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Science/Education Portraits I: Identifying Success Factors of Pre-Tertiary Bioinformatics Research Experience from Students' Perspective

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Abstract

Many studies suggest substantial benefits in incorporating research experience into science education, with several studies examining the success factors for undergraduate research experience. It has been known that early research experience has an impact on the career paths of the students. However, little has been known about the success factors of research experience at a high-school level. This study uses a reflective email interview method (2 years post-completion of the research experience) to identify success factors from the perspective of the students on their pre-tertiary bioinformatics research experience. Six success factors emerge from this analysis: (1) student's intrinsic motivation / interests, and goals, (2) peer pressure, (3) student's perceived workload, (4) context of project, (5) culture of science and recognition of student's work, and (6) quality of supervision.

Keywords: Email interview; Success factors; High school/pre-tertiary research; Reflective inquiry

Introduction

Research experience is becoming an important component of science education due to its many benefits [1]. These includes better understanding of research process [2], increased motivation and active learning [3], and a platform for developing analytical skills and a deeper understanding of theoretical principles [4]. There are evidence of benefits derived when the students are at the high-school level [5-8]. However, biology-inclined high-school students may not have sufficient time availability to carry out substantial laboratory experiments. Bioinformatics may be a suitable option as it can offer flexibility in time and resources [9]; yet, emphasizes on problem solving [10].

There has been some studies carried out on the success factors in undergraduate education [11-13] and undergraduate research experience [14-16]. However, studies on research experience by high-school students is sparse, despite acknowledging the impact of early researchers on their career path [17].

Previously, one of the authors in this study had published a personal narrative [18], from the perspective of a research mentor, on mentoring pre-tertiary biology/bioinformatics research; during which, an email interview was carried out from one of the pre-tertiary groups. Several advantages of email interviews had been suggested [19]; such as, unconstrained by geographical location and traveling time [20], reduced effort needed for transcription [19], reduced psychological barrier for interviewees to talk about sensitive topics [21], and created a space and time for iterative reflexivity between interviewers and interviewees throughout the interview process [22]. As this interview was carried out, Oliver Chan was away in USA to pursue his undergraduate study; hence, face-to-face interview was not possible. Email interview remained as viable option.

This email interview was carried out in 2017, reflecting on their group research experience between 2011 and 2015. As a reflection, the project mentor (Maurice Ling) took on the role as the interviewer and each question was emailed to both mentees (Oliver Chan and Bryan Keng), where replies were emailed to all three parties.

This study examines the resulting email interview transcript to identify success factors leading to their pre-tertiary bioinformatics research experience. Six success factors emerge from this analysis: (1) student's intrinsic motivation / interests, and goals, (2) peer pressure, (3) student's perceived workload, (4) context of project, (5) culture of science and recognition of student's work, and (6) quality of supervision.

Results and Discussion

A reflective email interview between the project mentor (as interviewer) and students/mentees (as interviewees) was carried out two years post-mentoring completion to identify success factors of pre-tertiary bioinformatics research experience from the perspective of the project students. The annotated email interview transcript is given in appendix. From transcript analysis, six success factors (F1 to F6) emerged: (1) student's intrinsic motivation / interests, and goals, (2) peer pressure, (3) student's perceived workload, (4) context of project, (5) culture of science and recognition of student's work, and (6) quality of supervision.

The first success factor (F1) is the student's intrinsic motivation / interests, and goals. One of the factors emerged early in the interview is the students' interest in science, especially in biology, and are keen to pursue science as a career. Hence, they are actively seeking for opportunities to gain exposure into the field. Compared to extrinsic motivation, persons who are intrinsically motivated are more inclined to seek challenges for learning, development and growth [23]. This is supported by a study [24] showing that students who are intrinsically motivated have a higher propensity to sought out lecturer rather than avoiding them.

