Mentorship and protégé success in STEM fields

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Einstein believed that mentors are especially influential in a protégé's intellectual development, yet the link between mentorship and protégé success remains a mystery. We marshaled genealogical data on nearly 40,000 scientists who published 1,167,518 papers in biomedicine, chemistry, math, or physics between 1960 and 2017 to investigate the relationship between mentorship and protégé achievement. In our data, we find groupings of mentors with similar records and reputations who attracted protégés of similar talents and expected levels of professional success. However, each grouping has an exception: One mentor has an additional hidden capability that can be mentored to their protégés. They display skill in creating and communicating prizewinning research. Because the mentor's ability for creating and communicating celebrated research existed before the prize's conferment, protégés of future prizewinning mentors can be uniquely exposed to mentorship for conducting celebrated research. Our models explain 34–44% of the variance in protégé success and reveals three main findings. First, mentorship strongly predicts protégé success across diverse disciplines. Mentorship is associated with a 2×-to-4× rise in a protégé's likelihood of prizewinning, National Academy of Science (NAS) induction, or superstardom relative to matched protégés. Second, mentorship is significantly associated with an increase in the probability of protégés pioneering their own research topics and being midcareer late bloomers. Third, contrary to conventional thought, protégés do not succeed most by following their mentors' research topics but by studying original topics and coauthoring no more than a small fraction of papers with their mentors.

mentors | coarsened exact matching | science of science | career success | computational social science

In 1921, two scientists debated mentorship's role in the development of scientific talent (1). Thomas Edison believed that mentors impart to students a subject matter's essential facts and formulas in aid of preparing students to be on the leading edge of application. Albert Einstein countered that mentors should promote new thinking in students. "The value of an education," he concluded, "is not the learning of many facts but the training of the mind to think something that cannot be learned from textbooks" (2).

Within the bounds of this debate, there are many anecdotes but limited research on whether mentorship—according to either definition—impacts protégé success (3–5). Socrates mentored Plato, who mentored Aristotle, who mentored Alexander the Great—a genealogical pattern found among some Renaissance scholars, such as Galileo, Viviani, Barrow, and Newton, as well as a handful of modern-day Nobelists (3, 5, 6). The NSF reported that "breakthrough scientists" cite "an intimate association with a great inspiring teacher" as a dominant factor in their success (7). Funding agencies also advocate for strong mentorship: A study of NIH awards in medicine reveals that 47% of principal investigators received funds for mentorship (8, 9). However, the systematic nature of these cases remains an open question (10) with mentorship sometimes being faulted for involving favoritism (11) or "cloning" (12). Data limitations have also created a preponderance of findings from self-report surveys rather than actual performance (9, 13).

New longitudinal datasets from the genealogy and academic records of 10s of thousands of scholars permit new exploration of the link between mentorship and protégé success. Using these datasets, we conducted one of the largest multidisciplinary investigations of mentorship and mentee performance. Our analyses follow 37,157 mentors and protégés who published 1,167,518 papers in biomedicine, chemistry, math, and physics between 1960 and 2017. Genealogical data on mentors and protégés come from the ProQuest PhD Dissertation & Thesis databank (PQTD), an official record of advisor–student relationships taken from PhD theses, and is supplemented with crowdsourced data from Academictree.org and the Mathematics Genealogy Project (MGP). We merged genealogy data with a scholar's discipline, publications, coauthors, citations, sex, research topics, and institutional affiliation using Web of Science and Microsoft Academic Graph databases. We measured protégé success using a variety of measures including 1) scientific prizewinning (14, 15), 2) election to the NAS (16), and 3) superstardom—a scientist who is a prizewinner, NAS member, and in the top 25% of citations in their field. The *SI Appendix* presents details on data and measures.

The analytical challenge in studying mentorship is assortativity. Assortativity results in highly talented mentors attracting highly talented students. Thus, it becomes indeterminate as to whether the success of students is due to innate talent or mentorship (3, 17, 18). Random assignment of equivalently talented protégés to mentors with different abilities would experimentally control student quality while allowing mentors' qualities to vary.

