Insights into student gains from undergraduate research using pre/post assessments

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Abstract

Undergraduate research experiences (UREs) in STEM fields expose students to scientific research and are thought to increase student retention in STEM. We developed a pre/post survey and administered it to participants of the Harvard Forest Summer Research Program in Ecology (HF-SRPE) to evaluate effectiveness of these programmatic goals. Between 2005 and 2015, the survey was sent to all 263 HF-SRPE participants; 79% completed it. Results, controlled for prior experiences, revealed significant improvements across all learning goals. Prior laboratory research experience and perception of being a respected member of a research team were positively associated with gains in research skills and abilities to do and present research. Although the pre/post surveys did not indicate changes in students' goals of pursuing STEM careers (or, more narrowly, ecological ones), the positive learning gains suggest that students with prior interests in STEM fields take advantage of UREs to solidify further their aspirations in STEM.

Keywords: Harvard Forest, retention, STEM, survey, Undergraduate Research Experience (URE)

Introduction

Undergraduate research experiences (UREs) in STEM fields (e.g. Research Experience for Undergraduates [REU] Sites) provide students with hands-on experiences in scientific research. For more than a quarter-century, the National Science Foundation (NSF), Howard Hughes Medical Institute (HHMI), and the National Academy of Sciences (NAS) have promoted UREs as a way of increasing retention of students and their pursuit of careers in STEM fields (Harsh et al. 2011, Lopatto 2004). These experiences also are thought to provide a wide range of transferable skills, with underrepresented groups showing the greatest increase in learning gains (Lopatto 2004, 2007). In the biological sciences, a wide range of UREs are available as classroom-based fieldwork (Maw et al. 2011, Scott et al. 2012), research apprenticeships (Sadler et al. 2010), and structured summer research programs (Lopatto 2004, 2007).

The NAS (NRC 2014) stressed promotion of undergraduate research at biological field stations for a number of reasons. The summer season often is the most intensive for data collection, and many sites rely on undergraduates to collect large quantities of field data (Hodder 2009). Because faculty and other senior investigators in ecology (sensu lato) also are focused on research in the summer, UREs at field stations also provide students with intensive mentor-mentee interactions resulting in focused research experiences and work in interdisciplinary research communities (Hodder 2009, Lopatto 2007).

Since its inception in 1985, when a single undergraduate worked on a study of old-growth forests, the Harvard Forest Summer Research Program in Ecology (HF-SRPE) has developed into a thriving and well-coordinated program that is central to the educational and research mission of this research department and biological field station. With core support since 1993 from a succession of NSF REU Site awards and NSF REU supplements, and with

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additional funding from Harvard University, the HF-SRPE has grown to support 20-30 undergraduate students annually. Participating students do research in ecology, soil science, paleoecology, wildlife biology, conservation biology, and atmospheric sciences while being mentored by principal investigators, senior scientists, post-doctoral fellows, and graduate students.

The five overarching goals of the HF-SRPE are to: enhance the ability of students to undertake high-quality interdisciplinary research; build teams of researchers in which students bring different strengths to the table, collaborate on cutting-edge projects, and find their own intellectual “voice”; encourage students to link fundamental and applied issues in their research; and cultivate the next generation of ecological scientists and educators that reflects the diversity of backgrounds and experiences of students in the United States. Student research in the HF-SRPE not only works towards meeting these five student-centered goals. It also has made, and continues to make, substantial contributions to a variety of long-term scientific investigations with national and international reach. These include the LTER (Long-Term Ecological Research) and NEON (National Ecological Observatory Network) initiatives of NSF, the Earth System Science Pathfinder (ESSP) – Earth Ventures (EV) program of NASA (National Aeronautics and Space Agency), the ForestGEO network of plots supported by the Smithsonian Institution, and the AmeriFlux program of the US Department of Energy (DOE).

Since 2005 NSF, one of the largest funders of UREs, has emphasized the use of project evaluations to measure both qualitatively and quantitatively the success of REU programs (NSF 2005); participant tracking for STEM employment and matriculation has been required for UREs supported by the all NSF directorates since the implementation of the America COMPETES Act of 2010 (42 USC 6621: Coordination of Federal STEM education). The initial objective of these

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project evaluations was to determine if student learning and other measurable outcomes were aligned with specific programmatic goals of individual UREs and of NSF. Prior work by Lopatto (2004) had examined the ability of summer UREs to attract and retain students, especially those from groups otherwise underrepresented in STEM, in STEM careers. However, the URE programs assessed at that time by the Survey of Undergraduate Research Experiences (SURE) study virtually all were programs focused on biomedical research and funded by HHMI (Lopatto 2004).

