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4 Enhancing senior high school student engagement and academic performance using an inclusive 5 and scalable inquiry-based program

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22 Abstract

23 The multi-disciplinary nature of science, technology, engineering and math (STEM) careers often renders difficulty
24 for high school students navigating from classroom knowledge to post-secondary pursuits. Discrepancies between
25 the knowledge-based high school learning approach and the experiential approach of undergraduate studies leaves
26 some students disillusioned by STEM. We present *Discovery*, a semester-long inquiry-focused learning model
27 delivered by STEM graduate students in collaboration with high school educators, in the context of biomedical
28 engineering. Entire classes of high school STEM students representing diverse cultural and socioeconomic
29 backgrounds engaged in iterative, problem-based learning designed to emphasize critical thinking concomitantly
30 within the secondary school and university environments. Assessment of grades and survey data suggested positive
31 impact of this learning model on students' STEM pursuits, notably in under-performing cohorts, as well as repeating
32 cohorts that engage in the program on more than one occasion. *Discovery* presents a scalable platform blurring the
33 divide between secondary and post-secondary learning, providing valuable learning opportunities and capturing
34 cohorts of students that might otherwise be under-engaged in STEM.

35 1 Introduction

36 High school students with diverse STEM interests often struggle to understand the STEM experience outside the
37 classroom¹. The multi-disciplinary nature of many careers fosters a challenge for many students when considering
38 the transition between high school study and future academic pursuits. Furthermore, this challenge is amplified by
39 the known discrepancy between the knowledge-based learning approach common in high schools and the
40 experiential, mastery-based approaches afforded by the undergraduate model². In the latter, focused classes,
41 interdisciplinary concepts, and laboratory experiences allow for the application of accumulated knowledge, practice
42 in problem solving, and development of both general and technical skills³. Such immersive cooperative learning
43 environments are difficult to establish in the secondary school setting and many high school educators struggle to
44 implement within their classroom⁴. As such, high school students may become disillusioned before graduation and
45 never experience an enriched learning environment, despite their inherent interests in STEM⁵.

46 Early introduction to varied math and science disciplines throughout high school is vital if students are to pursue
47 STEM fields, especially within engineering⁶. In the context of STEM education and career choices, student self-
48 efficacy regarding research skills has been shown to predict undergraduate student aspirations for research careers⁷.
49 Self-efficacy has also been identified to influence ‘motivation, persistence, and determination’ in overcoming
50 challenges in a career pathway⁸. It is suggested that high school students, when given opportunity and support, are
51 capable of successfully completing rigorous programs at STEM focused schools⁹. However, alternate studies have
52 shown no significant differences in participation rates in advanced sciences and mathematics for these students
53 compared to their peers at non-STEM focused schools¹⁰. In fact, Brown *et al* studied the relationships between
54 STEM curriculum and student attitudes, and found the latter played a more important role in intention to persist in
55 STEM when compared to self-efficacy¹¹. Therefore, creation and delivery of modern and exciting curriculum is
56 fundamental to engage and retain students.

57 Many public institutions support the idea that post-secondary led engineering education programs are effective ways
58 to expose high school students to engineering education and relevant career options, and also increase engineering
59 awareness¹². Although singular class field trips are used extensively to accomplish such programs, these may not
60 allow immersive experiences for application of knowledge and practice of skills that are proven to impact long-term
61 learning and influence career choices^{13,14}. Longer-term immersive research experiences, such as after-school

62 programs or summer camps, have shown successful at recruiting students into STEM degree programs and careers,
63 where longevity of experience helps foster self-determination and interest-led, inquiry-based projects^{3,7,15-17}. Such
64 activities convey the elements that are suggested to make a post-secondary led high school education program
65 successful: hands-on experience, self-motivated learning, real-life application, immediate feedback, and problem-
66 based projects^{18,19}. In combination with immersion in university teaching facilities, learning is authentic and
67 relevant, and consequently representative of an experience found in actual STEM practice²⁰.

