purposes. The questionnaire is reproduced in Figure 1. It was designed to investigate possible interactions between hobbies and skills, modes of scientific thinking, and measures of scientific success. Information was also gathered concerning when scientists solve problems, because little is known about problem-solving strategies or use of time among the general scientific population. It is possible that the time engaged in hobbies is, in fact, scientifically useful time, at least for some scientists, because it might promote nonconstrained (or "creative") thought. The number and types of hobbies and the participation of the scientists in athletic activities was also ascertained as a general measure of the amount of time they spend on nonscientific activities and their general mental and physical energy levels. All of these issues were also addressed in the interviews, and corresponding anecdotal evidence from each scientist was collated.

Thirty-six of the questionnaires were returned. The returned questionnaires were checked for consistency against Eiduson's interviews with each subject and as much information as possible was gleaned from these interviews for the two subjects who refused to or could not (for health reasons) fill out the present questionnaire. Thus, the data that follows are complete for 36 of the individuals and as complete as is possible from existing documents for the remaining two. Information concerning two individuals who died prior to 1988 was not included in the present study because these individuals did not have a complete set of interviews.

It is important to note that the 1988 questionnaire and the interviews were effectively done independently. Eiduson performed the vast majority of the interviews used in this study and died prior to the inception of the idea for the 1988 questionnaire. Moreover, Eiduson privately expressed to us great skepticism that any connection might exist between hobbies, artistic proclivities, and scientific work. There can be no question, therefore, of any positive interviewer bias of the interview results.

Figure 1. *Questionnaire.*

NAME ______________________________ (to be kept confidential)

Please check one or more relevant answers for each question. Any comments, suggestions, or elaborations can be made on page 2, and will be appreciated.

1) Is your scientific problem solving accompanied by any of the following (check where appropriate)?

_____ Visual images _____ Musical themes _____ Kinesthetic feelings
_____ Emotional feelings _____ Other (specify): ____________

2) Do you use any of the following modes of thinking while inventing or solving scientific problems? That is, how do you handle problems *in your head?* If possible, list from 1 to N in *decreasing* order of your use (1 = most used; N = least used; 0 = not used):

_____ Concrete, 3-dimensional images _____ Kinesthetic feelings
_____ Visualized 2-dimensional diagrams _____ Abstractions
_____ Visualized symbols or words _____ Verbal or auditory patterns
_____ Visualized formulae _____ Verbalized formulae
_____ Imageless, non-verbal thought _____ Verbalized symbols or words

3) What hobbies have you participated in as a child (C), young adult (A), and today (T)? Did you have private lessons (P), school lessons (S), or learn on your own (O)?

_____ Drawing _____ Painting _____ Sculpting _____ Photography
_____ Collecting art _____ Collecting records or music _____ Singing
_____ Playing instrument (Specify): ____________ _____ Composing music
_____ Crafts (Woodwork, metal work, etc.) Specify: ____________
_____ Writing (Poetry, stories, etc.) Specify: ____________
_____ Electronics _____ Other (Specify): ____________

4) When have you had your best ideas, illuminations, and insights?

_____ While directly addressing a problem at work _____ On vacation
_____ While addressing a different, but related problem _____ Dreaming
_____ While working on something else _____ As you fall asleep
_____ While relaxing _____ While exercising _____ Upon waking
_____ In the bath/shower _____ Other (specify): ____________

5) What physical or athletic avocations have you had as a child (C), young adult (A), and today (T):

_____ Running/Jogging _____ Walking _____ Sailing _____ Gardening
_____ Skiing _____ Swimming _____ Bike riding _____ Mountain climbing
_____ Football, baseball, etc. (specify): ____________
_____ Tennis _____ Surfing _____ Other (Specify): ____________

Results

1988 Survey

The aggregate results of our 1988 questionnaire are summarized in Tables 1 to 5. Table 1 shows that visual arts, particularly painting and drawing, although among the least common hobbies reported by the scientists, are significantly correlated with both high-impact and high publication citation cluster status. Other hobbies such as poetry and creative writing, photography, crafts, and total number of hobbies, were significantly correlated with status in high publication citation cluster groups, but not with impact ratio. These results suggest that highly successful scientists engage in a wide range of nonscientific cultural activities and that they tend to be productive outside of their science as well as in it.

Table 1. *Summary of Statistical Analyses Comparing Reported Hobbies With Impact Ratio and Publication Citation Cluster (N = 38)*

Hobby	Frequency	%	Correlation With: Impact Ratio[a]	Correlation With: Citation Cluster[a]	χ^2 for Citation Cluster[b]
Painting	6	16	.37**	.42***	7.64**
Collecting Art	6	16	–.04	.42***	7.64**
Drawing	12	32	.30*	.29*	5.74*
Sum Art[c]	12	32	.34**	.38**	Not done
Poetry	15	40	–.06	.31**	3.16
Photography	18	47	–.04	.30**	1.89
Crafts	14	37	–.14	.31**	2.83
Singing	8	21	.06	.25*	4.76
Sculpting	4	11	.30*	.12	2.07
Play an Instrument	20	53	.15	.19	2.20
Electronics	11	29	.07	.07	2.29
Collect Records	16	42	–.09	.23	2.89
Compose Music	2	5	–.11	–.02	1.94
Miscellaneous Hobbies[d]	14	37	.12	–.22	2.95
Sum All Hobbies			.13	.42***	Not done

[a]Pearson product–moment pairwise correlation coefficients. [b]Chi-square statistics for two-way contingency tables; degrees of freedom = 3. [c]Sum Art = combination of drawing and painting. [d]For example, collecting minerals, recreational computing, philately.
*$p < .10$. **$p < .05$. ***$p < .01$.

Table 2 shows that success as measured by high-impact ratio or inclusion in the high publication citaton cluster group was significantly correlated with the use of visual forms of thinking in general and the use of visualized three-dimensional models and visualized symbols and words in particular. In short, successful scientists tend to "see" their work inside their minds. Use of kinesthetic feelings and unusual forms of thought such as "word images," "acoustic images," "talking to self," and "doodling" was also correlated with a high impact score, suggesting that there are many ways of imagining a scientific problem besides words, equations, and diagrams. Despite anecdotal reports of musical themes accompanying mathematical work (Davis & Hersh, 1981), no scientist in this study reported hearing such themes. Other forms of thinking, such as imageless, nonverbal thought, verbalized words, symbols, and formulae, use of abstractions, and emotional feelings, although reported by at least a quarter of the participants in the study, were not associated with scientific success in this study.