A comprehensive assessment tool for NSF-supported REU programs in biology—the Undergraduate Research Student Self-Assessment (URSSA) survey—was implemented in 2010 (Hunter et al. 2009). The standard implementation of URSSA provides data to NSF on how well REU programs meet national programmatic benchmarks, but it is limited to a single post-program assessment and cannot measure changes in student learning or other programmatic goals resulting from a student's participation in a URE (Frechtling 2002, Hunter et al. 2009). Because students who participate in UREs have a range of different backgrounds and prior skills in scientific research, it is also important to determine how these factors can influence success of any URE.

Since 2005, the HF-SRPE has used a pre/post survey to measure changes in student learning, skills, and attainment of its programmatic goals. We also have used data from initial surveys to determine how students' backgrounds and prior research experiences influence their self-reported changes in meeting our programmatic goals and in their educational and career goals. We addressed three specific questions:

- To what level is HF-SRPE reaching its educational goals?

- Which prior experiences predict the greatest gains in students' perceptions of their research ability?
- Is HF-SRPE increasing student interest in STEM (including environmental) careers?

Methods

Questionnaire

In 2005, we developed a survey instrument to evaluate systematically the experiences and persistence in STEM/environmental education and careers of participants in the HF-SRPE. Questions were reviewed by program administrators for face validity, a subjective confirmation that the measurements are appropriate, and alignment with NSF-REU objectives. Data were collected from students three times during the summer program. First, students completed a short survey upon their arrival at HF-SRPE to determine how they were recruited; their expectations of the programmatic goals for the summer; and their educational and occupational aspirations. Second, students were surveyed in mid-summer. The questions on the mid-summer survey probed whether the program was meeting their expectations; their satisfaction with their independent research, their mentors, and field trips; their interactions with scientists, staff, and other student participants; and changes that could improve their experiences. At the conclusion of the summer, students completed a third survey containing follow-ups to the questions in the first and second surveys. These three surveys were supplemented with individual, semi-structured interviews to examine students' survey responses and to provide them with an opportunity to discuss in detail their experiences and specific aspects of the program. This design allowed the evaluator to explore new topics that arose during the interviews and to follow up on compelling responses (Neuman 2003). Interviews explored in more detail students' relationships with their mentors; how, if at all, their educational and occupational aspirations had changed; and their perceptions of science and the field of ecology.

Upon review of the 2005 pilot study, the decision was made to reduce the yearly assessment of participant experiences to a single pre-post survey according to NSF guidelines for REU Site evaluation (Frechtling 2002). This survey consisted of 22 multiple choice questions and 2 open response questions. The pre survey was sent to a total of 263 HF-SRPE participants (approximately 25 per cohort) with a 91.6% response rate. A similar post survey was sent to participants at the end of HF-SRPE with 79.5% of individuals responding to both surveys.

Data analyses

We used repeated measures analysis of variance (rm-ANOVA) to test for changes in the students' perceived research skills and their confidence in them; student responses to nine prior experiences (Table 1) entered the rm-ANOVA as fixed factors. Multicollinearity among the nine prior experiences was assessed using multiple correspondence analysis (MCA) using the {*FactoMineR*} package. Analyses were done using the {*car}* package in R version 3.2.3; linear models were fit for each of the responses, and significance was assessed using Type III sum of squares. Post-hoc Tukey tests were done only on statistically significant ($P \leq \alpha$=0.05) terms.

We used correspondence analysis, using the {*ca}* package, to examine if the HF-SRPE influenced long-term career goals. One-sided paired *t*-tests were used to evaluate the self-assessed likelihood that participants persisted in environmental or STEM research fields.

Anonymized raw data and associated R code are available from the Harvard Forest Data Archive (http://harvardforest.fas.harvard.edu/data-archive/), dataset number HF-279.

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Results

Student background

Students responding to the pre-survey during 2006 – 2015 ($N = 241$) came into the program with varied backgrounds. Most reported prior experience in laboratory (75%) or field (71%) research, often (52%) on research teams outside of a class. The majority of these students (72%) had worked with a more experienced researcher, but fewer had presented their research to peers (48%) or (co)-authored a scientific paper (7%). Although only 24% of the participants felt that they had contributed previously to the production of a scientific paper, 54% felt that they had been a respected member of their scientific research team.