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Significance

Mentorship is arguably a scientist's most significant collaborative relationship; yet of all collaborations, comparatively little research exists on the link between mentorship and protégé success. Using new large-scale data from the genealogical and performance records of 10s of thousands of scientists worldwide from 1960 to the present, we found that mentorship is associated with diverse forms of protégé success, significantly increasing protégés' chances of producing celebrated research, being inducted into the National Academy of Science, and achieving superstardom. Paradoxically, protégés achieve their highest impact when they display intellectual independence from their mentors. Protégés do their best work when they break from their mentor's research topics and coauthor no more than a small portion of their overall research with their mentors.

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However, in real-world settings, random assignment is impossible because it may harm students' careers.

To address these research constraints using observational data, we used a matching design (19, 20) popular for studying scientific performance (18, 21–24). Given assortativity, mentors of equivalent reputation and record should attract students of similar caliber, who, in turn, have similar expected levels of success based on innate talent and equivalent academic environments (17, 18, 25, 26). To identify students with equivalent talents in our data, we find groupings of mentors with similar

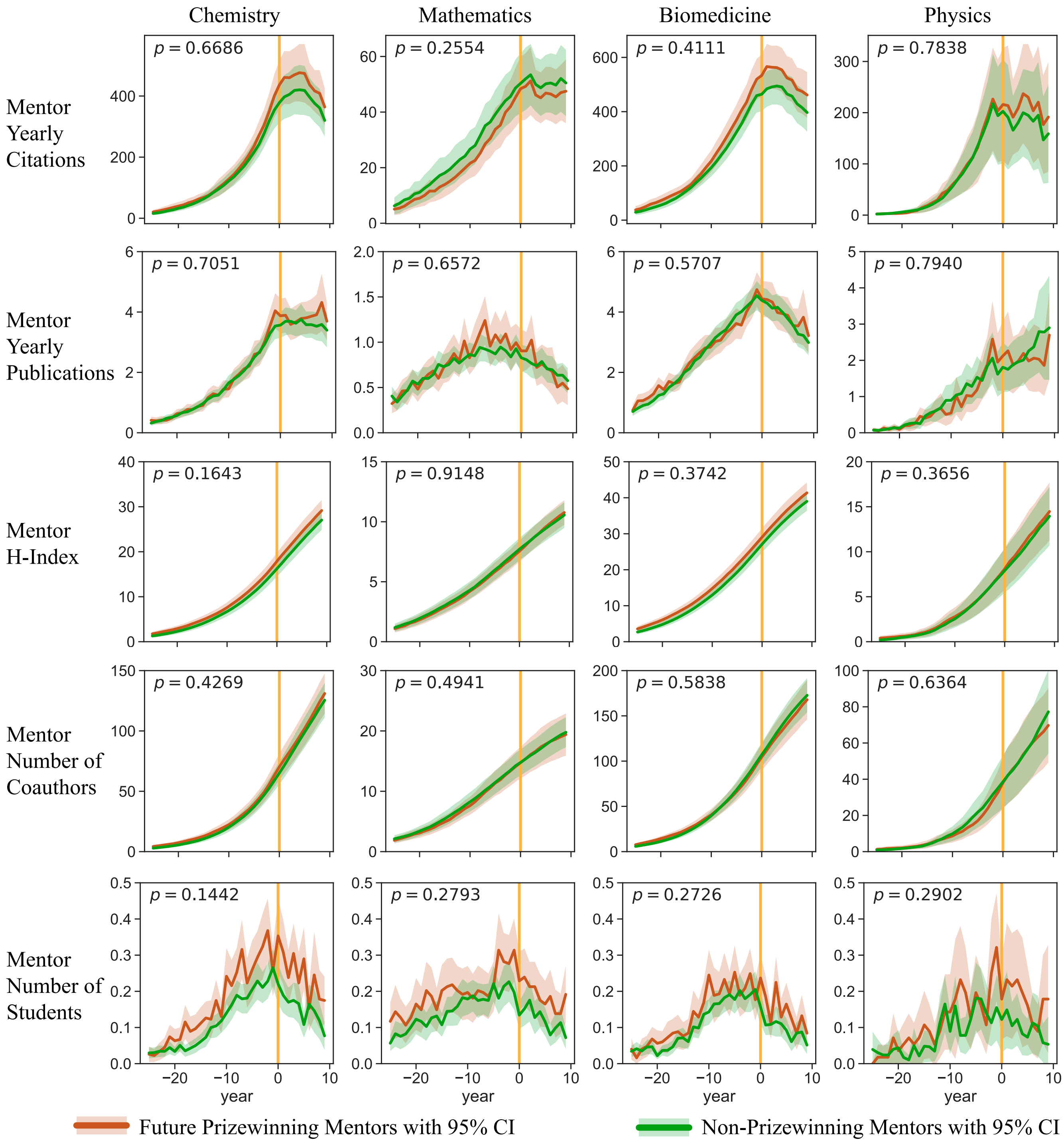

Fig. 1. Matched mentors are equivalent on 11 attributes of record and reputation. Plots show that matched future prizewinning mentors (FPWMs) and nonprizewinning mentors (NPWMs) have equivalent records and reputations from the start of mentors' careers to the prize year of the FPWM, except for the hidden talent of FPWMs. Time-varying attributes, such as citations and productivity are matched on an annual basis to capture dynamic career characteristics. Time-invariant attributes, such as discipline are matched discretely. Lines represent the mean values on each attribute (the areas around the lines are 95% CIs). Wilcoxon rank-sum tests of all shown attributes as well as h-index and university rank showed no significant differences (all P values > 0.05) between FPWMs and NPWMs. One hundred percent of the mentors match on discipline and gender. All mentors' career starting years match within 5 yr of one another.

