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Assessing science training programs: Structured undergraduate research programs make a difference

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Abstract:

Training in science, technology, engineering, and mathematics (STEM) is a top priority for driving economic growth and maintaining technological competitiveness. We propose that exposure to a rigorous research program as an undergraduate leads to success in a research STEM career. We compared the scientific outcomes of 88 participants from five National Science Foundation Research Experiences for Undergraduates (REU) Site programs with demographically-similar applicants to assess the impact that formal, organized, and funded undergraduate summer research experiences have on participants. Our study demonstrates that REU participants are more likely to enter a PhD program and generate significantly more valued products, including presentations, publications, and awards, relative to applicants. We believe that key components of the program, include funding for personal and professional needs, access to diverse intellectual, analytical, and field resources, and the presence of other undergraduate researchers, who continue to support each other and share their goals and interests.

Introduction:

Scientific, technological, and economic competitiveness is motiving greater interest and investment in science, technology, engineering, and mathematics (STEM) training around the world (Gentile et al. 2017), with an emphasis on addressing the current shortage of STEM PhDs (Brewer et al. 2011, National Academy of Sciences 2010). With annual spending on STEM training well over US$14 billion in the United States (US Department of Labor 2007), guiding future investments in STEM training demands good understanding of effective approaches (US National Science Board 2015, Hanauer et al. 2017, Lopatto 2004, Wei and Woodin 2011). For example, undergraduate research experience is often credited with preparing students for success in STEM careers (Graham et al. 2013, Kolb and Kolb 2005, US Department of Labor 2007, US National Academy of Sciences et al. 2010). However, quantitative assessments of STEM training are rare (Hanauer et al. 2017, Linn et al. 2015) due to a variety of problems including the difficulty of tracking long-term scientific outcomes in a controlled fashion.

Considering the global importance of sound investments of limited resources and the need to identify effective models for STEM training (Barney 2017), we quantitatively analyzed data from demographically matched students who participated (hereafter “participants”) or applied but did not participate (“applicants”) to the same United States National Science Foundation (NSF) Research Experience for Undergraduates (REU) Site summer program held from 2009 to 2011. These independent and geographically dispersed training programs fully support REU participants to conduct independent research projects. Participants are awarded an NSF-defined “take-home” stipend and travel and housing support. During fiscal years 2015-2017 NSF REU Site programs across the entire Foundation spent more than $185M across more than 500 grants, and trained over 150,000 REU participants (grant data available at https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5517).

In this study, we use 88 participant-applicant pairs of undergraduate students associated from five field biology-based REU Sites supported by NSF to determine the impact of structured research experience on future STEM productivity (measured as the number of scientific presentations, publications, merit-based academic awards as well as the terminal degree pursued; see data available in *Supplementary Information*).

Methods:

Participant and applicant information

Participant and applicant data from five field-based NSF REU Site programs held during summer 2009 (three Sites, 23 student pairs), 2010 (three Sites, 22 student pairs), and 2011 (five Sites, 43 student pairs) were collected from REU grant principal investigators (see *Supplementary Information*). A “participant” is defined as a student who was admitted and who successfully completed the program. An “applicant” is defined as a qualified undergraduate student who applied for admission to one of the participating REU Site programs, but was not admitted. Each student (participant and applicant) was tracked between 5 and 7 years post-REU experience. To account for this variation in time, paired (participant and applicant) data were treated as a random factor in our statistical analyses. For each REU Site, a demographically-similar (i.e., gender, race, ethnicity, age, home institution type (private or public) and size, major, focus area, and grade point average) applicant was paired with an REU participant (see *Supplementary dataset A*).