68 Supported by the outcomes of previously identified effective program strategies, University of Toronto (U of T)
69 graduate trainees created *Discovery*, a novel high school education program, to develop a comfortable yet
70 stimulating environment of inquiry-focused iterative learning for senior high school students. Built in strong
71 collaboration with science educators from George Harvey Collegiate Institute (Toronto District School Board),
72 *Discovery* stimulates application of STEM concepts within a unique semester-long applied curriculum delivered
73 iteratively within both U of T undergraduate teaching facilities and collaborating high school classrooms²¹. Based on
74 the volume of medically-themed news and entertainment that is communicated to the population at large, the
75 rapidly-growing and diverse field of biomedical engineering (BME) was considered an ideal program context²². In
76 its definition, BME necessitates cross-disciplinary STEM knowledge focused on the betterment of human health,
77 wherein *Discovery* facilitates broadening student perspective through engaging inquiry-based projects. Importantly,
78 *Discovery* allows all students within a class cohort to work together with their classroom educator, stimulating
79 continued development of a relevant learning community that is deemed essential for meaningful context and
80 important for transforming student perspectives and understandings^{23,24}. Multiple studies support the concept that
81 relevant learning communities improve student attitudes towards learning, significantly increasing student
82 motivation in STEM courses, and consequently improving the overall learning experience²⁵. Learning communities,
83 such as that provided by *Discovery*, also promote the formation of self-supporting groups, greater active
84 involvement in class, and higher persistence rates for participating students²⁶.

85 The objective of *Discovery*, through structure and dissemination, is to engage senior high school science students in
86 challenging, inquiry-based practical BME activities as a mechanism to stimulate comprehension of STEM
87 curriculum application to real world concepts. Consequent focus is placed on critical thinking skill development
88 through an atmosphere of perseverance in ambiguity, something not common in a secondary school knowledge

89 focused delivery but highly relevant in post-secondary STEM education strategies. Herein, we describe the observed
90 impact of the differential project-based learning environment of *Discovery* on student performance and engagement.
91 We specifically hypothesize that value of an inquiry-focused model is tangible for students that struggle in a
92 knowledge focused delivery structure, where engagement in conceptual critical thinking in the relevant subject area
93 stimulates student interest and resulting academic performance. Assessment of these outcomes suggests that when
94 provided with a differential learning opportunity, the performance of these students increased as they engaged more
95 thoroughly in STEM subject matter. Consequently, *Discovery* provides a framework to the potential efficacy of the
96 model for scalable application in bridging the gap in critical thinking and problem solving between secondary and
97 post-secondary education.

98 **2 Results**

99 **2.1 Program Delivery**

100 The outcomes of the current study result from execution of *Discovery* over five independent academic terms as a
101 collaboration between IBBME (graduate students, faculty, and support staff) and George Harvey Collegiate Institute
102 (science educators and administration) stakeholders. Each term, the program allowed senior secondary STEM
103 students (Grades 11 and 12) opportunity to engage in a novel project-based learning environment. The program
104 structure uses the engineering capstone framework as a tool of inquiry-focused learning objectives, motivated by a
105 central BME global research topic, with research questions that are inter-related but specific to the curriculum of
106 each STEM course subject (**Fig 1**). Over each 12-week term, students worked in teams (3-4 students) within their
107 class cohorts to execute projects with the guidance of U of T trainees (*Discovery* instructors) and their own high
108 school educator(s). Student experimental work was conducted in U of T teaching facilities relevant to the research
109 study of interest (i.e., Biology and Chemistry-based projects executed within Undergraduate Teaching Laboratories;
110 Physics projects executed within Undergraduate Design Studios). Students were introduced to relevant techniques
111 and safety procedures in advance of iterative experimentation. Importantly, this experience served as a course term
112 project for students, who were assessed at several points throughout the program for performance in an inquiry-
113 focused environment as well as within the regular classroom (**Fig 1; S3 Appendix III**). To instill the atmosphere of
114 STEM, student teams delivered their outcomes in research poster format at a final symposium, sharing their results

115 and recommendations with other post-secondary students, faculty, and community in an open environment. An
116 exemplary term of student programming can be found in **S1 Appendix I**.

