OF NOBEL CLASS: A CITATION PERSPECTIVE ON HIGH IMPACT RESEARCH AUTHORS

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ABSTRACT. The purpose of this paper was to determine if quantitative rankings of highly cited research authors confirm Nobel prize awards. Six studies covering different time periods and author sample sizes were reviewed. The number of Nobel laureates at the time each study was published was tabulated, as was the number of high impact authors who later became laureates. The Nobelists and laureates-to-be were also compared with non-Nobelists to see if they differed in terms of impact and productivity. The results indicate that high rankings by citation frequency identify researchers *of Nobel class* – that is, a small set of authors that includes a high proportion of actual Nobelists and laureates-to-be. Also, the average impact (citations per author) of Nobelists and laureates-to-be is sufficiently high to distinguish them from non-Nobelists in these rankings. In conclusion, a simple, quantitative, and objective algorithm based on citation data can effectively corroborate – *and even forecast* – a complex, qualitative, and subjective selection process based on human judgement.

Key words: citation analysis, citation impact, Nobel prize, Science Citation Index, scientometrics

1. INTRODUCTION

The Nobel prize is unique among all the awards in science. Since 1901 when the first laureates were named, the Nobels have become the universally recognized symbol of research excellence both by the scientific community and the general public. The public perception of an award's prestige is influenced by many factors. Among these, according to Harriet Zuckerman, Columbia University, are the age of the prize, the amount of its honorarium, the reputation of its sponsoring organization, and the stature of its recipients [1].

The Nobel Committee's power to confer so coveted and prestigious a prize on a small, elite group of scientists and the secrecy that shrouds its selection process also add to the prize's mystique and visibility. For a few weeks every October, the scientific community holds its breath in anticipation of the Nobel Committee's pronouncements on the new laureates in medicine, physics, and chemistry. And for several months after, the science and popular press profile the winners and try to intuit the Nobel Committee's subjective deliberations.

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For 25 years now, the Institute for Scientific Information® (ISI®) has published analyses of citation patterns in the research literature to determine whether or not they confirm – *and even anticipate* – the Nobel awards. The idea is straightforward. Presumably, the Nobel prize is awarded to researchers who have made breakthrough discoveries in science. The papers they publish ought to be seminal and more influential than the average, and thereby become important or significant.

One means of characterizing the impact of researchers, both Nobelists and non-Nobelists, is to count their papers and the number of times they are cited. The researchers can then be compared on the basis of *productivity* (articles per author), *author impact* (citations per author), and *article impact* (citations per paper).

The purpose of this study is to review six major ISI rankings of high impact authors to determine how many already were Nobel laureates at the time each ranking was published and how many authors later went on to win the prize. The Nobelists and laureates-to-be were also compared with non-Nobelists to see if they differed in terms of impact and productivity.

The results indicate that high rankings by citation frequency are strongly correlated with Nobel class authors. In the highest percentile, e.g. the top 0.1% of authors, a significant percentage have won the Nobel prize or go on to win the prize in later years. Also, the author impact of Nobelists is sufficiently high to distinguish them from non-Nobelists. But in terms of author productivity, the margin of difference between Nobelists and non-Nobelists is slight.

Out of the million scientists in the world, it is remarkable that any system can identify a small set of authors that includes a high proportion of both present and future Nobelists. It is even more remarkable because the citation-based system is a quantitative and objective algorithm that does not rely on subjective or qualitative enhancement.

2. REVIEW OF SIX MAJOR ISI STUDIES OF MOST-CITED AUTHORS

The ISI database includes more than 14 million source articles published in thousands of journals since 1945, and more than 200 million references they cited. Over the years, we have published literally scores of studies examining directly or indirectly the relationship between citedness and Nobel awards. The studies vary widely in the number of most-cited authors or articles considered, ranging from the top 50 to 1,000. They also vary by time span, some covering annual data files while others are based on multiyear cumulations of the *Science Citation Index*® (*SCI*®), *Social Sciences Citation Index*® (*SSCI*®) and *Arts & Humanities Citation Index*® (*A&HCI*®).

Instead of detailing the particulars of each study, we offer a summary of six major multipart studies of most-cited authors [2–18]. Table I provides data on total numbers of authors, time spans, and other statistical details for these studies. Readers may refer to the original papers [2–18] to examine the lists of authors and papers – far too extensive to reproduce here.