Measured outcomes

Five individual-specific outcomes were considered in this study, including (#1) general field of study (STEM or non-STEM; Figure 1A) and (#2) highest degree pursued (doctorate (PhD), healthcare (e.g., Doctor of Medicine, Doctor of Veterinary Medicine, Doctor of Pharmacy), masters of science (MS), masters of business administration (MBA), bachelor of science (BS), associate of arts (AA), and high school (HS); Figure 1B) and number of (#3) scientific presentations and (#4) publications and (#5) academic awards (Figure 2; see *Supplementary data*). Information for outcomes was collected using a combination of REU Site PI tracking data, social media (i.e., LinkedIn, Facebook, Google Scholar), and internet searches. Identities of each student were confirmed by name, undergraduate institution, and year of graduation. Pairs were included in our analyses only if all data were available for both members of the pair. Publications were counted if they were published in a scientific journal. Scientific awards (including grants) associated with merit and related to scientific contributions were counted. GPA related awards, such as Dean's List, were not included. Finally, presentations (including oral and poster formats) were counted if they were scientific in nature.

Statistical analyses

117 Chi-square tests were used to compare distributions of REU participants and applicants
118 according to their discipline (STEM or non-STEM, Figure 1A) and terminal degree
119 pursued (Figure 1B). No statistical difference was observed between REU participants'
120 and applicants' current discipline (STEM or non-STEM; Figure 1A, chi-square P =
121 0.214) or terminal degree types pursued (Figure 1B, chi-square P = 0.135). However,
122 REU participants pursued more PhD and less MS degrees than applicants (Figure 1B,
123 chi-square P = 0.018). Given that chi-square tests tend to perform poorly with limited
124 data for a specific group (e.g., n<5), another chi-square test was conducted without
125 including data for MBA, AA, and HS degrees. This analysis with fewer degree
126 categories also showed no significant differences between REU participants and
127 applicants (Figure 1B, chi-square P = 0.097).

128

129 A generalized linear mixed model fit by maximum likelihood (Laplace approximation)
130 with Poisson distribution and "Pair" as a random factor was used to compare the
131 scientific outcomes (i.e., presentations, publications, or awards) of de-identified,
132 demographically paired NSF REU participants and applicants (main effect = REU
133 experience). The REU experience effect is interpreted as the multiplicative increase in
134 scientific productivity an REU participant exhibits relative to the demographically-similar
135 applicant. Thus, an "REU effect" where the 95% confidence intervals include 1
136 indicates that paired students had statistically similar outcomes. An REU effect >1
137 (lower 95% confidence interval >1) indicates that an REU applicant was more
138 productive than a paired applicant.

139

Although we were not interested in evaluating differences across the five REU Sites included in this study, we conducted an additional generalized linear mixed model analyses including REU experience, Site, and REU experience x Site interaction for the three primary outcomes (presentations, publications, and awards) for thoroughness (see *Supplementary dataset B*). In general, our findings from these additional analyses were consistent with our primary analyses (presented in Figure 1B). For example, all three of the analyses showed significant REU experience effects (all $P \leq 0.024$). We did find significant Site x REU experience interactions for all three outcomes (all $P \leq 0.0074$). However, for all Sites and outcomes except one (publications at Site C), the estimated effect of the REU experience was positive (albeit not always significantly so).

Chi-square and generalized linear mixed model statistics were conducted using the base package of R and the *glmer* function in the *lme4* package of R (Bates et al. 2015), respectively.

De-identified data associated with REU participant and applicant pairs are available in the *Supplementary information*. Requests for additional information about this study can be made directly to the corresponding author, Alan Wilson, at wilson@auburn.edu

Results:

As a group, applicants to, and participants of, NSF REU Site programs are similarly biased toward selecting STEM field careers (Figure 1A; chi-square $P = 0.214$). However, REU participants are 48% more likely to pursue PhDs than applicants (Figure

1B; chi-square $P = 0.018$). This result alone supports the hypothesis that structured independent undergraduate research experience is an important stepping stone to a STEM terminal degree. Additionally, of the REU participants included in our analyses who provided demographic information (gender 72%; race 75%), females and under-represented minorities (including African-Americans, Hispanic Americans, and Native Americans) accounted for 57% and 42%, respectively. Further diversification is generated from NSF's expectation that REU participants will be selected from a broad range of schools, especially institutions with limited research opportunities. Typically, PhD students come from research intensive public universities or private liberal arts colleges (Fiegener and Proudfoot 2013). Thus, these results suggest an important broader impact of REU programs; namely that they serve as a powerful tool for supporting the economic and cultural diversification of Ph.D.-level scientists.