117 Over the course of five semesters there were 268 instances of tracked student participation, representing 170
118 individual students. Specifically, 94 students participated during only one semester of programming, 57 students
119 participated in two semesters, 16 students participated in three semesters, and 3 students participated in four
120 semesters. Multiple instances of participation represent students that enrol in more than one STEM class during their
121 senior years of high school, or who participated in Grade 11 and subsequently Grade 12. All assessments were
122 performed by high school educators for their respective STEM class cohorts using consistent grading rubrics and
123 assignment structure (summarized in **S3 Appendix III**). Here, we discuss the outcomes of student involvement in
124 this experiential curriculum model.

125 **2.2 Student performance and engagement**

126 Student grades were assigned, collected and anonymized by educators for each *Discovery* deliverable (background
127 essay, client meeting, proposal, progress report, poster and final presentation). Educators anonymized collective
128 *Discovery* grades, the component deliverable grades thereof, final course grades, attendance in class and during
129 programming, as well as incomplete classroom assignments for comparative study purposes. Students performed
130 significantly higher in their cumulative *Discovery* grade than in their cumulative classroom grade (final course grade
131 less the *Discovery* contribution; $p < 0.0001$). Nevertheless, there was a highly significant correlation ($p < 0.0001$)
132 observed between the grade representing combined *Discovery* deliverables and the final course grade (**Fig**
133 **2a**). Further examination of the full dataset revealed two student cohorts of interest: the “Exceeds Expectations” (EE)
134 subset (defined as those students who achieved ≥ 1 SD [18.0%] grade differential in *Discovery* over their final
135 course grade; $N=99$ instances); and the “Multiple Term” (MT) subset (defined as those students who participated in
136 *Discovery* more than once; 76 individual students that collectively accounted for 174 single terms of assessment out
137 of the 268 total student-semesters delivered) (**Fig 2b-c**). These subsets were not unrelated; 46 individual students
138 who had multiple experiences (60.5% of total MTs) exhibited at least one occasion in achieving a $\geq 18.0\%$ grade
139 differential. MT students that participated in 3 or 4 semesters ($N = 16$ and 3, *respectively*) showed no significant
140 increase by linear regression in their course grade over time ($p = 0.40$, **Fig 2e**), but did show a significant increase in
141 their *Discovery* grades ($p = 0.0009$, **Fig 2f**).

142 As students participated in group work, there was concern that lower-performing students might negatively
143 influence the *Discovery* grade of higher-performing students (or vice versa). However, students were observed to
144 self-organize into groups where all individuals received similar final overall course grades (**Fig 2d**), thereby
145 alleviating these concerns. In addition, students demonstrated excellent *Discovery* attendance; at least 91% of
146 participants attended all *Discovery* sessions in a given semester (**Fig 2g**). In contrast, class attendance rates reveal a
147 much wider distribution where 60.8% (163 out of 268 students) missed more than 4 classes (equivalent in learning
148 time to one *Discovery* session) and 14.6% (39 out of 268 students) missed 16 or more classes (equivalent in learning
149 time to an entire program of *Discovery*) in a semester (**Fig 2h**).

150 *Discovery* EE students (**Fig 3**), roughly by definition, obtained lower course grades ($p < 0.0001$, **Fig 3a**) and higher
151 final *Discovery* grades ($p = 0.0004$, **Fig 3b**) than non-EE students. This cohort of students exhibited program grades
152 significantly higher than classmates (**Fig 3d-h**) in every category with the exception of essays, where they
153 performed to a significantly lower degree ($p = 0.097$; **Fig 3c**). There was no statistically significant difference in EE
154 vs. non-EE student classroom attendance ($p = 0.85$; (**Fig 3i-j**).. There were only 4 single day absences in *Discovery*
155 within the EE subset; however, this difference was not statistically significant ($p = 0.074$).

156 *Discovery* MT students (**Fig 4**), although not receiving significantly higher grades in class than students
157 participating in the program only one time ($p = 0.29$, **Fig 4a**), were observed to obtain higher final *Discovery* grades
158 than single-term students ($p = 0.0067$, **Fig 4b**). However, MT students only performed significantly better on the
159 progress report ($p = 0.0021$; **Fig 4f**), with trends of higher performance for their initial proposals and final
160 presentations ($p = 0.081$ and 0.056 , respectively; **Fig 4e & 4h**); all other deliverables were not significantly different
161 between MT and non-MT students (**Fig 4c-d & 4g**). Attendance in *Discovery* ($p = 0.22$) was also not significantly
162 different between MT and non-MT students, although MT students did miss significantly less class time ($p = 0.010$)
163 (**Fig 4i-j**).