records and reputations who attracted protégés of similar talents and expected levels of professional success. However, each grouping has an exception: One mentor has an additional hidden capability that can be mentored to their protégés. They display skill in creating and communicating prizewinning research. Publishing prizewinning papers indicates a scientist's ability to conduct research that is impactful and celebrated (3, 14, 15, 27–30). It is a "hidden" ability because it necessarily exists prior to the prize's conferment (27, 31, 32). Because the mentor's ability existed before the prize's conferment, protégés of future prizewinning mentors can be exposed to mentorship skills that are associated with conducting extraordinary research.

Methodologically, we find six groupings of matched mentors who are statistically similar on 11 visible performance metrics of scholarly record and reputation: discipline, year of first publication, productivity, citations, h-index, average journal impact factor, number of students, number of coauthors, topic expertise, school rank, and gender (26, 33–36). Matching of mentors occurs on a yearly basis for time-varying criteria to capture career dynamics. For each grouping of six matched mentors, our matching periodization begins the year of the mentors' first publications and ends the year of the prizewinning mentor's first prize.

Fig. 1 shows the uniform statistical similarity of our matched future prizewinning mentors (FPWMs) and non-prizewinning mentors (NPWMs). In the figures, 100% of the mentors match on discipline and gender. Solid lines in the plots are means, and shaded areas are 95% CIs around the means. The figure demonstrates that FPWMs and NPWMs have no statistical differences in yearly citation rates, yearly publication rates, yearly h-indices, number of collaborators, or number of students. The *SI Appendix* provides cases of matched and unmatched mentors.

If matching has reasonably resulted in the protégés of FPWMs and NPWMs being comparable in talent, protégés of FPWMs and matched NPWMs would be expected to show similar first job placements (17) and early career records but different records beyond that early professional stage as the longer-term impact of a protégé's research crystallizes (26, 37). The rank of the university at which a protégé is placed in their first job is an important primary signal of matching because it measures whether the "market" views the students to be of equivalent talent and