Potentially as a result of an increase in advanced degrees pursued by REU participants, we found that participation in REU Site programs was also effective at boosting research productivity (Figure 2). For example, REU participants produced 2.14 times and 1.58 times as many scientific presentations and publications, respectively, and, earned 1.37 times as many academic awards than applicants (Figure 2D; generalized linear mixed model all $P \leq 0.012$). Considering that these outcomes are central forms of intellectual currency and indicators of future success in STEM (Laurance et al. 2013, Morales et al. 2017), our findings suggest that there are both short-term (products) and long-term (careers) benefits to participating in NSF REU Site programs. We did find a significant interaction between the REU experience and REU Site program location (any of the five participating programs, see *Supplementary dataset B*). However, the effect of REU experience was estimated to be positive across almost all REU Sites and outcomes, suggesting that the REU experience, in general, drives the patterns we observed despite variation in program location, management, and implementation.

Discussion:

Our quantitative results show the potential effectiveness of undergraduate research experiences (Figure 2) are consistent with earlier qualitative (Linn et al. 2015, Lopatto 2004) and quantitative findings (Hanauer et al. 2017)– structured independent research training is hugely effective at cultivating future scientists. However, an important question remains – Why do these experiences work? (Gentile et al. 2017) In general, NSF REU Sites provide structured and fully funded research experiences for student cohorts (~8-10 students) for several weeks (~8-10 weeks per summer) where REU participants collaboratively work with a senior scientist with an active research program and peer scientists while participating in a variety of professional development enrichment activities, such as learning to read research articles, presenting oral or poster presentations, preparing applications for graduate school, and networking with other scientists. All or some of these training characteristics could explain our findings (Abudayyeh 2003, Auchincloss et al. 2014, Fox et al. 2017, Linn et al. 2015, Morales et al. 2017, Rocchi et al. 2016, Shanahan et al. 2015, Taraban and Logue 2012). Nonetheless, NSF REU Sites are not prescribed. Instead, REU PIs have significant flexibility in leveraging available laboratory, analytical, field, and human infrastructure to create the most impactful experiential learning for their REU participants. Therefore, despite variation across NSF REU Sites in their research, professional development, and networking activities, we found strong effects of NSF REU experiences (Figure 2D). These findings are even more impressive considering that our comparison of paired participants and applicants to the same REU Site did not exclude applicants who conducted other undergraduate research, including participating in other NSF REU Sites or similar programs. Thus, our analyses may actually underestimate the impact of participating in undergraduate research programs, in general. Given the positive impacts of undergraduate research, we argue for continued investment in such programs, including making certain they are available to all demographic groups (Economy et al. 2014, Linn et al. 2015, MacLachlan 2012, US National Academy of Sciences et al. 2010), as a way of maintaining a strong, global STEM workforce.

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Author contributions:

AEW designed the study, JLP collected data, AEW and TDS performed the statistical analyses, AEW and IB wrote the first draft of the manuscript, and all authors contributed substantially to revisions, including the submitted draft.

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299 **Competing financial interests:** The authors declare no competing financial interests.