164 **2.3 Educator Perceptions**

165 Qualitative observation in the classroom by high school educators emphasized the value students independently
166 placed on program participation and deliverables. Throughout the term, students often prioritized *Discovery* group
167 assignments over other tasks for their STEM courses, regardless of academic weight and/or due date. Comparing
168 within this student population, educators spoke of difficulties with late and incomplete assignments in the regular

169 curriculum but found very few such instances with respect to *Discovery*-associated deliverables. Further, educators
170 speculated on the good behaviour and focus of students in *Discovery* programming in contrast to attentiveness and
171 behaviour issues in their school classrooms. Multiple anecdotal examples were shared of renewed perception of
172 student potential; students that exhibited poor academic performance in the classroom often engaged with high
173 performance in this inquiry-focused atmosphere. Students appeared to take a sense of ownership, excitement and
174 pride in the setting of group projects oriented around scientific inquiry, discovery, and dissemination.

175 **2.4 Student Perceptions**

176 Students were asked to consider and rank the academic difficulty (scale of 1-5, with 1 = not challenging and 5 =
177 highly challenging) of the work they conducted within the *Discovery* learning model. Considering individual
178 *Discovery* terms, at least 91% of students felt the curriculum to be sufficiently challenging with a 3/5 or higher
179 ranking (Term 1: 87.5%, Term 2: 93.4%, Term 3: 85%, Term 4: 93.3%, Term 5: 100%), and a minimum of 58% of
180 students indicating a 4/5 or higher ranking (Term 1: 58.3%, Term 2: 70.5%, Term 3: 67.5%, Term 4: 69.1%, Term
181 5: 86.4%) (**Fig 5a**).

182 The majority of students (94.6%) indicated they felt more comfortable with the idea of performing future work in a
183 university STEM laboratory environment given exposure to university teaching facilities throughout the program
184 (**Fig 5b**). Students were also queried whether they were i) more likely, ii) less likely, or iii) not impacted by their
185 experience in the pursuit of STEM in the future. The majority of participants (> 82%) perceived impact on STEM
186 interests, with 72.4% indicating they were more likely to pursue these interests in the future (**Fig 5c**). When
187 surveyed at the end of term, 84.9% of students indicated they would participate in the program again (**Fig 5d**).

188 **3 Discussion**

189 We have described an inquiry-based framework for implementing experiential STEM education in a BME setting.
190 Using this model, we engaged 268 participants (170 individual students) over five terms in project-based learning
191 wherein students worked in peer-based teams under the mentorship of U of T trainees to design and execute the
192 scientific method in answering a relevant research question. Collaboration between high school educators and
193 *Discovery* instructors allowed for high school student exposure to cutting edge BME research topics, participation in
194 facilitated inquiry, and acquisition of knowledge through scientific discovery. All assessments were conducted by

195 high school educators and constituted a fraction (10-15%) of the overall course grade, instilling academic value for
196 participating students. As such, students exhibited excitement to learn as well as commitment to their studies in the
197 program.

198 Through our observations and analysis, we suggest there is value in differential learning environments for students
199 that struggle in a knowledge acquisition-focused classroom setting. In general, we observed a high level of academic
200 performance in *Discovery* programming (**Fig 2a**), which was highlighted exceptionally in EE students who exhibited
201 greater academic performance in *Discovery* deliverables compared to normal coursework (> 18% grade
202 improvement in relevant deliverables). We initially considered whether this was the result of strong students
203 influencing weaker students; however, group organization within each course suggests this is not the case (**Fig 2d**).
204 With the exception of one class in one semester (24 participants assigned by their educator), students were allowed
205 to self-organize into working groups and they chose to work with other students of relatively similar academic
206 performance (as indicated by course grade), a trend observed in other studies^{27,28}. Remarkably, EE students not only
207 excelled during *Discovery* when compared to their own performance in class, but this cohort also achieved
208 significantly higher average grades in each of the deliverables throughout the program when compared to the
209 remaining *Discovery* cohort (**Fig 3**). This data demonstrates the value of an inquiry-based learning environment
210 compared to knowledge focused delivery in the classroom in allowing students to excel. It is a well-supported
211 concept that students who struggle in traditional settings tend to demonstrate improved interest and motivation in
212 STEM when given opportunity to interact in a hands-on fashion, which supports our outcomes^{3,29}. Furthermore,
213 these outcomes clearly represent variable student learning styles, where some students benefit from a greater
214 exchange of information, knowledge and skills in a cooperative learning environment³⁰. The performance of the EE
215 group may not be by itself surprising, as the identification of the subset by definition required high performers in
216 *Discovery* who did not have exceptionally high course grades; in addition, the final *Discovery* grade is dependent on
217 the component assignment grades. However, the discrepancies between EE and non-EE groups attendance suggests
218 that students were engaged by *Discovery* in a way that they were not by regular classroom curriculum.