Research skills

The students' perception of their research skills was higher after they had completed the HF-SRPE (Table 1: Questions 3 and 4). Both prior experience in laboratory research ($F_{1,396} = 3.25$, $P = 0.001$ for Question 3; $F_{1,396} = 10.70$, $P < 0.001$ for Question 4) and prior respect as a member of a scientific research team ($F_{1,396} = 4.43$, $P < 0.001$; $F_{1,396} = 19.80$, $P < 0.001$ for Question 4) contributed significantly to these perceptual gains (Figures 1, 2).

Doing and presenting research

Students' perception of their ability to participate in interdisciplinary research in teams (Question 5a), work with research mentors (Question 5b), and analyze, write-up, and present research data (Questions 5c-5e) all increased following participation in the HF-SRPE (Table 1). As with basic research skills, previous experience with laboratory research and felt like a

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respected member of a research team were significant predictors of our students' increased perception of their abilities to do and present research (Figures 1, 2).

Future aspirations in science

Students showed little change in their conceptual domains of educational and career aspirations (Figure 3). The first axis of the correspondence analysis separated environmental from non-environmental professions and accounted for 39.8% of the variation in the data. The second axis (27.9% of the variation) separated responses along a post-graduate education *vs*. employment in fields outside of environmental science. There were no significant changes in expressed long-term educational or employment goals (Question 8) or interest in environmental or STEM fields (Questions 10a, 10b) among students participating in the HF-SRPE (Table 1). Long-term goals were generally uncertain-to-clear, whereas likelihood of pursuing a career in environmental or STEM fields was generally likely or quite likely.

Interesting interactions

For the two questions in which students experienced the largest gains—scientific research skills (Table 1: Questions 3, 4) and presenting scientific results (Question 5e)—we also ran rm-ANOVAs in which the students' clarity of long-term goals prior to entering HF-SRPE entered the model a predictor variable. For students' perceptions of their scientific research skills, there were significant differences between pre- and post-participation responses ($F_{1,407} = 38.84$, $P < 0.001$), the level of clarity in their long-term goals ($F_{2,407} = 6.73$, $P = 0.001$), and their interaction ($F_{2,407} = 3.45$, $P = 0.033$). Even though students entering the program with a lower clarity of their post-graduation goals also had a lower perception of their research skills, the interaction plot

(Figure 4) illustrates that these students increased their perception of these skills to an equivalent level after the completion of HF-SRPE. Similarly for students' self-reported preparedness to present scientific results (Figure 4), there were significant differences between pre- and post-participation responses ($F_{1,403} = 24.95$, $P < 0.001$), and the level of clarity in their long-term goals ($F_{2,403} = 3.67$, $P = 0.026$). However, there was no interaction between these two factors ($F_{2,403} = 1.56$, $P = 0.212$).

Discussion

Learning gains

Undergraduate research experiences (UREs) have been widely touted as providing valuable research experiences that provide valuable skills for future scientists (Linn et al. 2015, Russell et al. 2007). Not surprisingly, HF-SRPE participants experienced a significant increase in the across various skills/self-assessments measured by our survey, but gains were greater for students lacking prior research experience (Figure 1). This result suggests that UREs should interested in promoting these various learning gains should emphasize recruitment of students without prior research experiences (see also (Hunter et al. 2009, Lopatto 2004, Maw et al. 2011).

One potential limitation of all self-assessment surveys is that student reporting of their own perception of their learning gains could be inflating our impression of success. The internal validity of self-assessment surveys is a known concern (Linn et al. 2015) and supports the use of pre/post designs to evaluate educational impacts (Pascarella 2001). Indeed, our conclusions are supported by an ethnographic study of similar URE programs that found a strong correlation between student and faculty perceptions of learning gains, especially with regards to constructs such as scientific identify and professional development (Hunter et al. 2007). So long as we

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remember to treat these data as perceptions, not objective measurements of cognitive or psychomotor domains, we can conclude that our results are helpful in assessing the impact of the HF-SRPE (see also (Turner et al. 2008).