The second success factor (F2) can be known as peer pressure. The effects of peer pressure has been well documented [25], and can be positive or negative. The effects of peer pressure may be independent of age as a recent study demonstrated the use of peer pressure as a motivator for research output among university faculty members [26]. Hence, it is plausible to conceive that peer pressure may play an important role as the tipping point should intrinsic motivation be insufficient as Oliver recounted – "*there was an assembly lesson or something where a teacher gave a talk about research, and by the end of it, planning groups to do research for the next year was pretty much all the academically-inclined peeps in our class were thinking or talking about.*"

The third success factor (F3) is the student's perceived workload required by the project. Many academically-inclined students have many activities that they must juggle. Despite intrinsically motived toward challenge, the challenge must be perceived to be surmountable; as Bryan puts it, "*yeah let's do it, I'm sure we can manage*". Hence, this suggests that there is a cost-benefit balance. Throughout the interview, there are many instances where the perceived workload is important, such as "*workload also didn't seem too demanding*"; or reduction of cost, such as work flexibility.

The fourth success factor (F4) is the context of project. Project students will like to know the "why" of what they are doing, such as the "*biological motivations behind invariance studies*". Bryan also recounted that "*learning the significance of E. coli as a model organism really help put everything in place, to understand why we were doing it. "Nevertheless,* the purpose of the research experience is a chance for the students / mentees to develop analytical skills and a deeper understanding of theoretical principles, which requires active learning [3] and not as the mentor's helper. In this aspect, research students should be viewed as apprentice where in time, able to succeed the mentor. This is supported by a study on research experience [27], which enforced that research experience is an opportunity for the students "*to learn about research methodology and ethical issues which inform their own research practice*" and in order to achieve this, "*educators should promote those elements of the research experience (e.g. critiquing studies, networking with researchers) that are most beneficial.*"

The fifth success factor (F5) is the culture of science and recognition of student's work. A major aspect of research experience is for the student to understand the research process and how scientists work on their problems [15]. The key to this is apprenticeship. A significant part of this apprenticeship is to for the mentor to give due recognition for the student's work; which will prepare him to be an independent scientist in the future, develop the student's professional identity within a community of practice [28]. This implies two contexts of apprenticeship. At the technical level, the student must learn the skills required of a scientist, as Bryan recounted "*I learnt a lot about statistical methodology, how to write up a decent paper, and how to prepare for manuscript submission.*" The technical level is dependent on the context of the project (F4). At the social and cultural level, the student must be acquainted with the social skills of science. This may include scientific progression as Bryan recounted, "*I remember this conversation about academic pedigree and career progression and the difficulties of publishing - it was certainly eye-opening.*"

The sixth and last success factor (F6) is the quality of supervision. The mentor can make or break the project and the relationship with the students, and affect the student's future choices, as Bryan recounted "*the positive research experience was a major factor which spurred me on to continue in the field of medical research*". It may impact the student's interest to serve as mentor during his professional career as

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experience as a mentee has been shown to indicative of the person's willingness to mentor [29,30]. An important task for the mentor is to ensure that the project is appropriately scoped, reduce apprehension and minimize distress to the mentor [27]. Oliver gave a succulent summary on the role and qualities of a mentor in a research experience – "*I'm of the opinion that a good supervisor is foundational in a good research experience, and has been the strongest determinant of whether I find a project fulfilling. One particular example stands out - I was involved in some optics research, which ran well with my passion for physics. But my mentor and I did not have a good fit, and a combination of infrequent communication and a high workload for him during my supervision resulted in an undirected, badly executed project. It was a subpar experience that put me off laboratory work ever since. Evidently, I'm a good anecdote for how a bad supervision experience can override 'interest in a field'.*"

In conclusion, a successful research experience, be it in bioinformatics or not, depends on both the motivation and willingness to embark on this journey on part of the student, and the willingness of a mentor to nurture a potential successor. As a result, six peer-reviewed manuscripts were published [31-36]. Both sides must be invested to make it work.

Appendix: Annotated Email Interview Transcript

1. In 2011, both of you were Secondary 3 students when you embark on research work. What led you to want to do research projects?

Bryan: I think that back in secondary school I already had quite a good idea that I wanted to pursue a career in medicine or science [F1]. So naturally, SMP seemed like a useful avenue to start getting involved in some research, which would strengthen my CV for university applications [F1]. Personally, I found SMP a lot more appealing than the other options (like humanities-related projects, service-learning etc.), both in terms of my individual interest and the skills we stood to gain through the research process. Oliver: Research was a natural extension of an interest and aptitude in science [F1]. I think there's a strong culture to push pre-tertiary students in Singapore to try research, especially in the hard sciences. There's also a good deal of planning and programmes in place to make it possible, so I think research was always in our minds as an option.