219 In addition to quantified engagement in *Discovery* observed in academic performance, we believe remarkable
220 attendance rates are indicative of the value students place in the differential learning structure. Given the differences
221 in number of *Discovery* days and implications of missing one day of regular class compared to this immersive

222 program, we acknowledge it is challenging to directly compare attendance data and therefore approximate this
223 comparison with consideration of learning time equivalence. When combined with other subjective data including
224 student focus, requests to work on *Discovery* during class time, and lack of discipline/behaviour issues, the
225 attendance data importantly suggests that students were especially engaged by the *Discovery* model. Further, we
226 believe the increased commute time to the university campus (students are responsible for independent transit to
227 campus, a much longer endeavour than the normal school commute), early program start time, and students' lack of
228 familiarity with the location are non-trivial considerations when determining the propensity of students to participate
229 enthusiastically in *Discovery*. We feel this suggests the students place value on this team-focused learning and find it
230 to be more applicable and meaningful to their interests.

231 Given post-secondary admission requirements for STEM programs, it would be prudent to think that students
232 participating in multiple STEM classes across semesters are the ones with the most inherent interest in post-
233 secondary style STEM programs. The MT subset, representing students who participated in *Discovery* for more than
234 one semester, averaged significantly higher final *Discovery* grades. The increase in the final *Discovery* grade was
235 observed to result from a general confluence of improved performance over multiple deliverables and a continuous
236 effort to improve in a STEM curriculum. This was reflected in longitudinal tracking of *Discovery* performance,
237 where we observed a significant trend of improved performance. Interestingly, the high number of MT students who
238 were included in the EE group suggests that students who had a keen interest in science enrolled in more than one
239 course and in general responded well to the inquiry-based teaching method of *Discovery*, where scientific method
240 was put into action. It stands to reason that even if they do not perform well in their specific course, students
241 interested in science will continue to take STEM courses and will respond favourably to opportunities to put
242 classroom theory to practical application.

243 The true value of an inquiry-based program such as *Discovery* may not be based in inspiring students to perform at a
244 higher standard in STEM within the high school setting, as skills in critical thinking do not necessarily translate to
245 knowledge-based assessment. Notably, students found the programming equally challenging throughout each of the
246 sequential sessions, perhaps somewhat surprising considering the increasing number of repeat attendees in
247 successive sessions (**Fig 5a**). Regardless of sub-discipline, there was an emphasis of perceived value demonstrated
248 through student surveys where we observed indicated interest in STEM and comfort with laboratory work

249 environments, and desire to engage in future iterations given the opportunity. Although non-quantitative, we
250 perceive this as an indicator of significant student engagement, even though some participants did not yield
251 academic success in the program and found it highly challenging given its ambiguity. Further, we observed that
252 students become more certain of their direction in STEM, correlating with preliminary trends of increased post-
253 secondary application rates by *Discovery* graduates (data not shown); further longitudinal study is warranted to
254 make claim of this result. At this point in our assessment we cannot effectively assess the practical outcomes of
255 participation, understanding that the immediate effects observed are subject to a number of factors associated with
256 performance in the high school learning environment. Future studies that track graduates from this program will be
257 prudent, in conjunction with an ever-growing dataset of assessment, to continue to understand the expected benefits
258 of this inquiry-focused and partnered approach. Altogether, a multifaceted assessment of our early outcomes
259 suggests significant value of an immersive and iterative interaction with STEM as part of the high school
260 experience. A well-defined divergence from knowledge-based learning, focused on engagement in critical thinking
261 development framed in the cutting-edge of STEM, may be an important step to broadening student perspectives.