Table 3 demonstrates that significant correlations exist between specific hobbies and the reported use of various modes of thinking by the scientists. Visual arts, such as painting, drawing and photography, and somewhat unexpectedly, musical hobbies (e.g., musical composition, collecting records, singing, and playing an instrument), were generally associated with reported use of visual images while problem solving. Analysis of the individual questionnaires suggests that the musicians in this group of scientists are unusually cultured in the visual arts, and thus the high association between artistic and musical skills may be an artifact unique to this group of men, or it may indi-

Table 2. *Summary of Statistical Analyses Comparing Reported Use of Different Modes of Thinking With Impact Ratio and Publication Citation Cluster (N = 38)*

Mode of Thinking	Frequency	%	Correlation With: Impact Ratio[a]	Correlation With: Citation Cluster[a]	χ^2 for Citation Cluster[b]
Visual Thinking	14	37	.32**	.43***	11.48**
Visualized 3D Images	17	45	.29*	.28*	6.87*
Visualized 2D Images	14	37	.21	.28*	5.27
Visualized Symbols, Words	13	35	.26	.36**	6.94*
Visualized Formulae	12	32	.17	.19	4.55
Abstractions	7	18	−.10	.17	4.59
Verbalized Words, Symbols	11	29	.22	.18	2.34
Verbal/Auditory Patterns	8	21	.32**	.19	1.63
Verbalized Formulae	9	24	.15	.08	1.09
Musical Themes	0	0	N/A	N/A	N/A
Kinesthetic Feelings	6	16	.32**	.20	3.12
Emotional Feelings	11	29	.14	.02	1.98
Imageless, Nonverbal	12	32	.28*	.14	2.66
Other[c]	7	18	.30**	.11	1.80

[a]Pearson product–moment pairwise correlation coefficients. [b]Chi-square statistics for two-way contingency tables; degrees of freedom = 3. [c]For example, word images, acoustic images, doodling, talking to self, logic.
$*p < .10$. $**p < .05$. $***p < .01$.

cate that musical proclivity is associated with active mental imagery. Collecting art was specifically associated with use of abstractions while problem solving, suggesting that careful analysis of paintings and drawings may facilitate that particular form of perception. Sculpting, by contrast, was not associated with visual thinking skills, but was significantly correlated instead with imageless, nonverbal thought and kinesthetic thinking, suggesting that a highly developed physical sense of space, texture, and movement may be involved. Clearly, making a sculpture is not primarily a visual experience for the sculptors in this group. Surprisingly, sculpting was also highly correlated with use of verbal forms of thinking as, not surprisingly, were creative writing and poetry. Creative writing and poetry were also signficantly associated with use of visualized symbols and words during problem solving, as might be expected. Electronics was also signficantly correlated with use of various modes of thinking, including visualized symbols and formulae, kinesthetic thinking, and verbal formulae. Given the skills necessary for reading and interpreting electronic diagrams, stating what they mean, and then physically acting on that information, this combination of correlations is perhaps not unexpected. General crafts skills were not associated with any particular mode of thought, possibly because the skills are too diverse for patterns of correlations to show up.

Table 4 shows that scientific ideas can arise in a wide variety of settings, from formalized problem solving settings to dreaming, shaving, and bathing. Only half of the scientists reported that they ever solved their problems while directly grappling with them. An equal number reported that they solved their problems while working on different scientific problems, either related or

Table 3. *Pairwise Correlations*[a] *of Reported Modes of Thinking With Hobbies (N = 38)*

	Mode of Thinking									
Hobby	**3D Images**	**2D Images**	**Visual Symbols**	**Visual Formulae**	**Imageless Nonverbal**	**Kinesthetic**	**Abstractions**	**Verbal Auditory**	**Verbal Formulae**	**Verbal Words Symbols**
Drawing	.31*	.31*	.35*	.38*	.40**	.33*	.26	.20	.29	.19
Painting	.19	.41**	.45**	.39*	.48**	.21	.17	.31*	.27	.36*
Photography	.31*	.48**	.43**	.53**	.26	.17	.09	.16	.34*	.32*
Sculpting	.21	.27	.29	.24	.50**	.32*	.28	.45**	.41**	.35*
Collecting Art	.19	.27	.29	.24	.17	.01	.35*	.13	.27	.20
Collecting Records	.41**	.56**	.51**	.62**	.22	.21	.28	.21	.15	.28
Singing	.18	.40**	.44**	.37*	−.20	.31*	.25	.21	.01	.10
Playing an Instrument	.32*	.40**	.46**	.44**	.08	.26	.18	.23	.28	.26
Composing Music	.26	.30*	.32*	.29	.09	.22	.19	.17	.15	.11
Writing, Poetry	.24	.28	.33*	.23	.03	.24	.17	.38*	.06	.32*
Crafts	.08	.21	.25	.16	.30	−.20	.20	.01	.22	.11
Electronics	.36*	.35*	.40**	.43**	.19	.36*	.15	.10	.33*	.23

[a]Pearson product–moment pairwise correlation coefficients.
*$p < .05$ ($r > .30$). **$p < .01$ ($r > .39$).

Table 4. *Summary of Statistical Analyses Comparing Reported Work Habits With Publication Citation Cluster (N = 38)*

Work Habit[a]	Frequency	%	χ^{2b}	F^c
Working Directly on Problem	21	55	4.66	1.40
Working on Different, Related Problem	13	34	5.23	4.97**
Working on Unrelated Problem	8	21	1.63	1.22
While Relaxing	9	24	4.00	0.00
While Falling Asleep	7	18	1.60	0.01
While Dreaming	5	13	7.27*	0.00
Upon Waking	9	24	2.54	0.01
In the Bath or Shower	4	11	5.28	0.22
While on Vacation	3	8	1.09	0.00
While Exercising	1	3	3.31	0.00
Other[d]	3	8	1.63	0.00

[a]Work habits were reported in response to the question: When do scientific ideas arise? [b]Chi-square statistics for two-way contingency tables; degrees of freedom = 3. [c]Statistics for one-way analyses of variance; degrees of freedom = 3, 34. [d]Includes while shaving, talking with others, arguing.
*$p < .10$. **$p < .05$.