2. The team you formed consists of Bryan, Oliver, and Sean. What led you to form this team?

Bryan: Maybe Oli can help with this question, because I honestly don't remember. I think Oli asked me to join him back at the end of Secondary 2 when we were told to start forming groups, and I just agreed. Not sure though. Oliver: I don't recall either. I remember something fuzzy along the lines of this: there was an assembly lesson or something where a teacher gave a talk about research, and by the end of it, planning groups to do research for the next year was pretty much all the academically-inclined peeps in our class were thinking or talking about [F2]. I knew I wanted to do something with Bryan, basically our class' all-star academics champion, and all round wonderful person. So I pestered him until he said yes and he's probably regretted it till today.

3. What led you to choose the project that I offered - finding reference gene(s) in *E. coli*?

Bryan: I remember we failed to get any of the SMP projects we applied for during the first two rounds of project selection, which was pretty disappointing. Fortunately, our teacher-mentor managed to get hold of a few more options for us, of which the *E. coli* project was one. I thought it sounded good because it seemed to have the most relevance to biology, which I was interested in. The workload also didn't seem too demanding [F3], which was nice because we were fairly heavily involved in CCAs and other activities at the time. So we came to a consensus that the *E. coli* project was the most appealing. Oliver: I recall doing the applications with Bryan. I think I didn't quite grasp the gravity of these applications; I probably fooled around with them and chose flippantly. Part of it was ambivalence - as a first stab into research, I didn't mind what I did because I was interested in almost everything. I think it was hard for me to form strong, genuine preferences with so little exposure, and if I did it was probably more a product of family or systemic influences than my own inclinations. In fact, both Bryan and I were offered to do the humanities research program, HSSRP, which was the parallel one to SMP (for the sciences). The other criteria we had was the commitment and quality of the mentor, but as you'd imagine, it's close to impossible to evaluate that off the short blurbs we were given.

4. What did you expect out of the project when you chose it?

Bryan: My primary aim was essentially to gain exposure and develop my skills in scientific writing and publication [F1]. This would include areas like data collection and analysis, proper scientific language, lit review, poster presentation etc. Learning more about bioinformatics and how to use Python was definitely a plus as well. I think Maurice did a really good job teaching us the fundamentals of scientific research and key bioinformatics concepts [F4, F7]. Oliver: I wanted to learn about research, about bio-informatics, and about how academia worked. I knew I wanted to learn something, and I definitely got that [F1]. Maurice successfully taught us statistical techniques in Secondary 2 that some of my college peers still fail to get in their third year. And Maurice invested a lot of time explaining how academia worked [F6], or the biological motivations behind invariance studies [F4].

5. The SMP project is on finding reference gene for *E. coli*. What's your interest on it? What's your views after hearing from Maurice about the project?

Bryan: My interest in the project stemmed from the fact that it was bio-related [F1], and that we stood to gain relevant knowledge and skills in scientific inquiry. Like Oli, I didn't know

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exactly what I wanted out of the project, but the initial premise seemed reasonable enough - finding invariant genes in a model organism, which could then be utilised in future studies [F4]. Bioinformatics was of course a new field to the three of us, and so we figured there was much to learn. After chatting with Maurice, we also realised he was a pretty cool guy [F6], so I was quite excited about getting to work on this project. Oliver: I don't think I was exposed to the field of bio-informatics prior to the project, so I can't say that I had any appreciable sophisticated interests when we started. We were pretty excited to work with the expression data; whether it was from *E. coli* was incidental. Learning the significance of *E. coli* as a model organism really help put everything in place, to understand why we were doing it [F4].

6. What roles do your interest in this project play?

Bryan: I think that Maurice's great explanations of the fundamentals helped us gain a certain level of clarity regarding the subject matter, and did make me more committed to seeing the project through, because I understood what was going on [F6]. I guess that having a general interest in the subject area just means we went into it with open minds, eager to learn whatever we could. Some of the information Maurice taught us (statistical techniques, genetics stuff like PCR) is still very applicable to my learning and research work in medical school today, and I certainly wouldn't have made the effort to truly understand the basic concepts if not for a genuine interest in the field [F1]. Oliver: Some underlying level of interest was there to keep us coming back to it [F1]. As we continued working under Maurice, he described the project and how it fit into the literature. It made us feel that our work was meaningful, and kept us on our toes to keep learning.