262 As we consider *Discovery* in a bigger picture context, expansion and implementation of this model is translatable.
263 Execution of the scientific method is an important aspect of citizen science, as the concepts of critical thinking become
264 ever-more important in a landscape of changing technological landscapes. Giving students critical thinking and
265 problem-solving skills in their primary and secondary education provides value in the context of any career path.
266 Further, we feel that this model is scalable across disciplines, STEM or otherwise, as a means of building the tools
267 of inquiry. We have observed here the value of differential inclusive student engagement and critical thinking
268 through an inquiry-focused model for a subset of students, but further to this an engagement, interest and excitement
269 across the body of student participants. As we educate the leaders of tomorrow, we suggest use of an inquiry-
270 focused model such as *Discovery* could facilitate growth of a data-driven critical thinking framework.

271 **4 Methods**

272 **4.1 Experimental Design**

273 All students in university-stream Grade 11 or 12 biology, chemistry, or physics at the participating school were
274 recruited into mandatory offerings of *Discovery* over five consecutive terms. Student grade and survey responses

275 were collected pending parent or guardian permission. Educators replaced each student name with a unique coded
276 identifier to preserve anonymity but enable individual student tracking over multiple terms. All data collected was
277 analyzed without any exclusions save for missing survey responses; no power analysis was performed prior to data
278 collection.

279 **4.2 Ethics statement**

280 This study was approved by the University of Toronto Health Sciences Research Ethics Board (Protocol # 34825)
281 and the Toronto District School Board External Research Review Committee (Protocol # 2017-2018-20).
282 Acquisition of student data (both post-hoc academic data and survey administration) followed written informed
283 consent of data collection from parents or guardians of participating students. Data was anonymized by high school
284 educators for maintenance of academic confidentiality.

285 **4.3 Program overview**

286 In facilitation of *Discovery*, a selected global health research topic was sub-divided into subject-specific research
287 questions (i.e., Biology, Chemistry, Physics) that students worked to address, both on-campus and in-class, during a
288 term-long project. The *Discovery* framework therefore provides students the experience of an engineering capstone
289 design project, and includes a motivating scientific problem (i.e., global topic), a discipline-specific research
290 question, and systematic determination of a professional recommendation addressing the needs of the presented
291 problem.

292 **4.3.1 High school partner**

293 The *Discovery* program evolved to the current model over a two-year period of working with one high school
294 selected from the local public school board. This partner school consistently scores highly (top decile) in the board's
295 Learning Opportunities Index (LOI). The LOI ranks each school based on measures of external challenges affecting
296 student success, therefore schools with the greatest level of external challenges receive a higher ranking³¹.
297 Consequently, participating students are identified as having a significant number of external challenges that may
298 affect their academic success. In addition, the selected school partner is located within a reasonable geographical
299 radius of our campus (i.e., ~ 40 min transit time from school to campus). This is relevant as participating students
300 are required to independently commute to campus for *Discovery* hands-on experiences.

301 **4.3.2 Student recruitment**

302 In agreement with school administration and science educators, *Discovery* was incorporated as a mandatory
303 component of course curriculum for senior students (Grade 11 and 12) in university stream Chemistry, Physics, and
304 Biology courses. Students therefore participated as class cohorts to address questions specific to their course
305 discipline knowledge base, but relating to the defined global health research topic (**Fig 1**). At the discretion of each
306 STEM teacher, assessment of program deliverables was collectively assigned as 10-15% of the final course grade
307 for each subject. All students were required to participate; however, students were given opportunity to opt out the
308 research study aspect of this program and parent/guardian consent was required for student data to be collected and
309 collated for research purposes.

310 **4.3.3 Instructional framework**

311 Each program term of *Discovery* corresponds with a five-month high school semester. U of T trainees (*Discovery*
312 instructors) and high school educators worked collaboratively to define a global healthcare theme in advance of each
313 semester. In addition, specific cutting-edge and curriculum-relevant research questions were developed for each
314 discipline to align within both the overall theme and the educational outcomes set by the provincial curriculum³².
315 *Discovery* instructors were consequently responsible for developing and introducing relevant STEM skills, as well
316 as mentoring high school students, for the duration of their projects; high school educators were responsible for
317 academic assessment of all program deliverables throughout the term (**Fig 1**).