Table 5. *Summary of Statistical Analyses Comparing Reported Athletic Activities With Impact Ratio and Publication Citation Cluster (N = 38)*

			Correlation With		χ^2 for
Athletic Activity	Frequency	%	Impact Ratio[a]	Citation Cluster[a]	Citation Cluster[b]
Running	7	18	.30*	.11	3.15
Walking	16	42	.09	.31**	8.99**
Sailing	8	21	.01	.31**	4.35
Gardening	19	50	–.19	.12	2.53
Skiing	13	34	.04	.26	4.16
Swimming	16	42	–.08	.26	7.41*
Biking	17	45	.11	.03	0.69
Mountain Club	12	32	–.20	.09	0.57
Football, etc.[c]	18	48	–.13	–.09	1.33
Tennis	15	40	–.05	.34**	4.51
Surfing	6	16	.17	.36**	6.43*
Other[d]	13	34	–.16	–.25	2.44
Sum All Athletics			–.03	.31**	Not done

[a]Pearson product–moment pairwise correlation coefficients. [b]Chi-square statistics for two-way contingency tables; degrees of freedom = 3. [c]Includes football, baseball, soccer, basketball, cricket. [d]For example, golf, volleyball, weight lifting, gymnastics.
*$p < .10$. **$p < .05$.

unrelated to the initial problem. One quarter reported solving their problems while relaxing, suggesting that hobbies provided useful problem-solving time. Over half the scientists reported having their best ideas while falling asleep, dreaming, or on waking in the morning. These results clearly indicate that most scientific problem solving does not occur while directly addressing scientific problems and that most scientists solve their problems in settings that include but are not limited to professional ones. Perhaps the most striking result of this part of the study was that there was a significant association between solving problems while working on different, related problems and being a high publication citation cluster scientist. A chi-square test indicated that high publication citation cluster scientists had an unusually high probability of solving their problems while dreaming, while in the bath or shower, or while working on a different but related problem. These data suggest that successful scientists work effectively on more than one problem simultaneously and often do so outside of the work environment—processes requiring unusual mental energy and persistence.

To try to assess the relative energy the scientists had, information was gathered about their physical activities. Table 5 displays the aggregate responses concerning athletic activities and their statistical analyses with regard to impact and publication citation cluster. No athletic activity was significantly associated with impact, although running was unusually common among high-impact scientists. Both walking and surfing were significantly associated with high publication citation cluster status on two statistical tests, and tennis, swimming, sailing, and the total number of athletic activities were significantly associated with high cluster status in one test. Analysis of the questionnaires themselves shows that highly cited scientists tended to continue athletic activities that could be carried from youth into old age (walking, swimming, sailing, and tennis) when their less successful colleagues participated in sports that could not be continued into older age (e.g., football, downhill skiing, basketball), or never participated in athletic activities at all. A most striking result was the correlation between eminence and surfing. All of the scientists lived or worked within easy commute to the beaches of Southern California. It appears that the most successful scientists had an unusual urge to experiment athletically as well as scientifically, which led them to try surfing and to engage in a wider range of athletic activities than their less successful colleagues.

To summarize, the 1988 questionnaire data suggest that specific hobbies are associated with the use of specific modes of scientific thinking. Whether these hobbies develop the corresponding mental skills, are a reflection of innate mental aptitudes, or the mental skills and hobbies develop recursively could not be determined from the survey. It was clear, however, that various artistic hobbies and their associated mental skills, such as visual forms of thinking and perhaps kinesthetic and verbal or auditory patterns, are used with unusual frequency by those scientists in the highest impact and citation cluster groups. The data also suggest that the most successful scientists are those who are most active scientifically (working on more than one problem), most active with their hobbies (often having several at one time), and most active physically (both in terms of number of physical activities and continued participation into older age).

Interviews (1958–1978)

The interviews conducted in 1958, 1964, 1969, and 1978 corroborate the 1988 questionnaire results, elucidate the interactions that the scientists themselves perceived between their science, their hobbies, and their physical energy, and suggest how differently scientists handle the problems that can result from having multiple talents and interests.

Several of the scientists in the highest impact and highest citation clusters explicitly discussed their predilection for artistic and musical hobbies and the connection between these and their scientific work. One Nobel laureate who is an artist and musician said,

> I have a big tendency to use my hands and I also have a tendency to use my intellect. Well, the sciences are a great way of combining these operations and there aren't too many professions that do this. ... My concept of the ideal [scientist], is that you do one thing real well, and its a very specialized thing, and then you do a lot of other things, but not too many, maybe 5 or 6 or 10 different other things, which you do well enough to give yourself and possibly others pleasure. This should be distributed quite widely among sports and artistic things and carpentry and things that involve using your hands and a little music perhaps and things of that sort. (#21, 1958, p. 3)

Another high-impact scientist recounted that

> I was always most interested in anything. I was always taking things apart and putting them together again and interested in anything at all. As a matter of fact, I guess I had too many interests because I collected everything and did everything I could think of. (#32, 1958, p. 1).

A third high-ranking scientist, when asked if his hobbies affected his scientific work, rationalized his own interest in music by saying,

> [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. I think for a scientist who is working very hard, anything is good which brings from time to time another angle about general ideas into the picture. (#11, 1958).

An unusually multi-faceted Nobel laureate summarized his unusual and extremely eclectic approach to life and science by saying simply that, "[I] just keep on playing the way I used to play when I was a kid" (#25, 1978, p. 19).

Three of the highest ranking scientists placed their extra-scientific pursuits in the context of the *two cultures problem*—C. P. Snow's (1959) term for the apparently irreconcilable split between the humanities and the sciences. Unlike Snow, these men believed that all knowledge was accessible, and their science was only a part of their explorations of nature. One said that

> It is an interesting point that scientists like music, read poetry, read books, are I think in general intelligent, interested in politics, and so forth. No poet, no painter has ever tried to study a little mathematics to know about the new things in this new world. The scientific world is extremely beautiful. I'm much more interested—I mean, if you ask me what I really care about—I care about the beauty in science; and this novelty of discovery is a really aesthetic pleasure. It's just comparable, I think, to any other of the great artistic emotions. It isn't rational. It's beyond reason. (#27, 1969, p. 12).