TABLE I
Summary information on most-cited author studies based on *Science Citation Index (SCI)* data

	1967[a]	1972[b]	1961–72[b]	1961–75[c]	1961–76[d]	1965–78[e]
Pre-Nobel						
Authors	8	5	5	13	15	26
Citations	6,274	4,859	40,376	94,586	99,468	120,248
Impact	784	972	8075	7276	6631	4625
Post-Nobel						
Authors	6	7	13	38	22	35
Citations	5,107	6,966	100,923	279,472	146,652	174,252
Impact	851	995	7763	7355	6666	4979
All Nobel						
Authors	14	12	18	51	37	61
Citations	11,381	11,825	141,299	374,058	246,120	294,500
Impact	813	985	7850	7334	6652	4828
Non-Nobel						
Authors	36	38	32	198	263	939
Citations	29,287	34,091	259,613	1,194,775	1,402,326	3,515,504
Impact	813	897	8113	6034	5332	3744
*Authors	35	37	31	197		
*Citations	26,366	28,166	224,415	1,136,471	NA	NA
*Impact	753	761	7239	5769		
Total						
Authors	50	50	50	249	300	1,000
Citations	40,668	45,916	400,912	1,568,833	1,648, 446	3,810,004

[a] Based on [2].
[b] Based on [3].
[c] Based on [4–6].
[d] Based on [7–11].
[e] Based on [12–17].
* Excluding citations to O.H. Lowry. (See sec. 4.3.1. below.)

In each of these studies we determined which and how many authors already were Nobel laureates (post-Nobel) or went on to win the prize later (pre-Nobel). We then compared them with non-Nobelists in terms of impact and productivity.

As this review will show, most-cited author rankings effectively identify groups or sets of authors *of Nobel class* [18], including actual Nobelists. This is not surprising, since citation data have been shown to correlate highly with other indicators of 'prestige' or 'eminence', such as peer ratings, academy memberships, etc.[19–21].

But ISI's system also effectively *forecasts* future laureates – that is, identifies a group of most-likely candidates. This is remarkable because a simple, quantitative, and objective algorithm can consistently anticipate a highly subjective and qualitative selection process.

Of course, not every most-cited author will go on to win the Nobel prize, although virtually all Nobelists are highly cited within their specialties. Some may rank high on the basis of just a few high impact papers. Others may be listed because of widely cited methods. But even the highest impact authors who have made major theoretical contributions are not assured of Nobel recognition – while many may be deserving, only a few are honored. Zuckerman refers to this group as occupants of the '41st chair' who are not included in the French Academy's limited membership of 40 – they are "peers of prizewinners in every sense except that of having the award" ([1], p. 42).

2.1. Nobelists Versus Average Authors

The six studies to be reviewed were initiated by a report presented in 1965 [22]. This was the earliest ISI study related to citedness and Nobel prize winners. It was based on a list of about 256,000 *primary* authors cited in the 1961 *SCI*. That is, only the *first* author of a cited paper was identified, credited with all citations, and ranked. Co-authors were excluded. The names of the 1962 and 1963 Nobel prize winners in physics, chemistry, and medicine were checked against the ranked list. Their publication and citation statistics were compared against those for the average author in the same file.

The results showed striking differences: the average Nobel author received 169 citations, 30 times more than the average author (5.5). In addition, Nobelists were far more productive than the average. They published 58.1 cited papers, 17 times more than the average (3.37). But as a result, the average Nobelist-authored paper was cited 2.9 times, 'only' about double the average article (1.6). These results – higher author impact, productivity, and paper impact – were characteristic throughout the later studies.

2.2. Nobelists Versus Most-Cited Authors

The results led us to ask early on whether lists of most-cited authors could be used to forecast Nobel prize winners. In a 1970 *Nature* paper[2], the 50 most-cited primary authors in the 1967 *SCI* were identified. The list included six scientists (12.0%) who had already won the Nobel prize through 1967. Even more interesting, eight others listed (16.0%) went on to become laureates after 1967. Out of that list, derived from a single annual file of 1967 data, 14 Nobelists (28.0%) have been identified through 1990.

Subsequent lists have identified authors most-cited in later years with increasing time frames and numbers of authors: 1972 (50 authors)[3], 1961–72 (50)[3], 1961–75 (249)[4–6], 1961–76 (300)[7–11], and 1965–78 (1,000)[12–17]. The first three were based on primary author data. But the last two were 'all author' rankings, which included high impact *co*-authors for the first time.

Figure 1 summarizes the number of Nobel laureates that appeared in these studies. The first bar indicates the number of *pre*-Nobel authors listed – that is, laureates-to-be who went on to win the prize after the concluding year in each study. The middle bar shows *post*-Nobel authors – those who had already won the prize. The last bar represents the *total* number of Nobelists.