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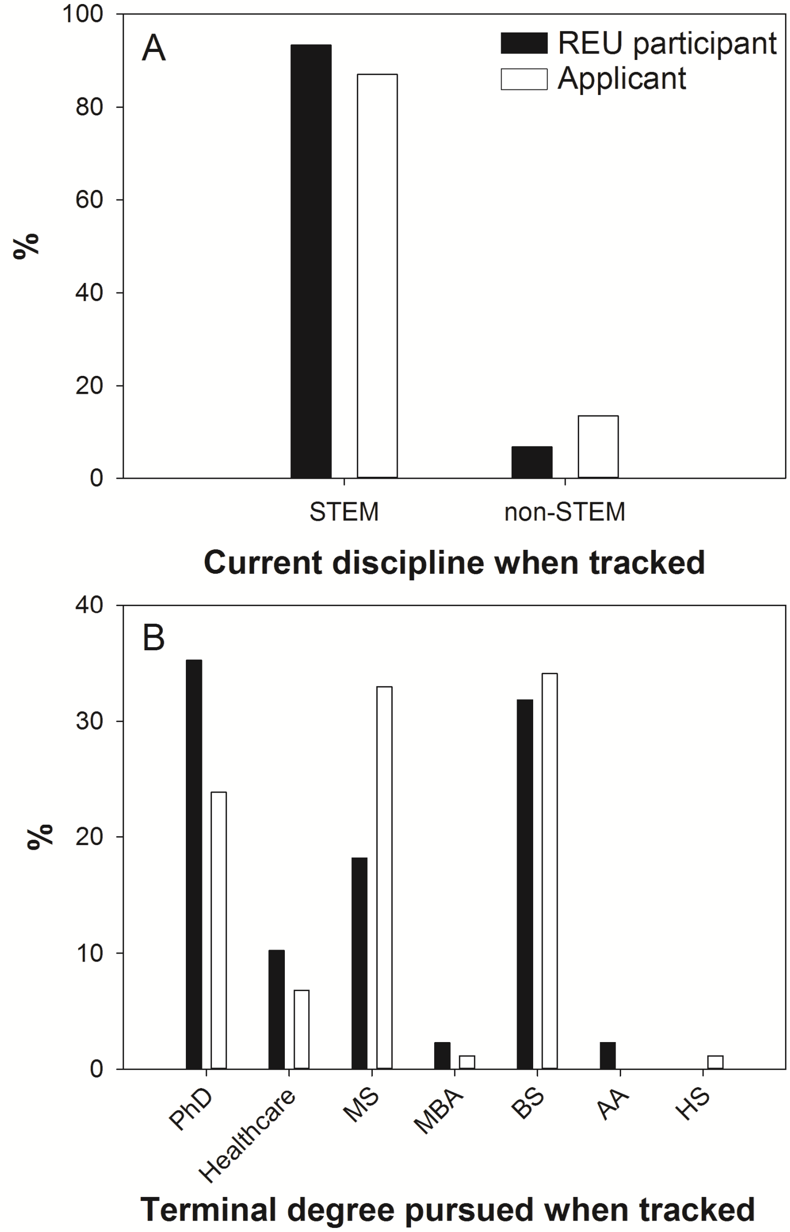
301 **Figures:**