Another, a man who later received a Nobel Prize, said that, "Every scientist realizes in his science only a small portion of his total ability. I suppose that's true in general—that you don't do everything you're capable of by a big factor. I don't" (#15, 1958, p. 15). In a later interview, he expanded on his thought: "If there are two cultures, the scientists are the ones who have had both. It's the nonscientists who have a separate culture." (#15, 1969, p. 22) Another agreed:

> I find that a student in the arts, for example, is completely ignorant of science and proud of it, but a student in the sciences, if he is ignorant of art will be attempting to make up that deficiency and in many cases the two seem to be combined. (#32, 1969, p. 21)

The arts, then, seemed to be an expression of a general aesthetic sensibility about nature for these extraordinary men. Their one oversight, as we shall see, is a common failure to realize that many of their scientific colleagues are more like the artists they criticize than like themselves.

Other members of the highest ranking groups remarked explicitly on the importance of hobbies as training for their science. One said that

> I was always interested in things to make. I used to make model airplanes and things like that. When I was old enough to go to the library, I used to go and get books that described things that kids could make. I can really say that my interest in science stems back to those very early days. (#39, 1958, p. 2)

He went on to say a few minutes later that this experience helped him in his later course work:

> I used to go to the junk yard and buy all sorts of old radios and things like that and bring them home and that was extremely significant in my later education because essentially what I had come across in college courses ... was not entirely new to me. (#39, 1958, p. 3)

Another high-impact scientist, whose interests in the psychology of science had been aroused by the testing, compared his own experiences with those that had just been published by Ann Roe (1953):

> I notice too in reading Dr. Roe's work, for example—I noticed with interest—that most of the people who were going to become chemists when they were little boys, they made radios and things like that. The people who played with chemistry sets when they were little, they were going to become physicists. When I was little, I made radios too, by the way. (#18, 1958, p. 8)

This scientist did become a chemist before switching to biology later in his career. This same scientist also spoke about the importance of explicit training in modeling and visual thinking during his college curriculum. His chemistry professor, Roscoe Dickerson of the California Institute of Technology,

> told us this and he told us every day: "You've got to really understand what you are doing." He'd talk about every principle, and he'd try to get everybody to really physically visualize this problem which might have to do with something about chemistry alright, but you were talking about it in the abstract and had to visualize in your mind what was actually happening. If we were plotting something, we had to see what this physically represents. All of a sudden, I learned to be able to physically visualize problems that would otherwise be abstract or physically visualize the meanings of equations and things like that. (#18, 1958, pp. 6–7)

The contrast between the statements just quoted from the highly successful scientists and their low-impact and low citation cluster colleagues could not be greater. Most of the latter had no comments on hobbies or artistic proclivities either because they had none or found them irrelevant to their work. Few discussed the two culture problem and only to say that scientists have nothing in common with artists and writers. Not one spoke of using visual thinking, modeling, or manipulative skills in their research. One of these low-ranking scientists, however, said explicitly, "I don't try specifically to develop hobbies. I would almost say that work is its own reward" (#23, 1958, p. 6). Another of his unsuccessful colleagues admitted that, "I was generally good at the academic subjects; pretty poor when I had to take shop or things like that" (#26, 1958, p. 3). A third, when asked whether his hobbies affected his scientific work, stated that, "I believe in a balanced life. That probably detracts from my becoming as great a scientist as I might" (#45, 1957, p. 17). In summary, these men, unlike their very successful peers, perceived little relation between their hobbies and skills and their scientific work. For them, science was one thing, and other aspects of their lives were totally independent competitors for time and energy.

The differences in the way the different groups of scientists treated their talents and interests was reflected in differences in how they approached the problem of allocating their time. Many of the highest impact or highest publication cluster scientists spoke explicitly about working on many things simultaneously and therefore of the importance of efficiency as a prerequisite to success. One said, "I think personal efficiency is required and especially in view of all of the outside requirements that demand our time" (#39, 1958, pp. 5–6). Another, a future Nobel laureate who took on extraordinary amounts of work, said,

> I can get a lot of things done in a given time, and I can shift from one thing to another, and I work, I suppose, very efficiently. ... I usually try to get twice as much done in a given time as is proper or customary. (#35, 1958, pp. 6, 11)

Yet another man who was to win a Nobel prize, confessed that

> All the way along it has been quite apparent to me, and it is particularly true as I got higher and higher in my profession, that I was dealing with people who were by and large in a completely intellectual sense, more intelligent than I was—better memories, better analytical ability and things like this. The thing that always made me able to compete advantageously with these people was organization and drive and determination, on the one hand, and a general certain amount of wisdom, on the other, which is derived probably from my [polymathic] background previous to my becoming interested in the sciences. (#21, 1958, p. 7)

In other words, the experience of doing many things and of doing them reasonably well drove these men to allot their time parsimoniously and to make hard decisions as to how much time and effort each of their activities was worth. It is worth noting that only two of the highest cluster scientists ever became engaged in administrative work and then only for very short periods of time. A third member of their group even went so far as to state

> I'm not going to help nobody [*sic*]. I'm a selfish, good-for-nothing, and I'm just going to enjoy myself. I think that attitude is necessary to avoid [entrapment], because you spend all your time after a while giving advice ... [or] setting up a new department. (#25, 1978, p. 19)

He consistently refused to do this sort of work throughout a career that led to a Nobel Prize, although he willingly and often "played" (his term) with many nonscientific ideas and problems that he did find valuable.

Once again, the contrast with the statements of scientists in the lowest impact and cluster groups is striking. As a group, they found it very difficult to do more than one thing or to allot their time and energy wisely. Unlike the highest ranking scientists, many of the low-ranking scientists did became administrators (Root-Bernstein et al., 1993). At the same time, many spoke of being overwhelmed by the teaching, administrative, and other duties their positions demanded. One, for example, said

> I've been so involved with keeping up with the things that are pressed on me, or something I take on for some reason. ... They don't give me the opportunity for real creativity in the initiative sense, you know. (#34, 1969, p. 26)

Another averred ironically that, "I have come to the opinion that creativity is closely allied to hard work—a good reason that I spend so much time reading" (#26, 1969, p. 4). A third scientist from this group confessed that he felt,

> many pressures here not to work. They're indirect ones, and I'm beginning to give in to them myself. ... I'm beginning to become very interested in mountain climbing, hiking. I hate to admit it, but I find myself [over] the last year trying to really find excuses not to do work and I'm quite disturbed about it. I don't know why. ... Many times, I've taken off in the afternoon to go play golf without it being planned. I just decided I didn't feel like working—even to a movie in the afternoon. (#42, 1959, pp. 2–3)

Still another low-ranking scientist blamed his lack of success on trying to lead a "balanced life," which including extensive political activities. His nonvocational committments left him little time for laboratory research. "All these things take away from one's creativity," he maintained (#45, 1957, p. 19; 1969, p. 24). Common to this entire group was their failure to prioritize their professional activities as their more successful colleagues clearly did or to unify their different activities into a mental and emotional whole. For example, none of these men reported using their time away from work to refresh their minds or to get a better perspective on their work, as their more successful colleagues did.