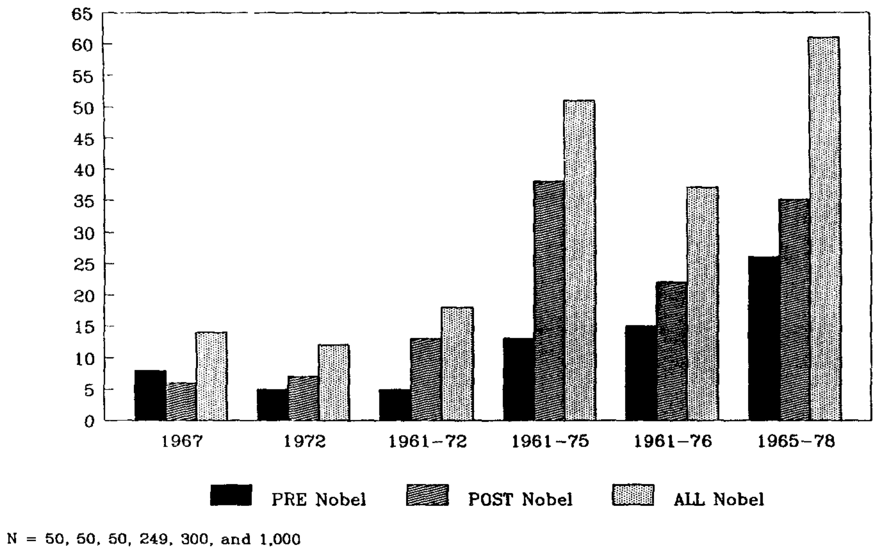

Fig. 1. Number of Nobelists appearing in six ISI studies of most-cited research authors. "Pre-Nobel" refers to researchers who become laureates *after* each study was published. "Post Nobel" refers to those who already were laureates. See Table I for detailed data on each study.

In general, more Nobelists are identified as the studies increase in time frame and numbers of authors (Table I). The exception is the 1961–76 list of 300 most-cited authors. It listed 37 Nobelists, including those who had already won the prize by 1976 and laureates-to-be through 1990, compared with 51 in the

1961–75 list of 249 authors. Keep in mind that the 1961–76 study was the first to restrict the publication years of cited papers. It identified most-cited authors based on papers published from 1961 through 1978. Thus, Nobelists who were highly cited for work prior to 1961 were not included. Also, this was the first 'all-author' list and included high impact *co-authors*. Adding co-authors increases the number of non-Nobel authors in the pool because Nobelists only occasionally write papers with other laureates.

The data also show that, in general, most-cited author rankings identify more Nobelists who have already won the prize than laureates-to-be. Whatever the number of authors or time frame for citation and/or publication, the method both *corroborates* existing Nobelists and *anticipates* a significant number. The forecasting power of the citation analyses we have conducted is remarkable in that 26 future laureates were identified [12–17].

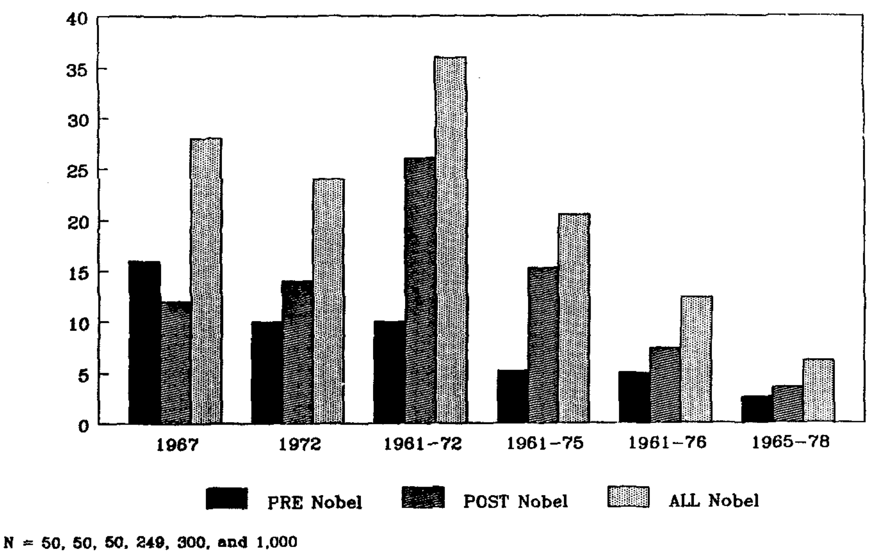

Fig. 2. Percentage of Nobelists appearing in six ISI studies of most-cited research authors. "Pre Nobel" refers to researchers who became laureates *after* each study was published. "Post Nobel" refers to those who already were laureates. See Table I for detailed data on each study.