302

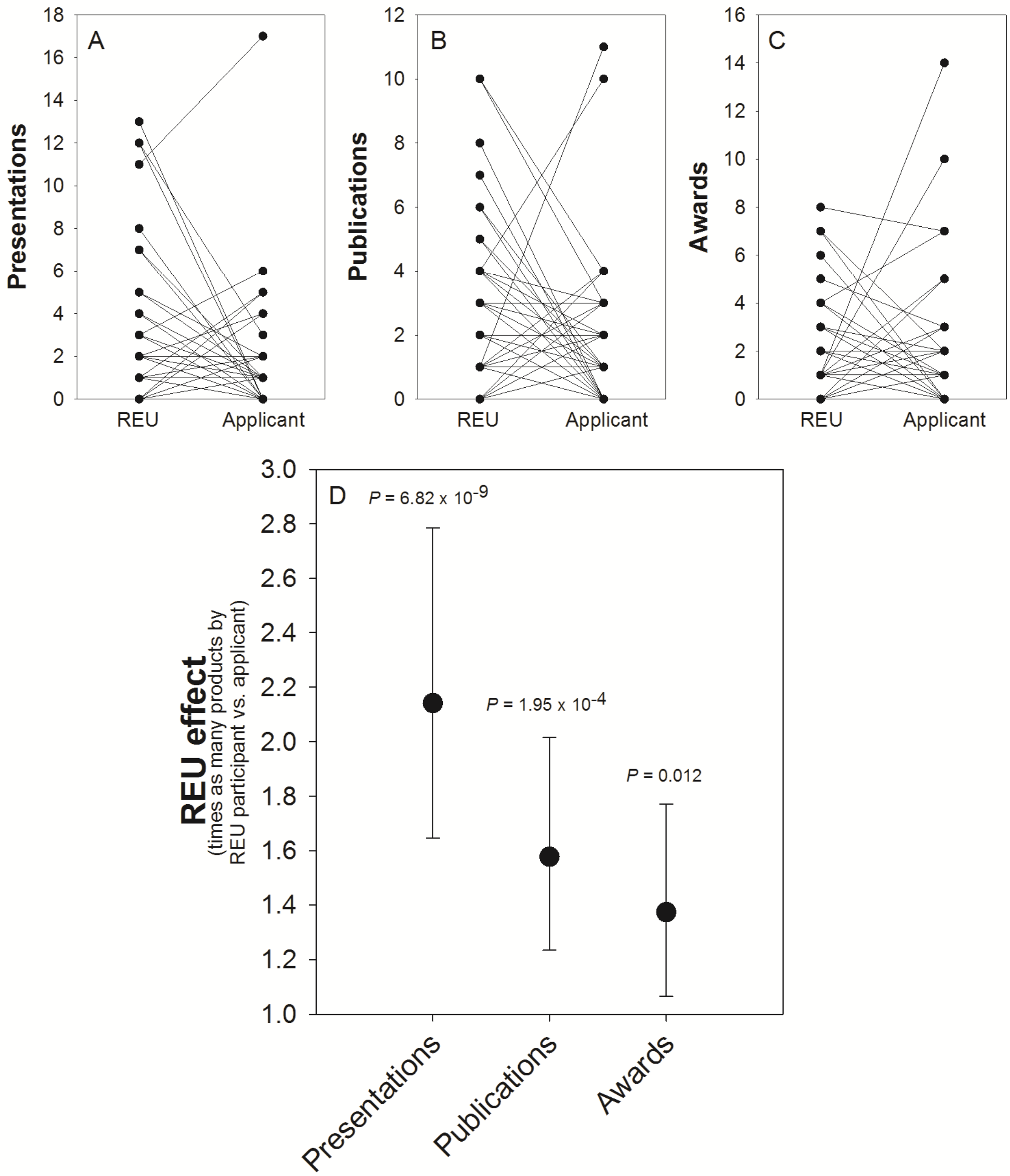
303 **Figure 1**. Interests and pursued degrees of REU participants and applicants. Percent
304 (%) placement of students (black bar = participant; white bar = applicant) included in the
305 REU assessment associated with their (A) current discipline (chi-square P = 0.214) and
306 (B) terminal degree pursued at the time of being tracked for this study (all degrees chi-

307 square P = 0.135; PhD and MS only chi-square P = 0.018). Degrees included Doctor

308 of Philosophy (PhD), Master of Science (MS), and Bachelor of Science (BS).

309 Healthcare includes all health related advanced degrees, such as Medical Doctor (MD).

310



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312 **Figure 2.** Paired responses (n=88 pairs) of Research Experiences for Undergraduates

313 (REU) participants vs. demographically-similar applicants for three assessed scientific

314 outcomes, including (A) presentations, (B) publications, and (C) awards. (D) REU

315 effects (estimate ± 95% CI) for the three scientific outcomes is the multiplicative

316 increase in scientific productivity by an REU participant relative to a demographically-
317 similar applicant. *P*-values are from a generalized linear mixed model fit by maximum
318 likelihood (Laplace approximation) with Poisson distribution and “Pair” as a random
319 factor.

Supplementary information:

Supplementary dataset A: De-identified REU participant and applicant dataset, including year of REU experience, Site IDs (A-E), pair # (1-88), REU participant code (0=applicant, 1=participant), individual-specific number of scientific presentations, individual-specific number of scientific publications, and individual-specific number of academic awards.