Although our results suggest positive effects of the HF-SRPE on student learning and skills development, we cannot compare our URE with others because the national survey instrument, URSSA, is only a post-program instrument. We encourage other programs to adopt a pre/post survey design so that individual program directors and funding agencies can learn from and improve all UREs. We also have been using the URSSA instrument in parallel with the HF-SRPE since 2010. Although there is some overlap between the two instruments in questions and conceptual domains, comparting results is challenging because responses to URSSA are completely anonymous, whereas respondents to our own pre/post surveys are known, albeit kept confidential from analysts. Thus, we can include additional covariates (*e.g.*, demographic information, mentor perceptions, long-term follow-ups) in the analysis of our results, as well as to control for the within-subject variability and impacts of prior experiences on learning gains with a sample size representative of a single URE program. The URSSA does a more robust job of measuring cognitive and affective domains such as thinking like a scientist, research skills, personal gains, and attitudes and behaviors (Weston and Laursen 2015). However the URSSA is unable to differentiate effects of a URE itself and any selection bias for type of programs (Linn et al. 2015).

Importance of laboratory experiences

For the most part, students with or without prior laboratory experiences displayed the same proportional change in strength and confidence in scientific skills, participation in interdisciplinary research, analysis of scientific data, and the writing of results (Figure 1). This suggests that HF-SRPE is providing equivalent opportunities for growth to participants with different research backgrounds. HF-SRPE's nationwide recruitment and breadth of research projects for which students are specifically selected suggest that the prior laboratory experiences reported by our participants are representative of students in other UREs. In another study of comparable summer UREs at liberal arts colleges, Hunter et al. (2007) found that broader and more confident laboratory skills increased the student's sense of independence and helped facilitate other gains beyond their current research projects. Further, they found that reinforcement of these skills also aided in shaping student's self-efficacy and scientific identity.

Respected member of a scientific team

In addition to scientific knowledge and skills, the affective domain also played a role in the expression of these learning goals and development of scientific identity. Prior feeling of respect as a member of a scientific research team also was a reliable predictor of higher self-assessment of research skills, including doing and presenting research, both prior to and after participation in HF-SRPE (Figure 2). As with learning gains, students who reported not having previously been a respected member of a research team displayed a greater degree of change. Respect in the context of UREs can aid in the development of student's scientific competence and individual identity as researcher (Hunter et al. 2007). Facilitating a culture of respect through inclusive, collaborative learning community reinforces students' interest and empowers them as active learners (Walsh et al. 2014). These positive interactions with other members of a research community can help foster students' understanding how they construct scientific knowledge and derive meaning from their experiences through a process called self-authorship. (Baxter-

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Magolda 1999a). This process of applying their contextual knowledge, a component within the constructive-developmental framework, is especially important for college students as they begin to identify and shape their career paths (Baxter-Magolda 1999b).

STEM retention

A common critique of UREs is that they tend to favor students who already have a high probability of persistence in STEM fields (Linn et al. 2015). Our competitive selection process, in which 600-900 applicants are competing for 25-30 positions, may be similarly biased. Our data showing that HF-SRPE has not changed participant's short-term career paths (Table 1: Questions 8, 10a, 10b; Figure 3) lends support to this characterization of URE programs.

Sadler et al. (2010) argued that one of the greatest insights gained through research apprenticeship is a sophisticated understanding of the nature of science. For our participants, prior laboratory research experience resulted in a higher clarity of long term goals of remaining in STEM fields. This may suggest that students without previous laboratory experience had an unclear image of research or at least the types of interdisciplinary research conducted at HF-SRPE. We intentionally recruit students whom we think would benefit the most from a URE at a major research institution; such students express in their application essays a strong interest in ecological research, or have demonstrated a potential as an environmental researcher but have not yet had experience with independent research. The HF-SRPE thus provides students with an opportunity to evaluate their true preparedness for environmental or STEM research disciplines. Alternatively, the absence of a change in their expressed long-term plants may result only from a lack of time to reflect on their summer experience. Long-term evaluation of student career paths will help us differentiate among these alternative hypotheses.