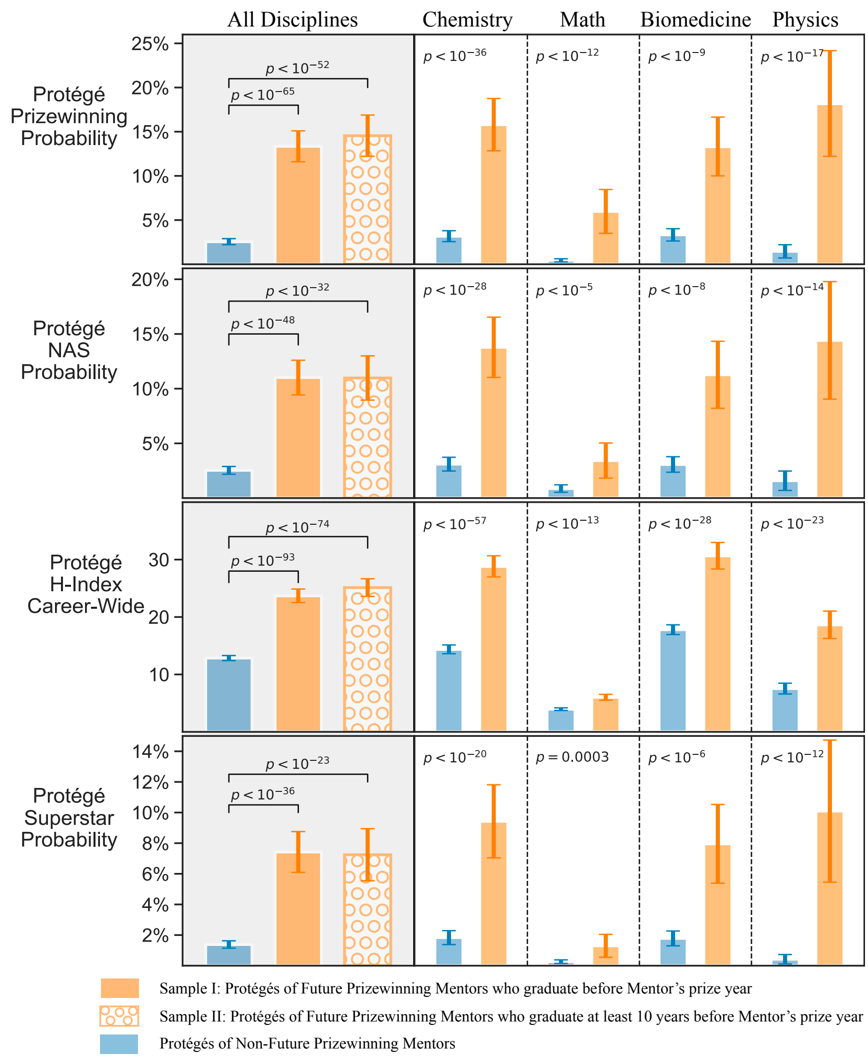

Fig. 2. Mentorship and probabilities of protégé performance. Plots show the raw data relationship between mentorship and protégé performance. FPWMs are over five, four, and three times more likely to win scientific prizes, be elected to the NAS, and achieve superstardom than protégés mentored by NPWMs; all disciplines are aggregated together (column 1) or shown separately (cols. 2–5). All P values are $P < 0.001$ and are shown separately per test in the figure. The results generalize across two samples of protégés to account for undue positive impressions that a protégé's work could conceivably receive after their advisor becomes a known prizewinner. Sample I includes protégés who graduated before their mentor's prize year, and sample II includes protégés who graduated 10 or more years before their mentor's prize year. All protégés of NPWMs are included in the analysis of both samples.

promise (18, 38). Also, institutional prestige strongly affects a mentee's future productivity and reputation (18, 39). In our sample, protégés of FPWMs and NPWMs have no statistical differences in first job placement. The proportion of protégés of FPWMs and NPWMs placed at universities of rank 1–3 are 5.1%, 64.5%, 30.4%, and 5.3%, 64.8%, 29.9%, respectively (χ^2 test P value = 0.889). Once hired, the size of a mentee's laboratory is an indicator of their ability to get research funding, attract top students, and show institutional leadership important for career advancement (4, 5). Both groups of protégés show no statistical differences in the number of students they advise (P value = 0.286). As an independent check on the comparable talent of mentees of FPWMs and NPWMs, we acquired data on mentees' IQ (which can explain up to 30% of the variance in problem-solving) (40). An analysis of Mensa IQ data on a sample of students showed that the protégés of FPWMs and NPWMs have no significant IQ difference (P value = 0.449) (see the *SI Appendix* for details).

Early career records are likely to create durable cumulative advantages over a scholar's career (41). Looking at mentees' early career records, we do find a difference. Protégés of NPWMs have stronger starting records than protégés of FPWMs. Up to about 10 y after graduation, protégés of NPWMs have higher yearly citations, productivity, h-indices, and the number of coauthors (P value < 0.001). For example, the average yearly citations of the protégés of NPWMs and FPWMs are 37 and 28, respectively. However, at about 10 y after graduation, the pattern reverses apparently due to the longer-term implications of a protégé's record gain recognition (37, 42). At about 10 y after graduation, protégés of FPWMs have statistically better records than the protégés of NPWMs in terms of yearly citations, productivity, and h-indices (P value < 0.001), suggesting protégés of FPWM are more likely to be mid-to-late career bloomers (P value < 0.001).