Interestingly, not only did the highest ranked scientists value efficiency over hard work in their interviews, but they also viewed their time rather differently than their less successful colleagues. Many of the low-impact and low cluster group individuals maintained that they would be better scientists, and even more creative scientists, if they could devote more effort or more hours to their research. One for example, said, "Let's say you spend ten hours in the lab instead of eight, assuming you can work at the same efficiency—you're going to get more work done in ten" (#45, 1957, p. 19). A second reported actually trying this method for nearly a decade. He would "frequently" work "through dinner or something and stay in the lab till 7—8—9 at night and, you know, start something even at 4 o'clock, let's say, that you know will have to run late and all that" (#42, 1964, p. 3). This strategy did not work, and at his next interview he confessed that he worked much less often in the evenings (#42, 1964, p. 3). Another blamed his own lack of mental and physical energy for his poor performance:

> Well, let's say first of all that I never had much energy. I can remember years ago coming across the statement somebody made that I thought was very apropos of myself, that if I have an impulse to exert myself, I just sit back and wait for it to pass. ... I've been very much aware of the fact that I don't have enough energy to do what I should. (#34, 1969, p. 27)

Self-perceived lack of time and energy were, for many of these scientists, the things that mediated their research success.

On the other hand, the Nobel laureates and those nominated for that award almost to a man have been known to call themselves "lazy." None, despite work loads at least comparable to the low-ranking scientists, complained of lack of time. One of the most famous confessed (and evidence indicates that he was being quite truthful), "Sometimes I work, and sometimes I don't" (#25, 1958, p. 17). Another said, "I do not have any regular hours" (#35, 1958, p. 6). A third said that, "Certain periods I work say, six nights a week, sometimes seven and weekends too. Other periods of time, I don't. It varies, very very much" (#21, 1958, p. 11). A fourth, when asked if he regularly worked long hours, said no,

> I've never been that type myself. If the problem needed solving, and required working to midnight continuously, I would accept it, but I didn't do it out of choice. I know that some people do this out of choice. They work continuously at their subject, and I've often wondered whether it's because they're terribly interested in their subject or because they have nothing else to do. (#32, 1958, p. 6)

A fifth scientist summarized the same experience: "I'm quite variable [in my work habits]. Sometimes I'm excited about something and feel I'm getting somewhere, and then I work hard and keep at it. Sometimes I just haven't got it in me; I don't work" (#47, 1958, p. 7).

In short, the most successful of the scientists in the group suggested that they allowed the state of their research to determine how much effort and time they allotted to it. If it was proceeding well and demanded a great deal of attention, they invested many hours in it. If it was going poorly, or they were lacking in ideas, then they turned to one or more of their many other pursuits and waited for inspiration. For them, time and energy followed hard on exciting ideas, not the other way around. It is important to note, however, that all of the top-ranking scientists had the physical and mental energy to focus their entire attention on their work when it did become interesting and potentially important. The lowest ranking scientists, by contrast, seem to have believed that the operative factor in achieving success was the number of hours worked per se rather than appropriately applied concentrated effort. They rarely had the time or energy to devote to their research when it did become promising.

Discussion

The results reported here offer a rare look at how diverse scientists place their work within the broader context of their mental and physical lives. The study obviously suffers from the inescapable problems of relying on a convenience sample and may be difficult to replicate. In this case, however, the amount, types, and timespan of information necessary to observe the correlations between hobbies, personal styles, and success in a scientific career is such that it is unlikely that the required information could have been obtained through anything but a convenience sample.

The most interesting result of the study is clearly the observation that avocations, styles of thinking, and scientific success are integrally linked. Our results certainly give added dimension to Max Planck's statement that, "The pioneer scientist must have a vivid intuitive imagination for new ideas, ideas not generated by deduction, but by *artistically* creative imagination" (Planck, 1949, p. 109). Perhaps the most extended discussion of this theme prior to the current study is to be found in Mitchell Wilson's (1972) *Passion to Know,* a personal view of what it takes to do successful science by a physicist who invented many key parts of the first nuclear reactors with I. I. Rabi and Enrico Fermi, while simultaneously writing short stories and later best-selling novels. Wilson avers that it takes more than logic and a love of science to make a scientist:

> The particular kinds of sensibilities required by a scientist are more complicated. Begin with his intense awareness of words and their meanings. Although the poet's affinity for words makes him sensitive to their sound, emotion, and rhythm, the scientist uses them as instruments of precision. He must be capable of inventing new words to express new physical concepts. He must be able to reason verbally by analogy—to explain how this thing is like that thing, and to be able to fit the many resemblances into one single generalization that fits them all.
>
> The scientist must also think graphically, in terms of dynamic models, three-dimensional arrangements in space. ... Scientists keep these three-dimensional pictures in mind as vividly as if they were actually seeing them. Formulas and equations printed on a two-dimensional page have three-dimensional meaning, and the scientist must be able to read three dimensions to "see the picture" at once. ...
>
> The split between the so-called two cultures is much more than a matter of humanists learning more about science, and the scientists spending more time on esthetics. Unless a man has some kind of spatial imagination along with his verbal sensibility, he will always be—as far as science goes—in the role of the tone-deaf struggling with a course in music appreciation. On the other hand, the possessor of both verbal and spatial sensibility will rather quickly be bored if asked to limit his imagination to the verbal domain, in the case of the humanities; or to only the spatial domain, in the case of the graphic arts.
>
> A man accustomed to working at the peak of his powers has no patience with anything that calls on him to work at only half load. With this dual sensibility then, the true scientist would find it difficult to be like everyone else even if he wanted to be. (Wilson, 1972, p. 12)

Perhaps ethologist, artist, writer, and Nobel laureate Konrad Lorenz best summed up this perspective when he wrote that

> He who has once seen the intimate beauty of nature cannot tear himself away from it again. He must become either a poet or a naturalist and, if his eyes are good and his powers of observation sharp enough, he may well become both. (Lorenz, 1952, p. 12; see also Woodward, 1989, p. 237; and Bekesy, 1974, p. 15)

Clearly our study corroborates these conclusions.