The HF-SPRE provides students already interested in environmental and STEM research with an opportunity to expand their skills and become part of the next generation of research scientists. Program-level tracking of our participants provided annually since 2001 to agencies supporting our URE show that a consistent 15% of each year's participants have published their summer work in peer-review journals, 10% (with rates rising up to 45% within the past 5 years) have presented posters at regional or national conferences, and a consistent 10% of students have developed their summer projects into senior theses. These data cannot be linked directly to individual survey responses reported here, but they do lend support to the idea that research skills gained from both prior experiences and HF-SRPE have led to the production of professional level research products. We note that the production of research products, often used to demonstrate value of professional reaserchers to universityies and funding agencies, may not serve as imformative indicators of undergraduate learning and growth (Hunter et al. 2007). However, identity theory argues that a collaborative and respectful learning environment helps students apply skills learned through the creation of these research products, increases the salience of their scientific identity, and further strengthens their likelihood of pursuing and remaining in of STEM careers (Merolla and Serpe 2013).

Conclusion

Our data suggest that to maximize gains in learning of scientific skills, UREs should emphasize recruitment of students without certain prior experiences within both cognitive and affective domains. The intellectual, social, professional, and financial support of young students by UREs increases the access to these valuable learning opportunities so that more students have a stronger research foundation to build upon in the future. Long-term assessments will illuminate further whether the short term gains of the HF-SRPE and other UREs have persistent effects (Linn et al. 2015). There is still much more to examine about the relationships between summer undergraduate research experiences and STEM retention; increased focus on recruitment methods and implementation of repeated measures designs would help align program-level evaluations with NSF objectives to provide meaningful research experiences for broader range of undergraduate students (NSF 2013).

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Table 1. Summary of student skills and aspirations. Directional paired *t*-tests were used to examine educational gains due to participation in HF-SRPE. Questions where post-surveys were not significantly greater than pre-surveys exhibited a decrease.

Survey Question*	Pairs (n)	Pre (±SEM)	Post (±SEM)	t-Value	p-Value
Q3	209	2.23 (0.05)	2.87 (0.05)	-11.28	<0.001
Q4	208	2.12 (0.03)	2.49 (0.04)	-9.42	<0.001
Q5a	208	3.90 (0.06)	4.31 (0.05)	-6.50	<0.001
Q5b	209	4.17 (0.05)	4.61 (0.04)	-7.56	<0.001
Q5c	209	3.56 (0.06)	3.81 (0.06)	-3.70	<0.001
Q5d	209	3.62 (0.06)	3.95 (0.06)	-5.19	<0.001
Q5e	207	3.47 (0.06)	4.21 (0.05)	-11.44	<0.001
Q8	205	1.99 (0.05)	2.04 (0.05)	-1.02	0.154
Q9	179	---	---	---	---
Q10a	209	3.53 (0.05)	3.43 (0.06)	2.45	0.993
Q10b	188	3.14 (0.06)	2.93 (0.07)	3.28	0.999

*Complete question text from survey:

Q3: Would you say that your scientific research skills are: *(1:Need development, 2:Adequate, 3:Strong, 4:Very strong)*

Q4: Would you say that your confidence in your scientific research skills is: *(1:Low, 2:Medium, 3:High)*

Q5a-e: How prepared are you to: *(1:Not at all prepared – 5:Very prepared)*

Q5a: Participate in interdisciplinary research with a team of researcher

Q5b: Conduct research supervised by a research mentor

Q5c: Analyze scientific data

Q5d: Write-up scientific results

Q5e: Present scientific results

Q8: Would you say that your long term post-college goals, either for education or employment, are: *(1:Uncertain, 2: Clear, 3:Very clear)*

Q9: What are your plans immediately after graduating from college: (*Grad school environmental; Grad school non-environmental; Job environmental; Job non-environmental; Not certain*)

Q10a-b: The likelihood that you will pursue a career in: *(1:Not at all likely – 4:Quite likely)*