On a percentage basis, however, the highest yields of Nobelists come in the smaller studies involving fewer authors, as shown in Figure 2. In the first three studies covering different years but including the top 50 authors, Nobelists on average represented 29.3–17.3% who already won the prize and 12.0% laureates-to-be. In the next two larger studies involving 249 and 300 authors, Nobelists averaged 16.0–10.9% post-Nobelists and 5.1% laureates-to-be. In the 1,000 author study, the Nobelist average drops to 6.1–3.5% post-Nobels and 2.6% pre-Nobels.

These data show that most Nobelists rank high on most-cited lists, because of their greater impact and productivity as authors. Extending lists beyond the top 50–100 names yields greater absolute numbers of Nobelists, but they inevitably account for a smaller proportion of the total.

2.3. Nobel Authors Have Higher Impact

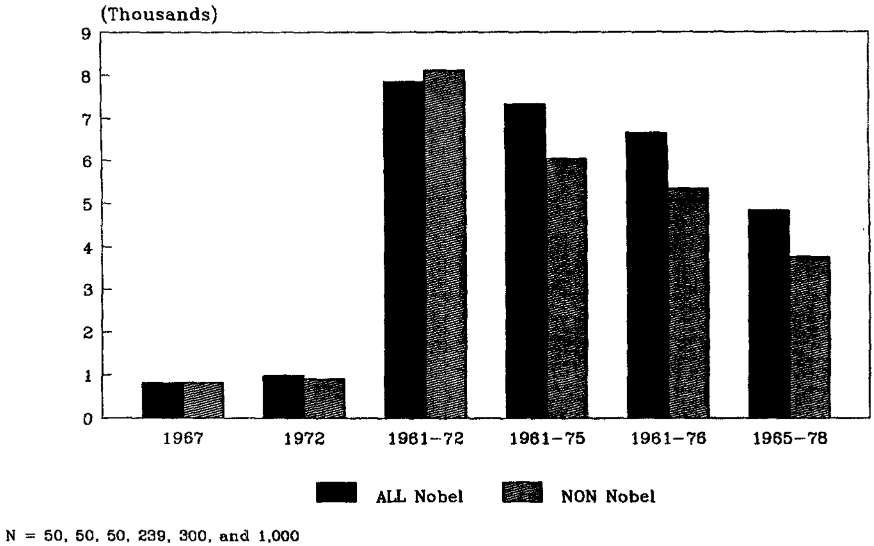

Fig. 3. Author impact (average number of citations per author) of Nobelists and non-Nobelists researchers appearing in six ISI studies of most-cited research authors. See Table I for detailed data on each study.

Figure 3 compares the average number of citations per author for Nobelists and non-Nobelists. In general, the impact of Nobelists is comparable to non-Nobelists but increases appreciably in larger studies covering more recent years. The difference is greatest in the 1,000 author study – the average Nobelist author impact (4828) is 28.9% higher than for the non-Nobelist (3744). When Nobelists who had already won the prize are compared with laureates-to-be, there is virtually no difference across the studies, as is shown in Figure 4.

Thus, the impact of Nobelists, both present and future, is sufficiently high to distinguish them from non-Nobelists. The difference is not as great as in

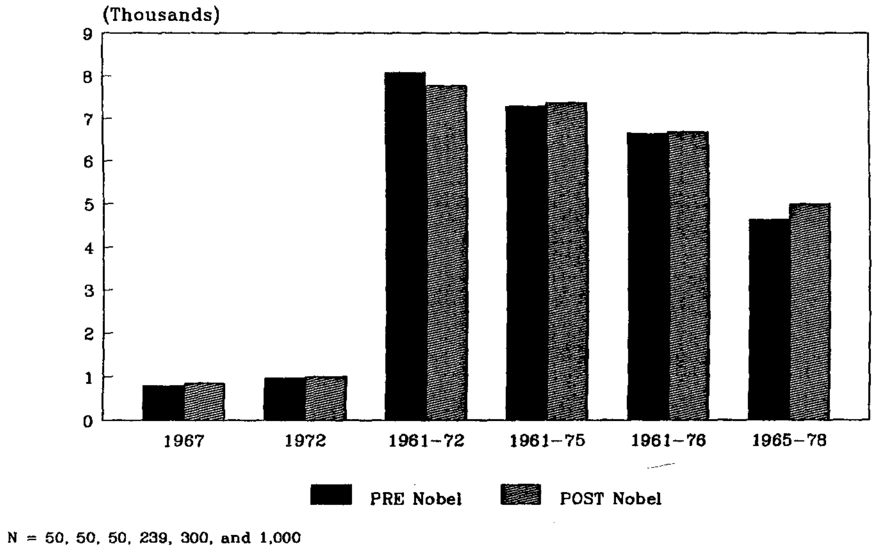

Fig. 4. Author impact (average number of citations per author) of Nobelists appearing in six ISI studies of most-cited research authors. "Pre-Nobel" refers to researchers who became laureates *after* each study was published. "Post-Nobel" refers to those who already were laureates. See Table I for detailed data on each study.