The results of both the survey and interviews further corroborate the notion that styles of research are related to a complex mix of modes of thinking, experiences with hobbies and skills, physical and mental energy, and the ways in which these variables are handled by an individual. Thus, on a broad scale, our results confirm the utility of Gruber's (1984) concept of *networks of enterprise.* Gruber defined such networks as consisting of a person's organization of purpose or definition of his or her working self; a structure that organizes what may appear to be a bewildering miscellany of activities; an organization of goals that provide different levels of risk and reward at different levels of aspiration to fit different, changing moods and needs; and finally a sense of what makes a person's work individual and unique (Gruber, 1984, 1988, 1989). It is clear from the results of our study that the most successful scientists in our group developed networks of enterprise as complex and varied as those Gruber described for Charles Darwin and some of the other scientists he studied.

The results also reveal an interesting limitation on the concept of networks of enterprise. Gruber studied only extremely successful scientists and has presented his concept as a strategy of research, or a way of organizing a successful scientific endeavor. Our study of unsuccessful scientists leads us to believe that there can be unsuccessful networks of enterprise. Some of the low-ranking scientists in our study engaged in as wide a range of activities as the successful scientists. What was clearly lacking in the lives of the less successful scientists was a unifying focus, or global perception of knowledge (whether personal or public) as something that could integrate many endeavors fruitfully. This lacuna was manifested in their uncritical acceptance of Snow's (1959) two cultures and their common belief that anything that took time away from their laboratory work was time lost to science. In other words, they organized their networks of activity poorly. These networks were not integrated, as were those of the successful scientists. Rather, the pieces of the unsuccessful networks competed with each other for the attention of the individual. Thus, a successful network of enterprise cannot be built by simply following a prescription in which a given number of slots are filled. "Paint; learn to think visually; work on several problems, related and unrelated, simultaneously; etc." Such a prescriptive approach will not work. Rather, successful networks of enterprise are living processes based on a working integration of the components.

Our study hints at what may be involved in some of this working integration. In a successful network of enterprise, each element has multiple connections with the other elements. Both the 1988 survey and the interviews revealed that many of the successful scientists explicitly recognized the utility of having built models, engaged in electronics projects, learned to think visually, or having played or composed music as means of informing their scientific skills and acumen. Thus, they viewed their hobbies not only as elements necessary to being fully cultured, but also as valuable forms of training for various aspects of their science. A study of several hundred eminent scientists from the last century carried out by Root-Bernstein (1989) reached a similar conclusion.

Also, the integrated nature of the successful scientists networks of enterprise allowed them to maximize their probability of successfully recognizing and solving scientific problems. Because all parts of the network are connected, the successful scientists were unusually willing to explore neighboring and even apparently unrelated scientific problems hoping for insight into their original problem. They recognized that time relaxing or engaging in their hobbies could be valuable and so were willing to view time away from their science as nonetheless of value to their scientific efficiency and thus to their careers. Indeed, some scientists, including physicists Albert Einstein and Luis Alvarez, and Charles Martin Hall, the man who figured out how to extract aluminum economically, specifically turned to their musical instruments when stymied by a problem and often found new insight while playing (Alvarez, 1987; Clark, 1984; Garrett, 1963). Some highly successful scientists have even reported purposefully manipulating elements of their networks of enterprise as seemingly intractable as sleep and dream time. Linus Pauling, for example, reported that he learned to purposely program his mind to solve problems during his sleep by thinking very hard about the problem each night as he went to bed for several days running. After several weeks of dreaming about his problem, very often, he reported, a solution would strike him on waking (Pauling, 1963, p. 47; 1981, p. 59). Several of the scientists in the present study reported using similar techniques, and many anecdotal cases of insights or illuminations occuring during relaxation or sleep time have been compiled by Root-Bernstein (1989).

Of particular importance are the subjective reports of the scientists concerning the value of their multiple, concurrent scientific activities. We have shown previously (Root-Bernstein et al., 1993) that the most successful scientists in the group had a signficantly higher number of major research areas than their less successful colleagues and that they switched their research areas significantly more times. Most of the high citation cluster scientists worked on several projects simultaneously. Their interview reports of working on several projects that are quoted in the present article are therefore validated by analysis of their publication records. The correlation found in the present study between scientific success and solving problems while working on other, related problems is also consistent with these data, and with a handful of previous studies that have been carried out concerning this matter (Finkelstein et al., 1981; Platt & Baker, 1931; Root-Bernstein, 1989).

Clearly, physical and mental energy are necessary to carry out this multifaceted type of research successfully, and many of the scientists specifically addressed the ability to muster that energy, or their inability to do so. Again, reference to the wider literature of scientific biography and autobiography suggests that these results are generalizable. Many of the most successful scientists are known as avid mountain climbers, swimmers, or runners into middle or old age. Some recognize the importance of their continued exercise for their productivity as well. For example, Nobel laureate George H. Whipple wrote that,

> I feel fortunate that I grew up in the country. As a result of this environment, I became interested in wild life and camping, also hiking, snowshoeing, skating, bob sledding, canoeing, fishing, hunting—all this was an essential part of my life. My physical development and stamina were favorably influenced by these factors. A continuing interest in hunting, fishing, and camping has carried throughout my life and I feel sure has increased my capacity for work, study, and teaching. (Ingle, 1963, p. 210)

One of the most important implications of these findings is the possibility that science education needs serious revision. At present, science classes and textbooks focus almost solely on the manipulation of words and numbers. A common way of approaching nature, almost a common way of life, however, is what seems to link the most successful scientists. Certainly, this study clearly demonstrates that words and numbers are not the main modes of thinking used by highly successful scientists, and this is not particularly surprising, because the best scientists have always argued that words and numbers are secondary in creative thought. Einstein, for example, wrote in response to Jacques Hadamard's classic psychological survey of scientists:

> The words of or the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be "voluntarily" reproduced and

> combined. ... Conventional words or other signs have to be sought for laboriously only in a secondary stage, when the mentioned associative play is sufficiently established and can be reproduced at will. (Hadamard, 1945, pp. 142–143)

Other eminent scientists agree. Cyril Stanley Smith, a metallurgist at MIT and a member of the Manhattan Project, wrote that in his experience, "The stage of *discovery* was entirely sensual and mathematics was only necessary to be able to communicate with other people" (Smith, 1981, pp. 353–354). Nobel laureate Barbara McClintock also described a similar experience to her biographer Evelyn Fox Keller, explaining that the basis of her thinking was not logic, but "a feeling for the organism" (Keller, 1983, p. 104). One of us has documented many similar statements by many equally famous scientists (Root-Bernstein, 1989, 1995).