Q10a: Environmental Field

Q10b: STEM research Field

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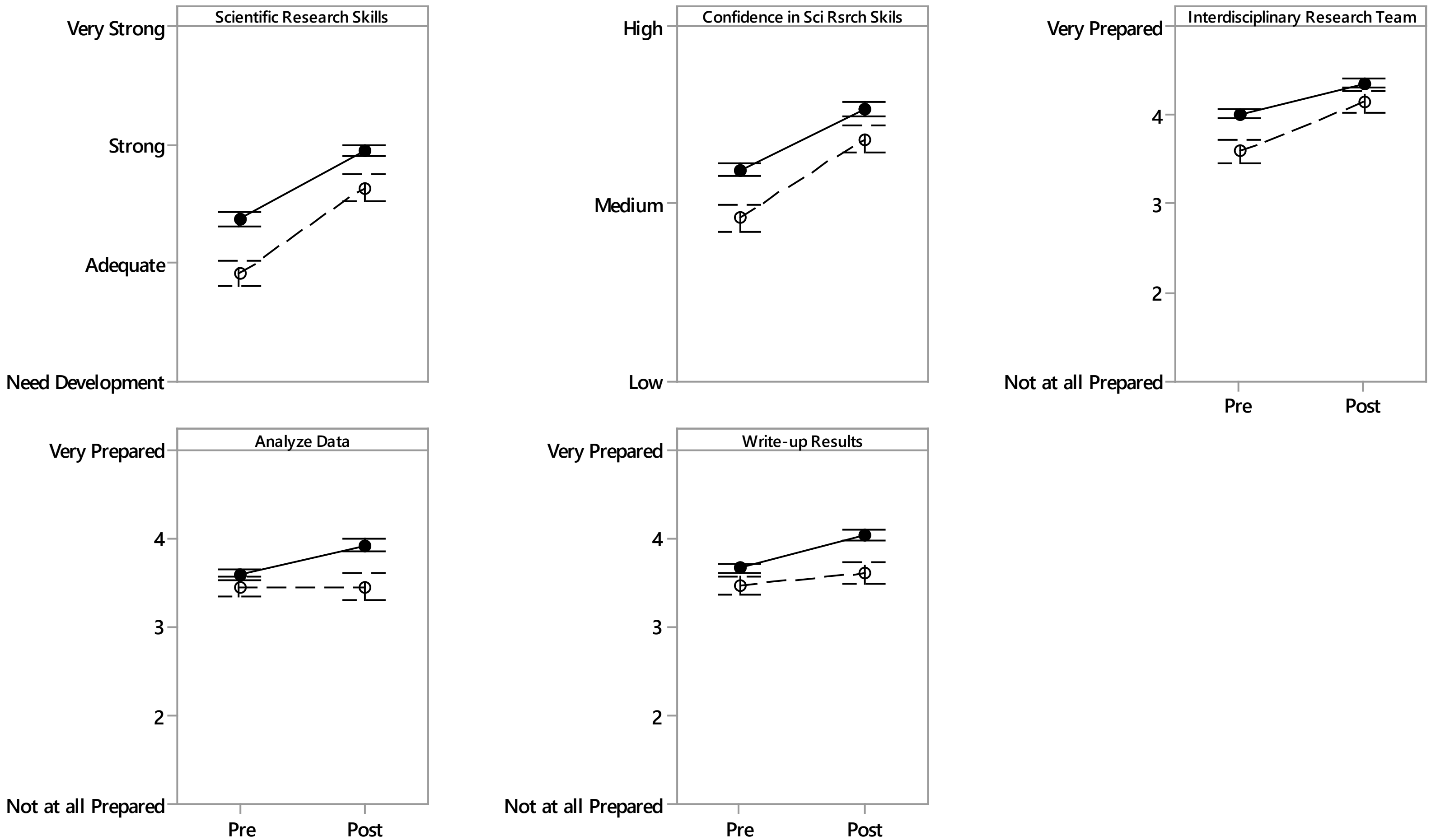

Figure 1 Change in learning gains based on the presence (closed) or absence (open) of prior laboratory experience. Bars are one standard error of the mean.