the study discussed earlier, which compared Nobelists with the average author in the *SCI* file [22]. Of course, the basis for comparison here is the *most*-cited authors, a very select group representing less than 1% of all scientists. In other words, these authors might be considered to be *of Nobel class*. The fact that several go on to win the prize merely reinforces this point. But, as stated earlier, not everyone listed will eventually win the Nobel prize. While virtually all Nobelists are highly cited, not every high impact author is a laureate-to-be.

2.4. Nobel Papers Have Higher Impact, Too

Two of the most-cited article studies included data on papers – the 1961–76 and 1965–78 all-author lists. They allow comparisons on the basis of paper impact (average citations per paper) and productivity (average papers per author) as well. The data are presented in Table II.

The average paper by a Nobel author was cited about 25% more than a non-Nobel paper. Papers by Nobelists who had already won the prize were cited about 38% more than papers by laureates-to-be. And the impact of papers by laureates-to-be is only slightly higher (about 15%) than that of non-Nobelists in the top group.

TABLE II
Article impact and author productivity in two most-cited author studies based on *Science Citation Index (SCI)* data

	1961–76[a]	1965–78[b]
Pre-Nobel		
Authors	15	26
Papers	2,546	3,304
Citations	99,468	120,248
Impact	39.1	36.4
Productivity	169.7	127.1
Post-Nobel		
Authors	22	35
Papers	2,496	3,919
Citations	146,652	174,252
Impact	58.8	44.5
Productivity	113.4	112.0
All Nobel		
Authors	37	61
Papers	5,042	7,223
Citations	246,120	294,500
Impact	48.8	40.8
Productivity	136.3	118.4
Non-Nobel		
Authors	263	939
Papers	40,016	114,119
Citations	1,402,326	3,515,504
Impact	35.0	30.8
Productivity	152.1	121.5
Total		
Authors	300	1,000
Papers	45,058	121,342
Citations	246,120	294,500
Impact	5.5	2.4
Productivity	150.2	121.3

[a] Based on [7–11].
[b] Based on [12–17].

In terms of productivity, *non*-Nobelists show the higher overall averages, accounting for 152.2 and 121.5 papers per author, compared to 136.3 and 118.4 for Nobelists. However, laureates-to-be have the edge – they produced 169.7 and 127.1 papers per author. But, again, the margin of difference is slight.

3. A FORECAST FOR THE 1990S

Despite the possible methodological limitations, to be discussed in the next section, lists of the highest impact authors in a given time period are still rather effective in identifying past, present, and future Nobelists. As an outlook on laureates-to-be of the 1990s, we have identified the 100 most-cited authors of articles published and cited in 1981–1990. They are listed in Table III.

TABLE III
The 100 most-cited authors of the 1980s, ranked by citations to papers indexed in the 1981–1990 *Science Citation Index (SCI)*

Author	Field[1]	1981–1990 Citations	1981–1990 Papers
Gallo RC	Virology	36,789	591
Schlossman SF	Immunology	21,682	348
Nishizuka Y	Cell Biology	20,143	181
Hood LE	Molecular Biology	18,288	324
Messing J	Molecular Biology	18,229	35
Fauci AS	Immunology	17,756	563
Bloom SR	Gastroenterology	16,543	1,468
Vale W	Neuroendocrinology	16,422	348
Dinarello CA	Immunology	16,143	482
Berridge MJ	Cell Biology	16,004	93
Rosenberg SA	Surgery/Oncology	15,922	430
Rivier J	Endocrinology	15,893	320
Seeburg PH	Neurobiology	14,454	124
Irvine RF	Cell Biology	14,431	108
Chambon P	Molecular Biology	14,190	246
Reinherz EL	Immunology	14,067	220
Wong-Staal F	Virology	13,910	254
* Baltimore D	Virology	13,847	222
* Goldstein JL	Genetics	13,120	202
* Brown MS	Biochemistry	13,031	171
Franke WW	Cell Biology	12,930	280
Hokfelt T	Neuropharmacology	12,881	381
Strominger JL	Virology	12,817	253
Ullrich A	Biochemistry	12,670	199
* Bishop JM	Virology	12,427	162
* Thomas ED	Oncology	12,306	412
Snyder SH	Pharmacology	12,302	308
Witten E	Physics	12,105	96
Sporn MB	Biochemistry	11,657	182
Lefkowitz RJ	Pharmacology	11,619	320
Weber K	Biochemistry	11,607	270
Polak JM	Histology	11,583	924
Springer TA	Cell Biology	11,234	199
Maniatis T	Molecular Biology	11,167	81
Evans RM	Molecular Biology	10,980	191
Weinberg RA	Molecular Biology	10,831	138

Table III (cont.)