7. Were you informed that a previous SMP group (from Nanyang Girls) published their SMP, on finding reference genes, in IUBMB Life? How do you think this information will affect you then?

Bryan: I do think we were told that a previous group had published their work, which was indeed a boon [F5], since it would be something extra that was not part of the SMP requirements. Not only would we learn the proper writing style and procedures necessary for formal publication [F1], we would actually get a paper under our names. But at the same time, perhaps I had not yet recognised the importance of scientific publication. Fortunately, Maurice did explain this in great detail. He also took the opportunity to impart to us a lot of knowledge about academia in general - I remember this conversation about academic pedigree and career progression and the difficulties of publishing - it was certainly eye-opening [F5]. Oliver: We were somewhat aware of a SMP group publishing, though I don't recall the exact group nor the journal. I believe Maurice described the publishing process and his intent for us to publish pretty early on. We were quite excited, because submitting to a journal would entail learning about proper academic writing. Plus, it'd be nice to have an authored paper [F5]. I was rather keen to pursue science as a career back then, and I gathered that publishing was a mark of successful scholarship [F1].

8. Focusing on the first project (finding reference genes for *E. coli*), can you briefly describe the course of working on this project?

Oliver: Without a physical experiment or lab to go to, our work was very flexible [F3], with a good deal accomplishable wherever we were. We met Maurice weekly or bi-weekly, usually on weekends, while us 3 met weekly or more to complete the work set out [F4, F7]. When we met, Maurice typically described the project steps on a high-level, or clarified any questions we had. Towards the end, as we moved closer to publishing, we spent more time sending edits over email, and spent our meetings with Maurice reading drafts. Bryan: I basically agree with Oli's response to the question. Maurice was very flexible regarding timing and goals set for each meeting [F3], and most of the work was done on the computer. We spent time learning the fundamental concepts, doing the data analysis, writing up the paper, and also preparing the oral presentation for SMP. On the whole, I felt we made decent progress and were generally able to adhere to deadlines.

9. On the first project, what did you learn from it and what difficulties you faced? How did you overcome those difficulties?

Oliver: We learnt that it was imperative to keep a good record of our findings and data, especially as we moved between versions. We learnt the value of keeping a well-documented log book, as we often got disoriented or outright lost when moving to new concepts. As novice data analyzers, we sometimes made mistakes processing the data, and sometimes even mixed up columns of identifiers etc. We would realize our mistake after we calculated a statistic that made no sense, and had to retrace our steps with prior versions of the data. Bryan: I remember fondly the first logbook we had, where I often messed up when writing stuff inside. It started out pretty haphazardly, with me just scribbling down whatever Maurice said during meetings, but we eventually learnt to be more organised, which made it easier for us to refer back to older entries. The logbook was really essential to keeping us on track, since we frequently got confused when attempting to tackle the data ourselves. To overcome this, I guess we learnt to be more meticulous and thorough when doing the calculations.

10. What are some of the success and failure factors contributing to this project? In another word, if you were to re-do this phase of your life or requiring to supervise a project now, what are the aspects that you will keep (success factors) and what aspects will you change (failure factors), and why?

Oliver: Overall I had a very positive experience. Weekly meetings were definitely necessary to keep us on task [F4, F7]. We might have drifted off track without the constant meetings with Maurice. The very targeted literature which Maurice chose

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for us review was also helpful for our learning [F6]- we would have been overwhelmed if simply told to search NCBI, and lost if we hadn't been given specific references to understand the field from. On the failure side, it would have been a lot more efficient if we had learnt basic programming first, such as SQL, R, or Python. Maurice made a strong effort to teach us, but I think we were unable to understand how much it could change our workflow. Bryan: I think Maurice was very understanding and patient when explaining concepts and teaching us how to analyse the data, which definitely helped to solidify my knowledge [F4, F7]. The flexibility of meetings [F3] also helped in ensuring we could all find a common time to meet, so none of us would fall behind. I recall that during some of our meetings without Maurice, we would get distracted and therefore not accomplish much. Setting targets for each meeting would probably have helped us stay on track. Other than that, I also agree with Oli's point regarding learning the programming. I think I could have put in more effort in that area, since it would prove to be important in both this project and subsequent ones.