These patterns demonstrate that our two groups of protégés have equivalency in talent and institutional environments at the starts of their careers and that our analysis errs on the side of being conservative because the early career lead of protégés of NPWMs normally grow with time (41, 43, 44). The *SI Appendix* shows protégé comparison tests by discipline (*SI Appendix*, Fig. S1).

Results

Our analysis presents tests over two different samples. Sample I includes students of FPWMs who graduated before their mentor's prize year. Sample II includes students of FPWMs who graduated, at least, 10 y before their mentor's prize year. Protégés who graduate 10 y before their mentor's prize represent a subset of protégés of FPWMs who cannot reasonably be suspected of anticipating whether a mentor will or will not be a future prizewinner. Furthermore, such protégés are likely to have established records and reputations of their own making (37) by the time their mentor becomes a prizewinner, removing any positive impression of students who graduate shortly before the prize year. All students of NPWMs are included in tests to capture the successes of the protégés of NPWMs that occur anytime before or after the prize year; looking at the protégés of NPWMs up to the prize year does not change the results. In all cases, mentee citations due to mentor–mentee coauthorship are excluded from the analysis.

Fig. 2 indicates that protégés of FPWMs have significantly higher probabilities of success across diverse measures of performance and disciplines. Protégés of FPWMs in sample I are 5.2, 4.4, and 1.8 times more likely to become scientific prizewinners, be elected to the NAS, and have higher citation impact than protégés of NPWMs, respectively. Analysis of the more restrictive sample II shows nearly identical probabilities of protégé success as in sample I. Protégés of FPWMs who graduate, at least, 10 y before their mentor's prize year are 5.7, 4.3, and 2.0 times more likely to win scientific prizes, become NAS members, and have higher citation impact than protégés of NPWMs, respectively. Finally, the protégés of FPWMs are 5.4 times more likely to become "superstar scientists" (45)—prizewinners, NAS members, and in the top 25% of citations in their field—than protégés of NPWMs.

To observe how the mentor–mentee relationship varies with other predictors of success, we used coarsened exact matching (CEM) regression (19, 20). CEM regression conceptually runs a separate regression for each matched grouping of mentors and then aggregates a weighted average of the separate regressions to theoretically account for confounds more stringently than standard regression can (19). The regression includes conrtols for a mentor's citation impact, a mentor's number of coauthors, a mentor's number of students, percentage of a protégé's work that is coauthored with their advisor, protégé's and mentor's topic dissimilarity, protégé's citation impact, protégé's number of coauthors, whether a protégé has a prizewinning coauthor, and protégé's graduation order (46–49). Fixed effects included the mentee's discipline and university rank and the mentor's prize year (see the *SI Appendix* for variable operationalizations).

Table 1 indicates that the CEM regression models explain 35–44% of the variance in protégé success. The control variables support previous conjectures that the amount of attention a mentor can give to each mentee as measured by the number of students a mentor has and the graduation order of the protégé is inversely related to protégé success (4, 5) while a protégé's coauthors and citation impact are positively related to success (6, 50, 51).

Protégés who have future prizewinning mentors are strongly and reliably predicted to be successful. The regressions estimate that protégés of FPWMs are 2.1 times more likely to become prizewinners, 1.4 times more likely to be elected to the NAS, and 1.5 times more likely to be superstars than protégés of matched nonprizewinning mentors. The influence of having a FPWM relative to other variables in the model depends on the success outcome measured. The model predicting the likelihood that a protégé becomes a prizewinner estimates that being a student of a FPWM has the largest influence of any binary variable. In the models predicting NAS election and superstardom, the relative influence of being a student of a FPWM must account for direct and indirect effects. For example, NAS membership election is based on having made fundamental lifetime contributions to science, which often depend on awards that are conferred before becoming a NAS member (16). These relationships suggest that the influence of a FPWM on a protégé's NAS election has direct effects (FPWM → protégé's NAS election) and indirect effects through the protégé being a prizewinner (FPWM → protégé's prizewinning → protégé's NAS election). Indeed, a mediation analysis showed that 74% of the total effect of having a FPWM on a protégé's NAS election comes indirectly through the protégé being a prizewinner. The superstar model has similar patterns (see the *SI Appendix* for methodological details and superstar model results). *SI Appendix*, Fig. S2 and Tables S2 and S5 in the *SI Appendix* report robustness checks accounting for FPWMs who win one vs. multiple prizes, correlations among the dependent variables, cross-validation, and null models.