318 During the course of a term, students engaged within the university facilities four times. The first three sessions
319 included hands-on lab sessions while the fourth visit included a culminating symposium for students to present their
320 scientific findings (**Fig 1**). Project execution was supported by U of T trainees who acted as engineering “clients” to
321 mentor student groups in developing and improving their assessment protocols, as well as generating final
322 recommendations to the original overarching questions. On average, there were 4-5 groups of students per discipline
323 (3-4 students per group; ~20 students/class). *Discovery* instructors worked exclusively with 1-2 groups each term in
324 the capacity of mentor to monitor and guide student progress.

325 After introducing the selected global research topic in class, educators led students in completion of background
326 research essays. Students subsequently engaged in a discipline-relevant skill-building protocol during their first visit
327 to university teaching laboratory facilities, allowing opportunity to understand analysis techniques and equipment

328 relevant for their assessment projects. At completion of this session, student groups were presented with a
329 discipline-specific research question as well as the relevant laboratory inventory available for use during their
330 projects. Armed with this information, student groups continued to work in their classroom setting to develop group-
331 specific experimental plans. Educators and *Discovery* instructors provided written and oral feedback, *respectively*,
332 allowing students an opportunity to revise their plans in class prior to on-campus experimental execution. Once at
333 the relevant laboratory environment, students executed their protocols in an effort to collect experimental data. Data
334 analysis was performed in the classroom and students learned by trial & error to optimize their protocols before
335 returning to the university lab for a second opportunity for data collection. All methods and data were re-analyzed in
336 class in order for students to create a scientific poster for the purpose of study/experience dissemination. During a
337 final visit to campus, all groups presented their findings at a research symposium, allowing students to verbally
338 defend their process, analyses, interpretations, and design recommendations to a diverse audience including peers,
339 STEM educators, undergraduate and graduate university students, postdoctoral fellows and University of Toronto
340 faculty.

341 **4.3.4 Data collection**

342 Educators evaluated students within their classes on the following associated deliverables: i) global theme
343 background research essay; ii) experimental plan; iii) progress report; iv) final poster content and presentation; and
344 v) attendance. For research purposes, these grades were examined individually and also as a collective *Discovery*
345 program grade. For students consenting to participation in the research study, all *Discovery* grades were anonymized
346 by the classroom educator before being shared with study authors. Each student was assigned a code (known only to
347 the classroom educator) for direct comparison of deliverable outcomes and survey responses.

348 Survey instruments were used to gain insight into student perceptions of STEM and post-secondary study, as well as
349 *Discovery* program experience and impact (**S2 Appendix II**). High school educators administered surveys in the
350 classroom only to students supported by parental permission. Pre-program surveys were completed at minimum one
351 week prior to program initiation each term and exit surveys were completed at maximum two weeks post-*Discovery*
352 term completion.

353 **4.4 Identification and comparison of population subsets**

354 From initial analysis, we identified two student subpopulations of particular interest: students who performed ≥ 1 SD
355 [18.0%] or greater in the *Discovery* portion of the course compared to their final course grade (“EE”), and students
356 who participated in *Discovery* more than once (“MT”). These groups were compared individually against the rest of
357 the respective *Discovery* population (“non-EE” and “non-MT”, *respectively*). Additionally, MT students who
358 participated in three or four (the maximum observed) semesters of *Discovery* were assessed for longitudinal changes
359 to performance in their course and *Discovery* grades. Comparisons were made for all *Discovery* deliverables
360 (introductory essay, client meeting, proposal, progress report, poster, and presentation), final *Discovery* grade, final
361 course grade, *Discovery* attendance, and overall class attendance.