11. The first project (finding reference genes for *E. coli*) was published. How did you feel about it?

Oliver: I was certainly happy that it got published; it was external validation that our work was at least at some baseline level of meeting expectations [F5]. Bryan: It's a bit tough to recall my initial feelings. I guess it felt good to author a published paper, although I too didn't fully understand the significance of it at the time.

12. When the *E. coli* project was published, did you understand the academic / professional significance of it? How about your thoughts now, after a couple of years?

Oliver: I definitely didn't grasp the full significance back then. I understood that publications were a commonly used metric for academic success, but I didn't know how much our teachers and future admissions centers would care. Maurice did give us the lowdown on the H-index, but at the time I just thought it a construct that university faculty talked about. Looking back, I'd say that publishing made this research experience stand out from my other science-related pursuits. Bryan: Back then, I probably didn't appreciate the significance of it. Looking back, I think the series of papers we wrote with Maurice was certainly a great boon to my CV, and contributed to me getting into medical school. The positive research experience was a major factor which spurred me on to continue in the field of medical research [F4, F7]. Many of the fundamentals and statistical techniques which Maurice taught us have come in handy as well. On the whole, it was a great first foray into the world of research. Right now, with the better understanding I have of the intricacies of academic publication, I definitely think the publication of that first paper was not to be overlooked.

13. What are the factors that driven you towards wanting to do a second project (finding lineage specific reference genes) given that you had completed the SMP project and this second project does not have the support of a structure (such as "being part of SMP programme")?

Oliver: We had a very good experience with Maurice [F6], and we all were interested in pursuing more science research [F1]. I think continuing with Maurice was the best choice available, since we saw no incentive to look elsewhere for other projects. Plus, we were keen to build on the rudimentary knowledge we were gaining about gene invariance. Delving deeper into the one field made more sense than trying a scattering of projects [F3, F5]. Bryan: I think it was quite a natural progression, actually. I had enjoyed the process of working on the first project and had learnt a lot from Maurice, so when he offered a continuation, it was easy to say yes. Especially since we had so much trouble in the initial stages of finding an SMP project. We were pretty comfortable working with each other, and were eager to continue on. Since we knew that we could publish the work, and that once again timings were flexible, not having the support of a fixed programme like SMP wasn't a big issue.

14. Looking back to 2 time points, start of SMP and the publication of SMP as a refereed paper, how will you rate your confidence in getting a paper published after going through this process yourself?

Bryan: I would say that before SMP I didn't have much idea about how papers were published, so that would be close to zero confidence. During the actual project, we really got to experience for ourselves all the steps, from the data analysis and writing to the journal submission and review procedures. So I would say that I gained a much better understanding of the processes involved, and this did build up confidence in my ability to prepare future manuscripts. That being said, there are still other aspects (intrinsic quality of research, finding appropriate impact factor journals, adequately dealing with reviewer comments) which I would not be adept at tackling on my own. I think that even now I would still require a healthy amount of guidance to approach these issues. Oliver: Time point 1, I'd not have imagined myself doing it. Time point 2, I'd still be pretty shakey about doing it. I don't recall exactly but I believe the first paper was mostly handled by Maurice, in terms of the admin, application, galley proofs etc. But I'd say that at least we were feeling more confident about academic writing.

15. Between experiences with a supervisor and delving deeper into a field, which is more important to you and why? For example, how will good or bad supervision experience affect your interest in a field?