Like the high-impact scientists in this study, many other successful scientists also attribute their understanding and creativity in science to experiences outside of the science classroom or laboratory. W. R. Hess, a Nobel laureate in medicine or physiology wrote of his youth, for example, that,

> During my free time I used to make toys such as bows and arrows, sail boats, and airplanes from improvised materials to be found in and around the house. This did much to develop not only manual skills, but a certain practical sense and inventiveness. (Hess, 1963, p. 43)

He expressed this inventiveness later not only in his science—he invented more techniques and equipment for physiological research than anyone else at the time—but also in the invention of the first true three-dimensional photographic technique (Hess, 1963, pp. 43–50). Nobel physicist Luis Alvarez attributed much of his scientific success to a plan devised by his father, the eminent physiologist Walter Alvarez. Seeing that Luis was interested in science, the elder Alvarez premeditatedly "hired one of the Mayo Clinic's machinists to give me private weekend lessons" (Alvarez, 1987, p. 14). Luis was also enrolled in the Polytechnic High School, rather than the academic one, where he learned mechanical and freehand drawing, which he subsequently used "often" in his research (Alvarez, 1987, p. 12). Similarly, Walter Cannon, the preeminent American physiologist of the early part of this century wrote in his autobiography that his experimental ingenuity was due to his boyhood experience with carpentry (Cannon, 1944, pp. 34–45). These men's experience suggests that perhaps the goal of education should be to train integrated minds rather than explicitly to train scientists.

In concluding, it is necessary to reemphasize a point made previously: There is no evidence to support the proposition that all scientists should take classes in painting or music composition or poetry simply for the sake of taking such classes or in the naive hope that simply taking such classes or engaging in such hobbies will necessarily or even often teach scientists tools of thinking that might benefit their science. On the contrary, the existence of a substantial number of polymathic scientists in this study who developed nonfunctional networks of enterprise clearly argues against a smattering of strict disciplinary learning. What appears to be needed is an education that makes apparent the specific connections between hobbies, skills, and science that the successful scientists discovered for themselves. We have little doubt that such connections can be taught for the simple reason that several of the scientists in our study explicitly recounted having been taught some specific skill, such as how to observe through classes in scientific drawing or painting (#15, 1958), or how to visualize a mathematical function or a chemical reaction through repeated example and practice (#18, 1958, pp. 6–7). It is time that we pay attention to these highly successful scientists and emulate how they were trained and the ways in which they think, rather than relying on the watered down pap of curricula and textbooks that have been devised at second and sometimes even third hand by unsuccessful scientists and science educators who have little knowledge and less experience actually doing important science.

And so this article returns to the words of eminent scientists such as Ramon y Cajal and Richet with which it opened. These scientists said of themselves and their most successful colleagues that in doing many things well, they appeared to be spreading themselves too thin, but in reality they were training their minds to do their greatest work. They apparently understood themselves well. This self-understanding is itself noteworthy, for it says that there is much to be learned from insightful scientists about how they do science simply by letting them tell the researcher how they work. The so-called "objective" statistical approach to data collection currently favored by psychologists certainly proved no more useful in this study than the "subjective" approach of the interviewer. In fact, it was only by paying attention to the self-analysis of famous scientists both in and independent of this study that the clues were gained concerning what questions to ask and what to look for. As unique as individual scientists may seem, they nonetheless can tell us valuable things about their work habits and means of success if the proper questions are addressed to them or if they are simply allowed to tell investigators what they have learned through a lifetime of experimentation. On the other hand, any method that assumes the investigator knows more about the subject of study than does the subject himself must cause us great concern.

References

Alvarez, L. W. (1987). *Alvarez. Adventures of a physicist.* New York: Basic.

Ashton, S. V., & Oppenheim, C. (1978). A method of predicting Nobel prizewinners in chemistry. *Social Studies of Science, 8,* 341–348.

Bekesy, G. von. (1974). Some biophysical experiments from fifty years ago. *Annual Review of Physiology, 36,* 1–16.

Bernard, C. (1957). *An introduction to the study of experimental medicine* (H. C. Greene, Trans.). New York: Dover. (Original work published 1927)

Cannon, W. (1944). *The way of the investigator.* New York: Hafner.

Clark, R. S. (1984). *Einstein. The life and times.* New York: Abrams.

Davis, P. J., & Hersh, R. (1981). *The mathematical experience.* Boston: Birkhauser.

Deutsch & Shea, Inc. (1957). *A profile of the engineer: A comprehensive study of research relating to the engineer.* New York: Industrial Relations Newsletter.

Eiduson, B. T. (1960). The scientist's image of himself. *Science, 132,* 552–554.

Eiduson, B. T. (1962). *Scientists: Their psychological world.* New York: Basic.

Eiduson, B. T. (1966a). Productivity rate in research scientists. *American Scientist, 54,* 57–63.

Eiduson, B. T. (1966b). Scientists as advisors and consultants in Washington. *Bulletin of Atomic Scientists, 22,* 26–31.

Eiduson, B. T., & Beckman, L. (Eds). (1973). *Science as a career choice.* New York: Russell Sage Foundation.

Ferguson, E. S. (1977). The mind's eye: Nonverbal thought in technology. *Science, 197,* 827–836.

Ferguson, E. S. (1993). *Engineering and the mind's eye.* Cambridge, MA: MIT Press.