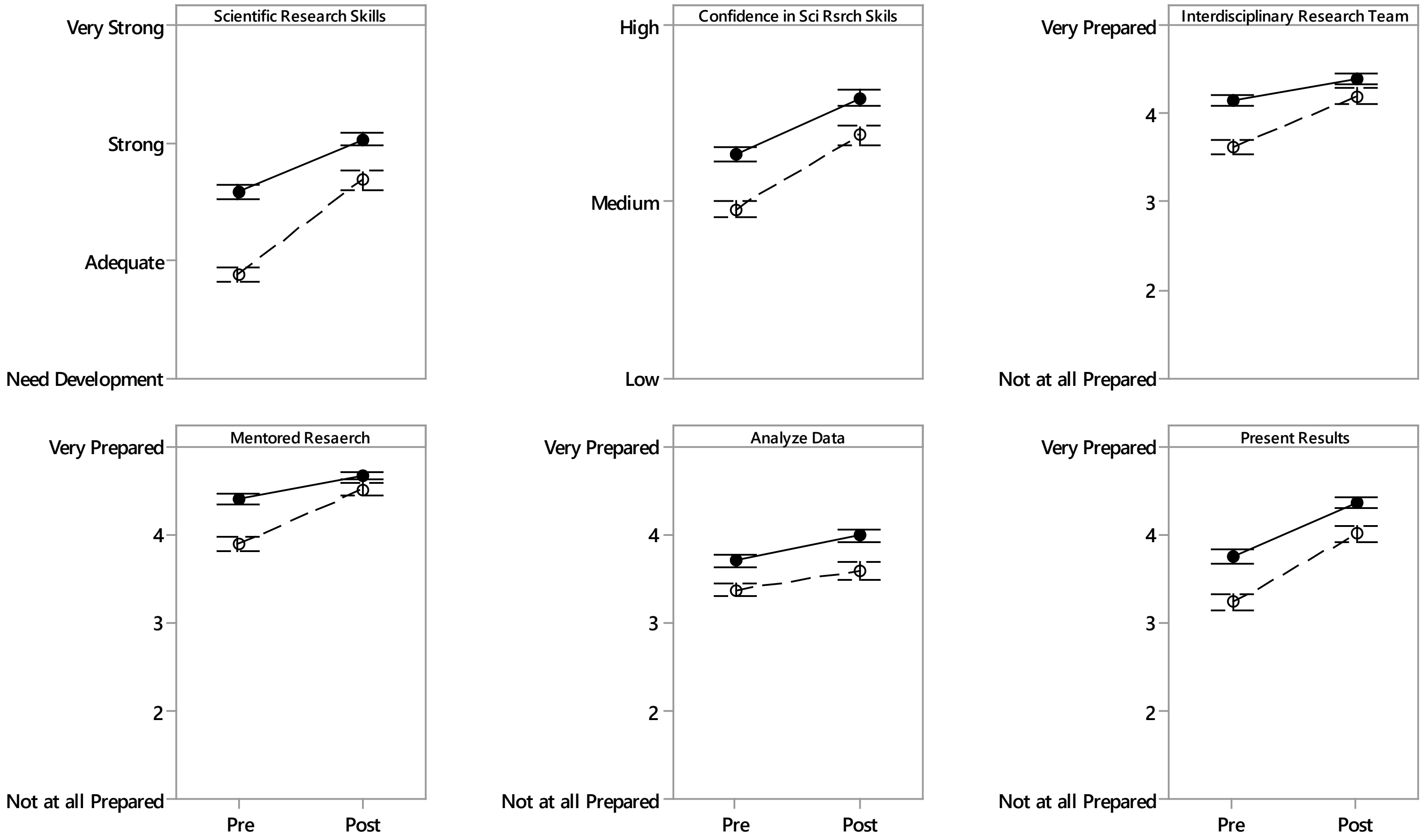

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Figure 2. Change in learning gains based on the presence (closed) or absence (open) of prior respect as a member of a research team.

Bars are one standard error of the mean.