Bryan:I guess this depends on my interest level in the field, and whether I'm working with more of an exploratory mindset or a strong commitment to long-term involvement in that area [F1]. Personally, I wouldn't say that one is strictly more important than the other. If my goal were to delve into different areas of science and see which I liked best, then I think a good supervisor

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who explains basic concepts and is committed to nurturing my interest would certainly be a major factor [F6]. I don't recall any particularly bad supervision experiences I've had, but I suppose such an experience could dampen my interest. Oliver: Depending on my position and commitment to a field, that answer could go both ways. One could imagine the hypothetical student who adores a subject so dearly that he would not be held back by any lack of supervision or guidance. But overall I'm of the opinion that a good supervisor is foundational in a good research experience, and has been the strongest determinant of whether I find a project fulfilling. One particular example stands out - I was involved in some optics research, which ran well with my passion for physics. But my mentor and I did not have a good fit, and a combination of infrequent communication and a high workload for him during my supervision resulted in an undirected, badly executed project. It was a subpar experience that put me off laboratory work ever since. Evidently, I'm a good anecdote for how a bad supervision experience can override 'interest in a field' [F4, F7].

16. What are your views on the second project (finding lineage specific reference genes)? How similar or different are your views compared to the first project (finding *E. coli* reference genes)?

Bryan: I feel that we naturally thought of the second project as an extension of the first, and were eager to apply the knowledge we had gained through the course of working on the first project, while also delving deeper into the field. So we decided to continue on, for reasons explained in some of the previous questions. I would say that as compared to the first project, we had a better idea of what exactly we were getting into. We went into the second project with a bit more confidence and understanding of the basic concepts in bioinformatics. Oliver: The second project was rather similar to the first. We progressed from searching for generic invariant genes to lineage-specific ones, but overall it was a manageable extension of the concepts we had learnt in the first [F4]. I think the second project was more interesting overall, because we could comment on the biological significance of lineage-specific genes (should they exist).

17. During this second project, Maurice went to America to work for a year? How had that impacted on the project? How did you maintain your interests and passions? Are there any points in time where you felt that this project is not going anywhere and what did you do about it?

Bryan: I suppose progress was definitely slower than it would have been if Maurice had been around. I remember that during each of our meetings we had to chat with Maurice on gmail to ask (numerous and often repetitive) questions, and then try to work things out the best we could. Online discussion was undoubtedly a lot less productive than face-to-face meetings with Maurice, but we did try to work more independently and do more self-directed reading. Progress was certainly slow during our busy periods due to other commitments, but we didn't feel too down since we knew that, as always, the timeline was quite flexible. I think working together in a group really helped, because we were able to do a lot of discussion and bounce ideas off each other. If I remember correctly, we still tried to keep to our weekly meetings as much as possible, to make sure we got stuff done. Oliver: Definitely was a slow-down. As Bryan mentions, we did emailing and instant messaging to keep in touch with Maurice [F6], but some clarifications are just best done over pen and paper in person. We asked many dumb questions multiple times, which Maurice was patient [F6] with, but was clear evidence of the lowered efficiency. We never thought of abandoning it though. We were sure that we'd complete it eventually - it was just a question of how much progress we could discipline ourselves into accomplishing that week [F6].

18. How was the learning experience from the second project different from the first project (if any), considering that the first project has a very directed goal (finding suitable reference genes) whereas the second project is examining a hypothesis (is there lineage-specific reference genes)? In a way, the second project was constructed in a way that both positive results (there is lineage-specific reference genes) and negative results (there is no lineage-specific reference genes) are publishable – how has this affected your scientific views?

Bryan: I don't think the second project was very different from the first for me. I suppose it felt a bit more relaxed because it wasn't set within the structure of the SMP and we didn't have strict deadlines to adhere to [F3]. Although the second project was «examining a hypothesis», we still had a pretty clear idea of what we needed to do and how to go about tackling it. So there was a sense of direction. At first I thought it quite weird that we were publishing negative results, so the process was quite eye-opening for me [F5]. Oliver: I think I knew back then that negative results were valid and meaningful too. I'm glad we did that second paper, though, because most literature I had been exposed to emphasized positive findings. It was fun writing the discussion because we had to think of reasonable explanations for the lack of Spermophilius liver specific reference genes. Compared to reasoning about the Gene Ontology in the first project, this felt like it had more biological significance.

19. After these 2 projects, how will you gauge your scientific competencies and confidence, compared to your peers? What are some key points, in terms of scientific method and the process of scientific research, that you had learnt from the first project and the second project?