Year	Site ID	Pair #	REU participant code	Presentations	Publications	Awards
2009	Site A	44	0	0	0	0
2009	Site A	44	1	2	0	1
2009	Site A	45	0	0	1	0
2009	Site A	45	1	4	1	1
2009	Site A	46	0	1	3	1
2009	Site A	46	1	0	3	2
2009	Site A	47	0	3	4	7
2009	Site A	47	1	12	10	8
2009	Site A	48	0	0	1	2
2009	Site A	48	1	13	6	7
2009	Site A	49	0	1	0	1
2009	Site A	49	1	5	7	2
2009	Site A	50	0	0	0	0
2009	Site A	50	1	0	1	0
2009	Site C	24	0	0	0	0
2009	Site C	24	1	0	0	0
2009	Site C	25	0	0	0	0
2009	Site C	25	1	1	0	2
2009	Site C	26	0	0	0	3
2009	Site C	26	1	0	1	0
2009	Site C	27	0	4	2	7
2009	Site C	27	1	0	2	4
2009	Site C	28	0	0	1	0
2009	Site C	28	1	2	0	0
2009	Site C	29	0	0	3	0
2009	Site C	29	1	0	0	0
2009	Site C	30	0	0	0	0
2009	Site C	30	1	2	2	0
2009	Site E	1	0	0	0	0
2009	Site E	1	1	0	5	2

Year	Site ID	Pair #	REU participant code	Presentations	Publications	Awards
2009	Site E	2	0	0	3	5
2009	Site E	2	1	0	1	1
2009	Site E	3	0	5	10	14
2009	Site E	3	1	0	4	1
2009	Site E	4	0	0	0	0
2009	Site E	4	1	0	0	0
2009	Site E	5	0	0	0	2
2009	Site E	5	1	12	6	3
2009	Site E	6	0	0	0	0
2009	Site E	6	1	0	4	1
2009	Site E	7	0	1	1	0
2009	Site E	7	1	0	0	1
2009	Site E	8	0	2	1	5
2009	Site E	8	1	2	2	0
2009	Site E	9	0	1	1	2
2009	Site E	9	1	3	4	7
2010	Site C	38	0	1	11	1
2010	Site C	38	1	0	1	2
2010	Site C	39	0	0	3	2
2010	Site C	39	1	3	1	0
2010	Site C	40	0	0	1	0
2010	Site C	40	1	2	0	0
2010	Site C	41	0	1	1	0
2010	Site C	41	1	4	0	6
2010	Site C	42	0	0	0	0
2010	Site C	42	1	2	5	2
2010	Site C	43	0	0	3	1
2010	Site C	43	1	0	0	0
2010	Site D	68	0	0	0	0
2010	Site D	68	1	1	1	1
2010	Site D	69	0	1	0	1
2010	Site D	69	1	1	0	2
2010	Site D	70	0	0	1	0
2010	Site D	70	1	0	0	0
2010	Site D	71	0	2	2	0
2010	Site D	71	1	5	4	2
2010	Site D	72	0	0	2	0
2010	Site D	72	1	0	0	0
2010	Site D	73	0	1	0	2
2010	Site D	73	1	1	1	2
2010	Site D	74	0	1	4	0
2010	Site D	74	1	1	0	0

Year	Site ID	Pair #	REU participant code	Presentations	Publications	Awards
2010	Site D	75	0	1	3	3
2010	Site D	75	1	1	3	0
2010	Site E	10	0	1	0	2
2010	Site E	10	1	1	1	0
2010	Site E	11	0	0	4	0
2010	Site E	11	1	0	1	0
2010	Site E	12	0	0	4	1
2010	Site E	12	1	0	0	1
2010	Site E	13	0	0	0	0
2010	Site E	13	1	2	3	2
2010	Site E	14	0	1	1	0
2010	Site E	14	1	2	3	1
2010	Site E	15	0	17	3	3
2010	Site E	15	1	11	3	5
2010	Site E	16	0	0	1	0
2010	Site E	16	1	0	6	3
2010	Site E	17	0	0	0	0
2010	Site E	17	1	0	0	0
2011	Site A	51	0	1	4	3
2011	Site A	51	1	0	0	1
2011	Site A	52	0	0	0	0
2011	Site A	52	1	0	0	0
2011	Site A	53	0	0	0	0
2011	Site A	53	1	0	0	0
2011	Site A	54	0	2	0	0
2011	Site A	54	1	0	0	0
2011	Site A	55	0	1	1	0
2011	Site A	55	1	1	2	0
2011	Site A	56	0	1	1	0
2011	Site A	56	1	0	2	2
2011	Site A	57	0	0	0	0
2011	Site A	57	1	12	6	7
2011	Site A	58	0	0	0	1
2011	Site A	58	1	0	0	1
2011	Site B	79	0	0	0	1
2011	Site B	79	1	8	1	2
2011	Site B	80	0	0	0	1
2011	Site B	80	1	2	1	2
2011	Site B	81	0	1	0	1
2011	Site B	81	1	7	1	3
2011	Site B	82	0	6	1	1
2011	Site B	82	1	3	1	4