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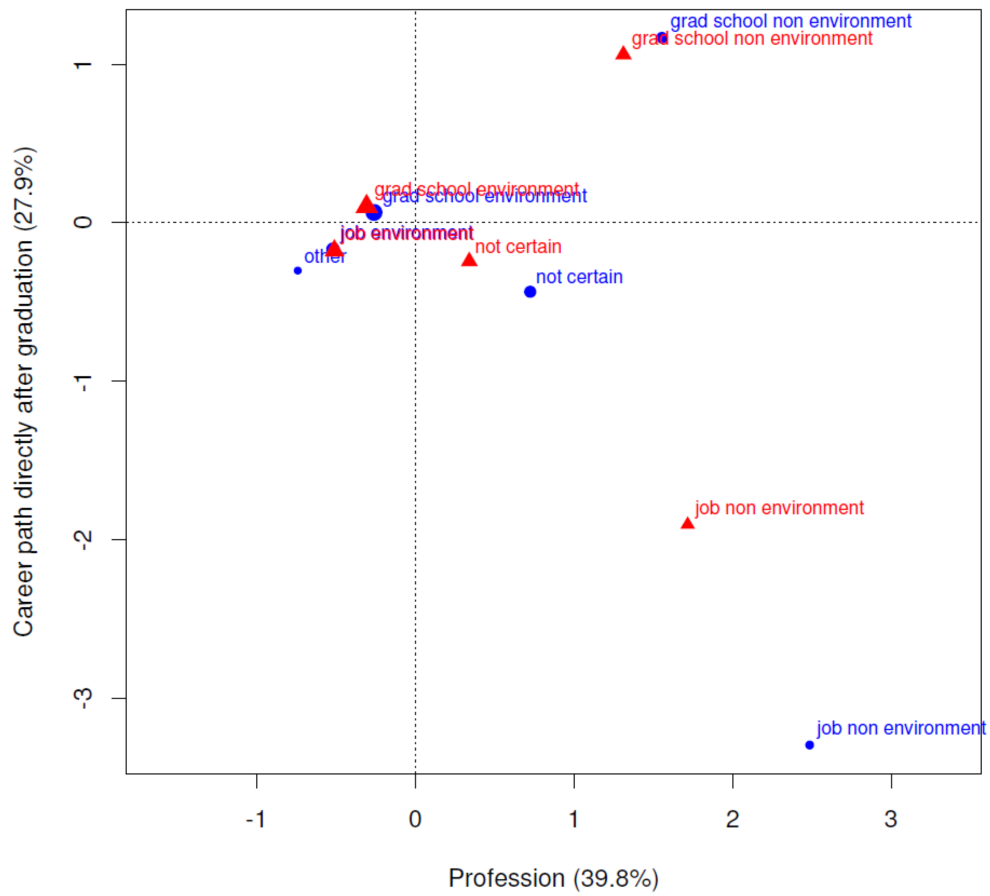

Figure 3. Correspondence analysis for plans after graduation. Pre-test responses (treated as rows) are indicated by blue circles and post-test responses (treated as columns) are indicated by red triangles. The size of the symbols indicates the relative proportion of individuals responding to a given category. χ2 distance approximations are only valid among their respective profiles.

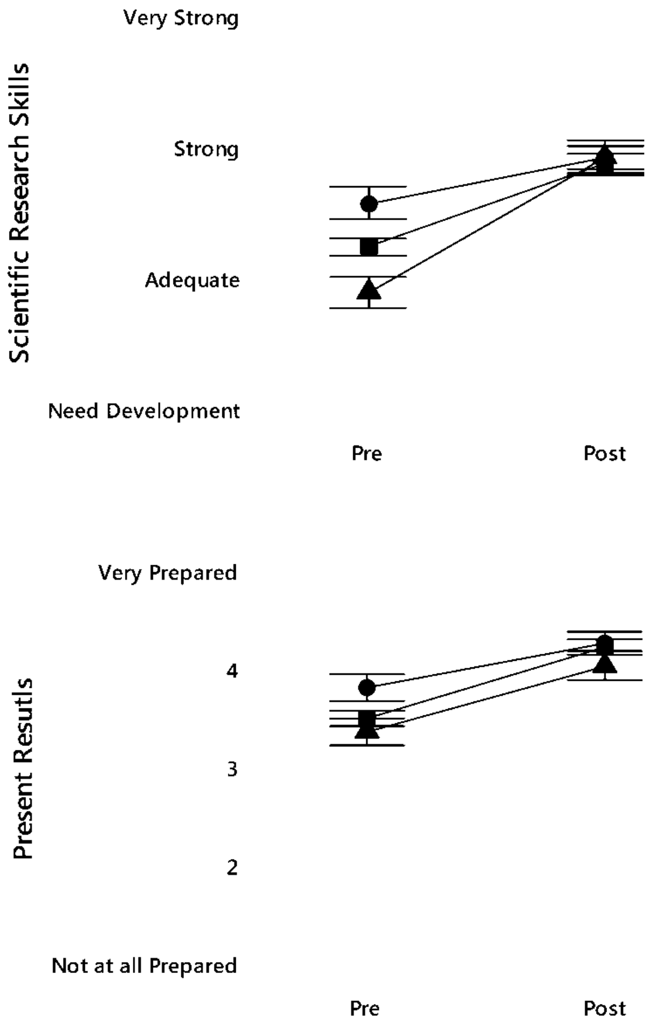

Figure 4. Change in learning gains based on the clarity of post-graduation plans prior to starting the HF-SRPE. Participants identified clarity as either low (triangle), medium (square), or high (circle). Bars are one standard error of the mean.