We found that patterns of mentor–protégé's topic dissimilarity and coauthorship shape the link between mentorship and mentee success. Topic dissimilarity—the degree to which a protégé studies topics that differ from the topics studied by their advisor—is significantly and positively related to mentee success. The proportion of coauthored papers between a mentee and a mentor within the mentee's total body of work negatively relates to mentee success. If a protégé goes from 0 to 100% of coauthored papers with their advisor, their average log odds of prizewinning drops 1.5 points. These findings are surprising given the expectation that successful protégés are the next rising stars of their advisor's hit research topic (4). For example, a study of 62 highly productive mentors at research universities found that mentors "overwhelmingly nominated

Table 1. Coarsened exact matching regressions of the relationship between mentorship and protégé scientific success

	(1)	(2)	(3)	(4)	(5)	(6)
	Protégé is prizewinner	Protégé is prizewinner	Protégé elected to NAS	Protégé elected to NAS	Protégé is superstar	Protégé is superstar
Protégé's mentor is a future prizewinner		0.732***		0.364*		0.415*
		(0.174)		(0.171)		(0.211)
Protégé's mentor is NAS	0.768***	0.438*	0.914***	0.757***	0.916***	0.732***
	(0.146)	(0.175)	(0.164)	(0.181)	(0.190)	(0.216)
% Protégé's papers coauthored w/mentor	−3.087***	−2.769***	−3.097**	−2.923**	−6.953***	−6.648***
	(0.791)	(0.771)	(0.944)	(0.928)	(1.713)	(1.703)
Protégé–mentor topic dissimilarity	1.900***	1.843***	3.020***	2.997***	2.810***	2.819***
	(0.549)	(0.560)	(0.615)	(0.621)	(0.836)	(0.846)
Protégé's graduation order	−0.337*	−0.416*	−0.551**	−0.593**	−0.479*	−0.540*
	(0.170)	(0.177)	(0.182)	(0.185)	(0.240)	(0.244)
Protégé citation impact	1.277***	1.282***	1.346***	1.347***	3.354***	3.346***
	(0.171)	(0.169)	(0.184)	(0.183)	(0.371)	(0.370)
Protégé no. of coauthors	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Protégé has prizewinning coauthor	0.231	0.242	0.434**	0.441**	0.431*	0.434*
	(0.145)	(0.145)	(0.148)	(0.148)	(0.183)	(0.184)
Mentor citation impact	−0.049	0.027	−0.011	0.029	0.183	0.230
	(0.094)	(0.097)	(0.106)	(0.107)	(0.113)	(0.120)
Mentor no. of coauthors	−0.002**	−0.002***	−0.001*	−0.002*	−0.001	−0.001*
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Mentor no. of student's	−0.298***	−0.260**	−0.231*	−0.212*	−0.331**	−0.310**
	(0.086)	(0.085)	(0.093)	(0.093)	(0.106)	(0.105)
Protégé univ. rank	Yes	Yes	Yes	Yes	Yes	Yes
Protégé discipline	Yes	Yes	Yes	Yes	Yes	Yes
Mentor prize Y. decade	Yes	Yes	Yes	Yes	Yes	Yes
constant	−5.763***	−5.943***	−6.866***	−6.953***	−13.578***	−13.674***
	(0.725)	(0.718)	(0.780)	(0.773)	(1.334)	(1.324)
Pseudo R-square	0.34	0.35	0.36	0.37	0.43	0.44
N	18265	18265	18265	18265	18265	18265

The models explain 34–44% of the variance in protégé success and indicate that mentorship is among the most influential predictors. Notably, protégé success is blunted by a lack of intellectual independence from their mentor's line of research. Protégés succeed most when they break away from their mentor's line of research by conducting research on topics not studied by their mentors and coauthoring a small fraction of their overall body of research with their mentor. The *SI Appendix* presents regression details of robustness checks. $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

as their most successful protégés those (16) whose careers were essentially identical to their own…" (12). These findings suggest that while mentorship is positively related to protégé success, protégé success requires intellectual independence. The greatest returns to mentorship are likeliest when mentees break away from their advisor's research program and chart their own course of research.