Year	Site ID	Pair #	REU participant code	Presentations	Publications	Awards
2011	Site B	83	0	0	0	2
2011	Site B	83	1	3	2	2
2011	Site B	84	0	2	1	0
2011	Site B	84	1	5	0	3
2011	Site B	85	0	0	2	1
2011	Site B	85	1	1	1	4
2011	Site B	86	0	1	1	2
2011	Site B	86	1	4	2	7
2011	Site B	87	0	0	0	1
2011	Site B	87	1	2	1	1
2011	Site B	88	0	0	0	1
2011	Site B	88	1	2	1	3
2011	Site C	31	0	0	2	0
2011	Site C	31	1	0	1	0
2011	Site C	32	0	5	0	1
2011	Site C	32	1	1	1	1
2011	Site C	33	0	0	0	1
2011	Site C	33	1	0	0	1
2011	Site C	34	0	0	0	3
2011	Site C	34	1	0	0	0
2011	Site C	35	0	1	2	2
2011	Site C	35	1	1	1	0
2011	Site C	36	0	1	0	0
2011	Site C	36	1	1	4	4
2011	Site C	37	0	0	0	1
2011	Site C	37	1	2	0	1
2011	Site D	59	0	1	0	0
2011	Site D	59	1	1	4	0
2011	Site D	60	0	1	1	1
2011	Site D	60	1	5	5	3
2011	Site D	61	0	0	0	1
2011	Site D	61	1	0	1	4
2011	Site D	62	0	0	0	0
2011	Site D	62	1	7	8	2
2011	Site D	63	0	1	0	0
2011	Site D	63	1	1	2	2
2011	Site D	64	0	1	1	0
2011	Site D	64	1	0	1	1
2011	Site D	65	0	0	1	2
2011	Site D	65	1	0	2	1
2011	Site D	66	0	2	2	0
2011	Site D	66	1	1	2	0

Year	Site ID	Pair #	REU participant code	Presentations	Publications	Awards
2011	Site D	67	0	0	1	0
2011	Site D	67	1	1	2	1
2011	Site D	76	0	1	3	1
2011	Site D	76	1	2	10	0
2011	Site D	77	0	2	1	1
2011	Site D	77	1	2	4	1
2011	Site D	78	0	1	0	0
2011	Site D	78	1	1	0	3
2011	Site E	18	0	2	3	3
2011	Site E	18	1	1	4	1
2011	Site E	19	0	1	1	0
2011	Site E	19	1	4	1	3
2011	Site E	20	0	1	1	0
2011	Site E	20	1	2	1	2
2011	Site E	21	0	4	2	10
2011	Site E	21	1	2	1	1
2011	Site E	22	0	0	0	0
2011	Site E	22	1	1	1	0
2011	Site E	23	0	0	2	0
2011	Site E	23	1	1	3	1

Supplementary dataset B: Output from generalized linear mixed models fit by maximum likelihood (Laplace approximation) with Poisson distribution and “Pair” as a random factor that include REU experience, Site, and Site by REU experience interaction for each outcome. These statistics were conducted using the *glmer* function in R version 3.1.1. *P-values* are from Type II Wald Chi-square tests calculated using the ‘Anova’ function from the ‘car’ package.

Outcome	Fixed factors	χ^2	*P-value*
Presentations	REU experience	26.89	<0.001
	Site	7.56	0.11
	Site x REU	14.41	0.0051
Publications	REU experience	12.59	<0.001
	Site	7.06	0.13
	Site x REU	13.94	0.0074
Awards	REU experience	5.07	0.024
	Site	8.56	0.073
	Site x REU	15.34	0.0040