Author	Field[1]	1981–1990 Citations	1981–1990 Papers
Lundberg JM	Physiology	10,810	304
Waldmann TA	Immunology	10,658	195
Leder P	Molecular Biology	10,620	115
Cerami A	Biochemistry	10,593	263
Ruoslahti E	Molecular Biology	10,468	180
Hunter T	Molecular Biology	10,465	216
Marrack P	Immunology	10,377	157
Tjian R	Molecular Biology	10,334	109
Pastan I	Biochemistry	10,319	337
Sarngadharan MG	Virology	10,181	118
Vogelstein B	Oncology	10,128	99
Sharp PA	Molecular Biology	10,099	167
Storb R	Immunology	9,995	439
Collen D	Hematology	9,985	381
Gossard AC	Physics	9,954	304
Vieira J	Molecular Biology	9,921	21
Herberman RB	Oncology	9,907	345
Austen KF	Immunology	9,846	366
Tsien RY	Physiology	9,742	94
Ling N	Neuroendocrinology	9,604	244
Gilman AG	Pharmacology	9,590	72
Goeddel DV	Neuroscience	9,552	93
Montagnier L	Virology	9,494	189
Feinberg AP	Genetics	9,375	21
Tatemoto K	Neurochemistry	9,272	195
Greengard P	Cell Biology	9,246	264
Koprowski H	Microbiology	9,231	332
Goldstein G	Immunology	9,086	183
Aaronson SA	Oncology	9,039	178
Roberts AB	Molecular Biology	9,024	145
Popovic M	Virology	8,992	181
Rosenfeld MG	Molecular Biology	8,959	135
Takai Y	Biochemistry	8,927	136
Fiers W	Molecular Biology	8,863	256
Paul WE	Immunology	8,862	177
Van Houtte PM	Cardiology	8,837	475
Gillis S	Immunology	8,723	204
* Varmus HE	Virology	8,680	120
Sugimura T	Oncology	8,533	427
Greene WC	Oncology	8,495	172
Starzl TE	Surgery/Transplants	8,447	640
Caron MG	Biochemistry	8,428	247
Braunwald E	Cardiology	8,427	290
Matsuo H	Biochemistry	8,402	295
Numa S	Molecular Biology	8,341	112
Oppenheim JJ	Immunology	8,300	200
Crystal RG	Medicine	8,293	315
Verma IM	Molecular Biology	8,254	112

Table III (cont.)

Author	Field[1]	1981–1990 Citations	1981–1990 Papers
Ui M	Molecular Biology	8,211	163
Croce CM	Genetics	8,208	218
Genest J	Biochemistry	8,162	353
Cantin M	Medicine	8,124	382
Doolittle RF	Biochemistry	8,046	79
Timpl R	Biochemistry	7,961	253
Wuthrich K	Molecular Biology	7,897	197
Minna JD	Oncology	7,897	165
Hsu SM	Molecular Biology	7,847	123
* Corey EJ	Chemistry	7,833	307
Waterfield MD	Biochemistry	7,803	79
Rutter WJ	Endocrinology	7,802	159
Swanson LW	Neuroscience	7,723	171
Schlessinger J	Molecular Biology	7,691	170
Goldstein M	Neurochemistry	7,611	303
* Tonegawa S	Immunogenetics	7,571	84

Eight Nobelists through 1990 are included, indicated by asterisks. While this article was in press, the 1991 Nobel prizes were announced. The new laureates for medicine or physiology are Erwin Neher of the Max Planck Institute for Biophysical Chemistry, Göttingen, and Bert Sakmann, Max Planck Institute for Medical Research, Heidelberg. Although neither appears in Table III, both *are* among the 300 most-cited scientists of the 1980s with over 5,800 citations each to their 1980s papers. The 1991 Nobel prize winner in chemistry is Richard Ernst of the Eidgenossische Technische Hochschule, Zürich. With more than 6,200 citations to his 1980s publications, Ernst also ranks among the 300 most-cited scientists of the decade. Pierre-Gilles de Gennes, College de France, Paris, was awarded the 1991 Nobel prize for physics. His 1980s papers were cited over 2,100 times, which places him among the 1,500 most-cited researchers of the decade. No doubt, he would rank among the top 100 if we considered only the most-cited *physicists* of the 1980s, for reasons discussed in the following section.