Bryan: We were pretty fortunate to have gotten this opportunity - I know a few people who had much less rewarding SMP experiences. I learnt a lot about statistical methodology, how to write up a decent paper, and how to prepare for manuscript submission [F5], though I probably wouldn't be confident in doing these without supervision. Another major takeaway for me was learning more about academia in general [F5]. Overall I think we became more competent at planning and executing

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on a given project - possibly more so than our peers without scientific background - but our work needed a lot of refinement, so confidence was still lacking. Oliver: I suppose I would describe it as high? Statistics and significance finding were amongst the technical skills we obtained. On the research side, I learnt that proper writing of the introduction and discussion comes really late. I also began to internalize the importance of setting a hypothesis clearly.

20. So, what are the factors that made you decide on doing the third project (developing an algorithm for finding reference genes)?

Oliver: I guess we still weren't tired of doing this bio-informatics thing [F1]. I don't recall how the transition was like from the second to third project, but I think it was relatively frictionless. Bryan: The fact that we had succeeded in publishing two papers gave us confidence in starting another one [F1, F6]. I think we had gained a much better understanding of the field at the time, plus the premise of the third project sounded quite interesting - not just using available tools to find reference genes like the first two projects, but actually developing our own algorithm [F1].

21. How is the third project different from the first two projects and what challenges you faced?

Oliver: The third project was significantly different from the first two. Coming up with an invariance measurement using a basket of existing methods required knowledge of the commonly-used ones. We also had to think of variations on them to produce more candidates. Beyond that, we had to propose a definition of invariance, and defend it (I believe we used Normfinder). For challenges, I was a little sloppy with our data manipulation, which led to problems and occasional roll-backs. Bryan: Out of all the projects we did, I'm most proud of the third one. Formulating a new algorithm as a preliminary scan for new reference genes felt like a meaningful project, that we were actually doing something proactive and not just adding on to an existing database of reference genes. I feel like we took more ownership of this project compared to the first two, applying what we had learnt to optimise our algorithm [F1, F5]. We had quite an aesthetically pleasing poster for SSEF too, unlike the one we made for the first project. In terms of challenges, I suppose we still needed quite a bit of guidance to direct our thinking. On the whole, this project was a pretty good experience for me though.

22. You had also published a paper for the third project (PMID 25763136). How did you feel about it?

Oliver: Publishing papers was becoming a less foreign concept to us as we went on. About the project, I think I was quite happy with the work we did, especially as we experimented with GeNorm vs Normfinder and BestKeeper. Regarding the publishing, I don't recall, but I think we were happy that it was validated as something worth publishing. Bryan: As mentioned before, I was pretty happy about the third project because I think we took more ownership of it. Seeing it published was somewhat an acknowledgement that we were fairly competent [F5].

23. Did you have an expectation to be publishing papers for every project from this point onwards? Are you able to articulate the scientific and publication process? How do you think that you had developed professionally through these 3 projects?

Oliver: Objectively, I know that projects and papers don't have a bijective relationship - we shouldn't be expecting to get a paper out of every project we try. It's a matter of the scientific approach and how stumbling across ideas may match our targeted hypotheses but not necessarily so. In spite of that,I was effectively expecting something to be published [F5]. I think the process starts with a query, then a hypothesis, then literature research, then deciding on the methodology, then after you get your results you might iterate a few more times to refine the approach, then you write the paper, then you find an appropriate journal, then you submit, then if accepted you write more galley proofs, or make edits as recommended, then you format appropriately for the publication's requirements, and lastly it is published. Bryan:I kinda did have such an expectation [F5]. Of course, the learning process was really important, but getting published seemed to be the standard way of validating the work we did. In terms of the process, I agree with what Oli said. I think formulating the research question correctly is an essential initial step, otherwise you end up having to redo the methodologies to get the appropriate results. Personally, I felt a greater sense of familiarity with the journal submission process for the third project, and probably understood better how to make the necessary edits as per the reviewers' comments.

24. By the end of the third project, you are already in JC1. Given the amount of school work, what pushed you ahead to do the fourth project (on codon usage bias)?

Oliver: I really don't recall.

Bryan: Well I guess we were just talking about it at Coffeebean, and somebody said «ok why not» and the other person said «yeah let's do it, I'm sure we can manage» [F3]. I don't think we really pondered too much into it.