Finklestein, S. N., Scott, J. R., & Franke, A. (1981). Diversity as a contributor to innovative performance. In E. B. Roberts (Ed.), *Biomedical inno-*

vation (pp. 135–143). Cambridge, MA: MIT Press.
Galton, F. (1874). *English men of science: their nature and nurture.* London: Macmillan.
Galton, F. (1892). *Hereditary genius: An inquiry into its laws and consequences.* London: Macmillan.
Gardner, H. (1993). *Creating minds.* New York: Basic.
Garfield, E. (1970a). Citation and distinction. *Nature, 242,* 485–488.
Garfield, E. (1970b). Citation indexing for studying science. *Nature, 227,* 669–671.
Garfield, E. (1973). Editorial. *Current Contents, 40,* 5–7.
Garrett, A. B. (1963). *The flash of genius.* Princeton, NJ: Van Nostrand.
Gruber, H. E. (1984). *Darwin on man: A psychological study of scientific creativity* (2nd ed.). Chicago: University of Chicago Press.
Gruber, H. E. (1988). The evolving systems approach to creative work. *Creativity Research Journal, 1,* 27–51.
Gruber, H. E. (1989). The evolving systems approach to creative work. In D. B. Wallace & H. E. Gruber (Eds.), *Creative people at work* (pp. 3–24). Oxford: Oxford University Press.
Hadamard J. (1945). *The psychology of invention in the mathematical field.* Princeton, NJ: Princeton University Press.
Hess, W. R. (1963). From medical practice to theoretical medicine. In D. J. Ingle (Ed.), *A dozen doctors. Autobiographic sketches* (pp. 41–64). Chicago: University of Chicago Press.
Hindle, B. (1981). *Emulation and invention.* New York: New York University Press.
Hindle, B. (1984). Spatial thinking in the bridge era: John Augustus Roebling versus John Audolphus Etzler. *Annals New York Academy Sciences, 424,* 131–148.
Holton, G. (1973). On trying to understand scientific genius. In *Thematic origins of scientific thought, Kepler to Einstein* (pp. 353–382). Cambridge, MA: Harvard University Press.
Keller, E. F. (1983). *A feeling for the organism: The life and work of Barbara McClintock.* San Francisco: Freeman.
Koch, W. E. (1978). *The creative engineer. The art of inventing.* New York: Plenum.
Lorenz, K. (1952). *King Solomon's ring.* New York: Crowell.
Lowinger, A. (1941). *The methodology of Pierre Duhem.* New York: Columbia University Press.
McClelland, D. C. (1962). On the psychodynamics of creative physical scientists. In H. E. Gruber, G. Terrell, & M. Wertheimer (Eds.), *Contemporary approaches to creative thinking* (pp. 141–174). New York: Atherton.
Mitroff, I. I. (1974). *The subjective side of science.* New York: Elsevier.
Möbius, P. J. (1900). *Die Anlage zur Mathematik* [The basis of mathematics]. Liepzig: Barth.
Nachmansohn, D. (1972). Biochemistry as part of my life. *Annual Review of Biochemistry, 41,* 1–28.
Ostwald, W. (1909). *Grösse Manner* [Great men]. Leipzig: Akademische Verlag.
Pauling, L. (1963). The genesis of ideas. *Proceedings of the third world congress of psychiatry, 1961, 1,* 44–47).
Pauling, L. (1981). Chemistry. In W. Shropshire Jr. (Ed.), *The joys of research* (pp. 132–146). Washington, DC: The Smithsonian Institution Press.
Planck, M. (1949). *Scientific autobiography and other papers* (F. Gaynor, Trans.). New York: Philosophical Library.
Platt, W., & Baker, R. A. (1931). The relationship of the scientific 'hunch' to research. *Journal of Chemical Education, 8,* 1969.
Ramon y Cajal, S. (1937). *Recollections of my life* (E. H. Craigie & J. Cano, Trans). Cambridge, MA: MIT Press.
Richet, C. (1927). *The natural history of a savant* (O. Lodge, Trans.). London: Dent.
Roe, A. (1951). A study of imagery in research scientists. *Journal of Personality, 19,* 459–470.
Roe, A. (1953). *The making of a scientist.* New York: Dodd Mead.
Root-Bernstein, R. S. (1984). Creative process as a unifying theme of human cultures. *Daedalus, 113,* 197–219.
Root-Bernstein, R. S. (1985). Visual thinking: The art of imagining reality. *Transactions of the American Philosophical Society, 75,* 50–67.
Root-Bernstein, R. S. (1987). Harmony and beauty in biomedical research. *Journal of Molecular and Cellular Cardiology, 19,* 1–9.
Root-Bernstein, R. S. (1989). *Discovering, inventing and solving problems at the frontiers of science.* Cambridge, MA: Harvard University Press.
Root-Bernstein, R. S. (1995). The sciences and arts share a common creative aesthetic. In A. I. Tauber (Ed.), *The elusive synthesis: Science and aesthetics.* Baltimore: Johns Hopkins University Press.
Root-Bernstein, R. S., Bernstein, M., & Garnier, H.

(1993). Identification of scientists making long-term, high-impact contributions, with notes on their methods of working. *Creativity Research Journal, 6,* 329–343.

Smith, C. S. (1981). *A search for structure. Selected essays on science, art, and history.* Cambridge, MA: MIT Press.

Snow, C. P. (1959). *The two cultures.* Cambridge, England: Cambridge University Press.

Taylor, C. W. (1963). Some possible relations between communication abilities and creative abilities. In C. W. Taylor & F. Barron (Eds.), *Scientific creativity: Its recognition and development* (pp. 365–371). New York: Wiley.

Taylor, D. W. (1963). Variables related to creativity and productivity among men in two research laboratories. In C. W. Taylor and F. Barron (Eds.), *Scientific creativity: Its recognition and development* (pp. 228–250). New York: Wiley.

Van't Hoff, J. H. (1967). Imagination in science (G. F. Springer, Trans.), *Molecular biology, biochemistry, and biophysics, 1,* 1–18. (Original work published 1878)

Whipple, G. H. (1963). Experimental pathology—as student and teacher. In D. J. Ingle (Ed.), *A dozen doctors. Autobiographic sketches* (pp. 210–246). Chicago: University of Chicago Press.

White, R. K. (1931). The versatility of genius. *Journal of Social Psychology, 2,* 460–489.

Wilson, M. (1972). *Passion to know.* Garden City, NY: Doubleday.

Woodward C. E. (1989). Art and elegance in the synthesis of organic compounds: Robert Burns Woodward. In D. B. Wallace & H. E. Gruber (Eds.), *Creative people at work* (pp. 235–260). New York: Oxford University Press.

Zuckerman, H. (1977). *Scientific elite: Nobel laureates in the United States.* New York: Free Press.