Data are available to test whether productivity, author impact, and paper impact are possible 'markers' of laureates-to-be. These rankings are in preparation and will be published when completed. They may prove to be more or less effective in targeting laureates-to-be, especially when combined with other independent indicators, such as Lasker Award winners, academy elections, etc.

This was done in a forecast of Nobel winners in medicine for 1989 that appeared in *The Scientist* [23]. Out of a list of about 200 most-cited authors in the 1973–84 *SCI*, the field of most-likely candidates was narrowed down to just

20 names by also considering who had already won the Albert Lasker Basic Medical Research Award, the Gairdner International Award, and other 'predictor prizes'. The 1989 winners, J.M. Bishop and H.E. Varmus, were on the list.

4. DISCUSSION

4.1. Nobelists in Smaller Specialties

All the lists we have reviewed are undifferentiated rankings of the most-cited authors in a given time period. The most-cited authors in larger fields achieve higher citation rates. So molecular biology, genetics, biochemistry, and other life sciences tend to dominate, and fewer authors in physics and chemistry are represented. Despite this limitation, the method still effectively anticipates future Nobel awards.

However, the Nobel Committee sometimes selects relatively small specialties for recognition. Authors in these areas may not show up in listings for the established disciplines. But when citation data for the specialty is *disaggregated*,[2] the forecasting results significantly improve.

An example is radio astronomy, recognized by 1978 Nobel awards to R.W. Wilson and A.A. Penzias. Both ranked among the top 5 authors in their field, cited in the 1961–1975 *SCI* [18]. Another example is computerized axial tomography. The 1979 Nobel was awarded to G.N. Hounsfield and A.M. Cormack. They were among the 15 authors in this specialty most-cited in the 1961–79 *SCI* [18]. In both instances, a small set of authors ranked by citation frequency included, that is, anticipated, the Nobel awards.

4.2. Nobelists in Economics and Literature

The Nobel prize for economics, first awarded in 1969, provides another opportunity for citation comparisons. In 1990, we listed the top 50 economists most-cited as *primary* authors of both articles *and* books in the 1966–86 *SSCI* [24]. It included seven authors who were deceased and therefore not eligible for the prize, which is restricted to living individuals.

Fifteen Nobelists were listed – an incredible 62.5% of the 24 economics awards through 1986. In addition, two laureates-to-be, R.M. Solow (1987) and R.H. Coase (1991), were listed. Of course, future prizes may still be won by those listed who are eligible.

The Nobel prize for literature abounds in controversies about personal, geographic, and philosophical biases. Still, citation rankings succeed in corroborating a significant proportion of Nobel literature awards.

For example, a list of the 100 authors most-cited in the 1977–78 *A&HCI* included 25 Nobelists [25]. Only two so far are laureates-to-be – Gabriel Garcia Marquez (1982) and Octavio Paz (1990). But this is 7.1% of the 28 names on the list still eligible for the award in 1990. Five authors who became Nobelists within the five years previous to the study were identified. It would seem that citation rankings can also be effective in forecasting Nobel literature prizes.

4.3. The Odds Against Forecasting Nobels with Citation Data

As stated earlier, 26 laureates-to-be in science have been identified by a quantitative and objective algorithm that ranks authors by total citations [12–17]. One-third of all Nobel prizes in medicine, chemistry, and physics from 1979 to 1990 have been anticipated by the list of most-cited authors in the 1965–78 *SCI*. Considering all the possible factors that can limit an undifferentiated citation ranking, it is remarkable that such a large number of laureates-to-be can consistently be identified.

We have already discussed one such limitation, the trend for life science fields to dominate the rankings. Another is the purported dominance of methods papers and authors. ISI's lists of most-cited authors and articles [26–47] would provide a good sample to test this anecdotal assumption, but it remains to be done. Of course, high impact methods – and their authors – will appear and can 'skew' the results.

4.3.1. The Lowry Phenomenon

A classic example is Oliver Lowry, whose 1951 methods paper has been extraordinarily cited – more than 205,000 times through 1990 [48]. If the most-cited author data are adjusted (censored) for the 'Lowry factor', the average impact of non-Nobelists drops about 5% to 18% across the four applicable lists. The summary data in Table I shows this.