25. How is the fourth project different from the rest? What challenges you face and what did you learn?

Oliver: The last project differed in its usage of CUB, which we had never heard of prior. It was an alternate way of measuring or correlating species 'closeness', and I think we had to start our understanding from scratch, versus gene expression invariance. We learnt about using a dendrogram to visualize statistical relationships and correlations. We also learnt about the implications of evolutionary distance and the basis for CUB. Bryan: It was pretty different in terms of the basic concepts. We had to learn a bit about evolution and genetics to better understand the project, which was good for me since I had to

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know some of that stuff for bio anyway. We once again needed a bit of guidance for the statistical methods. Other than that, no particular challenges really stand out to me.

26. Looking back from this point in time, do you think you do through this route again? Why?

Bryan: Overall, I enjoyed the process of working on this series of papers, and if given the opportunity, I would do it again [F1]. Doing multiple interrelated projects in the same field really helped to solidify my understanding and made me better able to assume greater ownership of the work we did. I think the process was a lot more meaningful, in terms of personal growth as a researcher, as compared to completing just a single project [F5, F6]. Oliver: I'd definitely go for a 'yes'. This research experience taught me a great deal about the way science is done and the rationale behind it [F5]. As a student I learnt much about a specific set of bioinformatics fields and as a growing adult I learnt much about myself. Student research provides opportunities that are uncommonly replicated elsewhere - independent work, depth of inquiry, exposure to a field expert.

27. Are there any points in time where you wanted to give up? If yes, how did you keep yourself motivated? If no, how did you manage to sustain your motivation?

Bryan: I don't recall any particular points where we felt like quitting. Certainly there were the busier academic/CCA periods where we had to put our research on hold for a while, but eventually we would find time to continue. I think we tried to keep the end goal in mind - we understood the research process and knew the steps to getting our manuscript published - so we just worked towards it. We both also recognised that authorship of publications would be useful when applying for university, which helped keep us motivated too [F1, F6]. Oliver: No, at least not to my recollection. There were times when it got slow but I was frankly more worried about Maurice dropping us than vice versa. In keeping motivated, I'd venture that a keen interest in science helps a lot [F1].

28. What are the roles and qualities of your group mates in this process?

Bryan: Oli and I tried to complete the vast majority of the work when we met for discussion (we weren't very productive individually), so it was really quite a team effort. If it were an individual thing I would probably have procrastinated to no end. Most of the work was split equally and working together allowed us to clarify doubts, helping to ensure we got stuff done. Oliver: Qualities were a general sense of responsibility / accountability. I apply the term loosely for we were rather flexible in manifesting this responsibility. On occasions we'd sit down and knock out 2 pages of the introduction in one sitting, and on others, we'd start by playing computer games for an hour or so. But regardless, I think we held in mind what we ought to be doing, and always returned to it eventually. A problem-solving mentality is another. We had many problems to solve on the way, many with solutions well within our grasp. We just had to be willing to give them a try before conceding.

29. What are the roles and qualities of your mentor in this process?

Bryan:Maurice was really instrumental [F6]in showing us the steps and patiently teaching us the fundamentals of bioinformatics, especially in the first couple of projects where we were quite lost. He played a crucial role throughout the series of projects by posing questions and providing comments, often taking the time to explore concepts in greater depth. I've gained much insight into the world of research and publication thanks to his tireless teachings. Oliver: Maurice was invested in our growth, approachable, andable to detect where our understanding strayed [F6].

30. Will you encourage your juniors to go through the same path as you did? Why? And what advice will you give them when they are starting out (prior to the first project)?

Bryan: I would encourage them to choose a field they find interesting and delve deeper into it, rather than just skimming the surface by doing a single project for SMP. I feel that completing multiple projects is useful in honing the skills necessary to reach the eventual publication of a manuscript. My advice would be that a certain degree of commitment is needed in order to make the most out of the research experience, and to take the opportunity to learn as much as you can [F1, F5, F6]. Oliver: Yes. Please embark on a project. Don't stop at one paper because a good working relationship takes time to build [F6] and so does a base of usable field knowledge [F4]. Even if you develop it fast, the project will be over just as you've got it.

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