Discussion

Our analysis of large-scale genealogical and scientometric databases indicate that mentorship is positively linked to mentee scientific impact. We created groups of matched mentors who were equivalent on 11 attributes of record, resources, and reputation and who, by assortativity, should attract comparably talented protégés. However, each matched groupings had one mentor with a hidden talent—they had the skills to become future prizewinners. Protégés of FPWMs are more likely to produce prizewinning research of their own, be inducted into the NAS for career-long scientific contributions, and do high impact work late into their careers when creativity often wanes.

A possible account for the findings is that working under a FPWM exposes protégés to rare skills for conducting and communicating novel high impact scientific findings. Harriet Zuckerman referred to this special scientific knowledge as "tacit information" (3). Tacit information is the kind of knowledge that is difficult to codify in writing and, therefore, tends to be transferred between people informally, through face-to-face interaction, and learned outside regimented instruction. Organizational researchers consider tacit knowledge an important intangible asset for building effective problem-solving routines (52, 53). In scientific contexts, tacit knowledge can include strategies and skills for selecting problems, framing research questions (3), responding to reviews (6), or communicating results in a way that makes the analysis and findings both competent and stylish (5, 6). Tacit knowledge is also thought to be fungible enough to be applied to new problems (54). In science, this may explain why protégés of FPWMs are more likely to pioneer their own original lines of research rather than follow their mentor's established lines of research. The common expectation is that protégés of successful mentors professionally excel, in part, because they are perceived as the next rising star working on their advisor's hit topic (4). We found, however, that protégé success increases when they study topics that differ from their mentor's topics and coauthor a small proportion of their total papers with their mentors. Thus, protégés of FPWMs may gain, from their advisors, rare and versatile skills that can be applied to new research topics. In this way, mentees follow a path of intellectual independence that breaks from their advisor's research and correlates with success. Future research should extend these findings and related ones (5, 6) by directly measuring tacit knowledge's specific components and range of functions in science.

Future research should also examine the finding's generalizability. A NIH study showed that 47% of funded PIs in medicine received funds for mentorship (8), indicating that faculty evaluations are based partly on mentorship (55). We examined four diverse scientific fields and 10s of thousands of scientists over their careers; yet given our focus on scholarly measures of performance, our sample reflects primarily scientists and scholars from research institutions. It remains an open question whether mentorship at nonresearch institutions works in a similar manner. Similarly, we focused on the relationship between mentorship and protégé scholarly success without addressing social support, a key factor of most successful mentor–protégé relationships. Carl Jung, a student of Sigmund Freud, observed "One looks back with appreciation to the brilliant teachers…The curriculum is so much necessary raw material, but warmth is the vital element for the growing plant and for the soul of the child" (56). As laboratories grow over time and more work is performed in larger teams (50), there may be more opportunities and professional work competing for a mentor's time, putting this source of social support at risk. Further study to increase understanding of social support's role in successful mentorships may help mitigate that risk.

Similarly, we attempted to crudely quantify soft skills by measuring the amount of coauthorship a mentor shares with their mentee and by measuring a mentor's number of students. We found that coauthorship—which may, in fact, be a necessary means of social support—is, nonetheless, negatively associated with protégé success because it may create an impression that the protégé lacks intellectual independence. Determining, in practice, the correct balance between soft skills mentorship and mentee independence may be another avenue of future research.

During the Edison–Einstein debate, Edison developed a test to measure a student's formal knowledge. He gave it to job applicants at his company, thinking that a basic knowledge of science offered an ideal background for helping develop new products (incidentally, Einstein took the test and failed it). Einstein's insight that the essence of mentorship is less about the teaching of facts and more about training the mind to think may have been farsighted as scientific facts are increasingly just a click away, but human creativity remains limited.

Materials and Methods

Our sample covered the careers of scientists working in biomedicine, chemistry, math, and physics from 1960 to 2017. Genealogical data on mentor–protégé ties came from the PQTD and was supplemented by crowdsourced data from Academictree.org and the MGP. Microsoft Academic Graph and Web of Science (WoS) databases were our sources for the academic records and institutional affiliation. NAS data and scientific prize and prizewinner data came from Wikipedia, Wikidata, and the official prize websites and are listed in the *SI Appendix*. See the *SI Appendix* for details on measures, CEM regression methods, null models, and cross-validation.

Data Availability. The data are publicly available from PQTD, academictree.org, MGP, WoS, and Wikipedia. The study used no special computer code.

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