However, Lowry is a statistical anomaly, an extreme far beyond the normal citation range of methods papers or authors. No doubt, other authors of high impact methods papers will appear on undifferentiated lists. But the fact that so many present and future Nobelists also appear would argue that theoretical authors rank high as well. Their individual paper impact may be lower, but the cumulative impact resulting from their higher than average productivity puts them in the upper echelon of cited authors.

It is interesting that researchers tend to hold theoretical advances in greater esteem than methodological contributions. But new methods, techniques, and instruments play an important and even critical role in scientific research. They frequently increase the efficiency, speed, and sensitivity of laboratory and clinical studies. They also often enable researchers to conduct experiments that otherwise would have been extremely difficult if not impossible. For these reasons, methodological contributions deserve appreciation and recognition on a par with theoretical advances. Indeed, the Nobel prizes have recognized exceptional methodological breakthroughs – for example, the 1991 chemistry award to R. Ernst for his development of nuclear magnetic resonance spectroscopy; the 1986 physics award to E. Ruska for devising the electron microscope, and to G. Binnig and H. Rohrer for designing the scanning tunneling microscope; the 1979 physiology or medicine award to A.M. Cormack and G.N. Hounsfield for inventing the computerized axial tomography scanner, and so on.

4.3.2. The Obliteration Phenomenon

It is well established that certain papers reporting landmark findings are paradoxically *under*-cited or even *un*cited. They are rapidly incorporated into the canonical knowledge of a field, and references are no longer *explicitly* cited in bibliographies or footnotes. This is known as 'obliteration by incorporation' [49,50].

A good example is the 1953 Watson and Crick letter to *Nature* describing the double-helical structure of DNA [51]. It was cited 'only' about 1,400 times through 1990. Its citation is now virtually 'totemic' – it is cited more for its place in science history than for its content.

4.3.3. Premature and Post-Mature Discovery

Certain ideas or methods seem to have been overlooked by contemporary scientists and then 'rediscovered' many years later. These discoveries may have been *pre*mature – literally ahead of the prevailing wisdom of their times, conceptually or practically [52]. Or they may be *post*-mature – advances that, in retrospect, should have been made earlier [53].

Illustrative cases have been rare and anecdotal. Citation data suggest the phenomenon is perhaps more common than usually thought. In a still-continuing series on the most-cited papers of 1945–1988, annual citation distributions were used to identify possible 'sleepers' or 'late bloomers'[54–56]. Whether or not they are genuine cases of pre- or post-mature discovery depends on the informed opinion of experts close to the subject.

5. CONCLUSION

The data reviewed here indicate that author citation rankings are an effective method for identifying both past and present Nobelists as well as laureates-to-be. It is difficult to say what is really more remarkable. That a simple, quantitative, objective algorithm can corroborate and anticipate a complex, qualitative, subjective selection process? Or that a highly subjective process can consistently select authors having the highest quantitative and objective impact in medicine, chemistry, physics, economics, and literature?

As stated earlier, Nobelists are consistently highly cited while only a small percentage of most-cited authors win the prize. It would be expected that a large percentage of the latter are elected to national academies of science. But a study remains to be completed. Certainly in the former USSR and elsewhere, other factors besides scientific achievement enter the equation.

NOTES

[1] Authors' fields in Table III were self-defined in questionnaires sent to those who appeared in the 1965–1978 study of the 1,000 most-cited scientists [12–17]. For non-respondents and authors who did not appear in that study, fields were defined by the department affiliation in the addresses listed in their recent papers. When departments were not specified, fields were defined by titles of articles and journals.

[2] Citation data can be disaggregated for various specialties in several ways. The simplest method is to use *journal titles* to define specialties. This can be done by broad field categories (e.g., journals of life sciences, medicine, chemistry, physics, and so on) or by particular subdisciplines within fields (e.g. journals of genetics, immunology, electrochemistry, particle physics, and so on). Of course, this method relies on the subjective definitions of fields and specialties made by journal publishers, editors, or subject specialists. In addition, multidisciplinary journals – such as *Nature* or *Science* – defy easy categorization by field or specialty.

A more sophisticated method is to use co-citation analysis to identify discrete clusters of research specialties. The method has been described in detail in previous publications [57,58]. Simply described, co-citation clustering involves tracking *pairs* of papers that are cited together in articles ISI indexes on an annual basis. An algorithm pairs all references cited in a particular article, and identifies other papers that co-cite the same pairs of articles. When the same pairs are co-cited with other papers by many authors, a *cluster* of research begins to form. The co-cited papers in these clusters share some common topic, subject area, or method. The cluster is automatically named by using the words and phrases that citing authors themselves provide in the titles of their articles.

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