362 **4.5 Statistical analysis**

363 Student course grades were analyzed in all instances without the *Discovery* component contribution (ranging from
364 10% to 15% of final mark depending on class and year) to prevent correlation. Student course grade vs. matched
365 *Discovery* grade was first compared by paired t-test. Student performance (N=268 total students, comprising 170
366 individuals) in *Discovery* was initially assessed in a linear regression of *Discovery* grade vs. final course grade.
367 Trends in course and *Discovery* performance over time in students participating 3 or 4 semesters (N=16 and 3
368 individuals, *respectively*) were also assessed by linear regression. For subpopulation analysis (EE and MT, N=99
369 instances from 81 individuals and 174 instances from 76 individuals, *respectively*), each data set was tested for
370 normality using the D’Agostino and Pearson omnibus normality test. All subgroup comparisons vs. the remaining
371 population were performed by Mann-Whitney U-test. Data are plotted as individual points with mean \pm SEM
372 overlaid (grades), or in histogram bins of 1 and 4 days, *respectively*, for *Discovery* and class attendance.
373 Significance was set at $\alpha \leq 0.05$.

374

375 **5 References**

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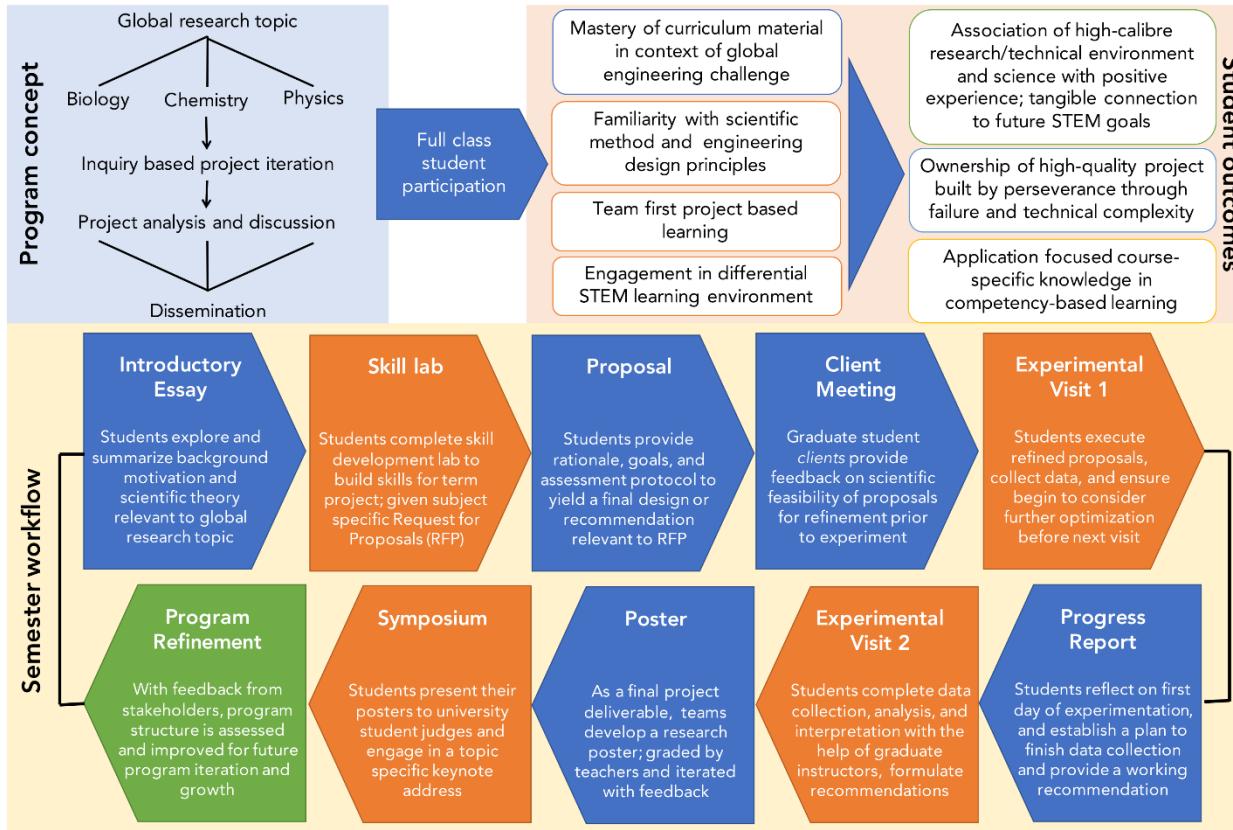
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447 6 Acknowledgements

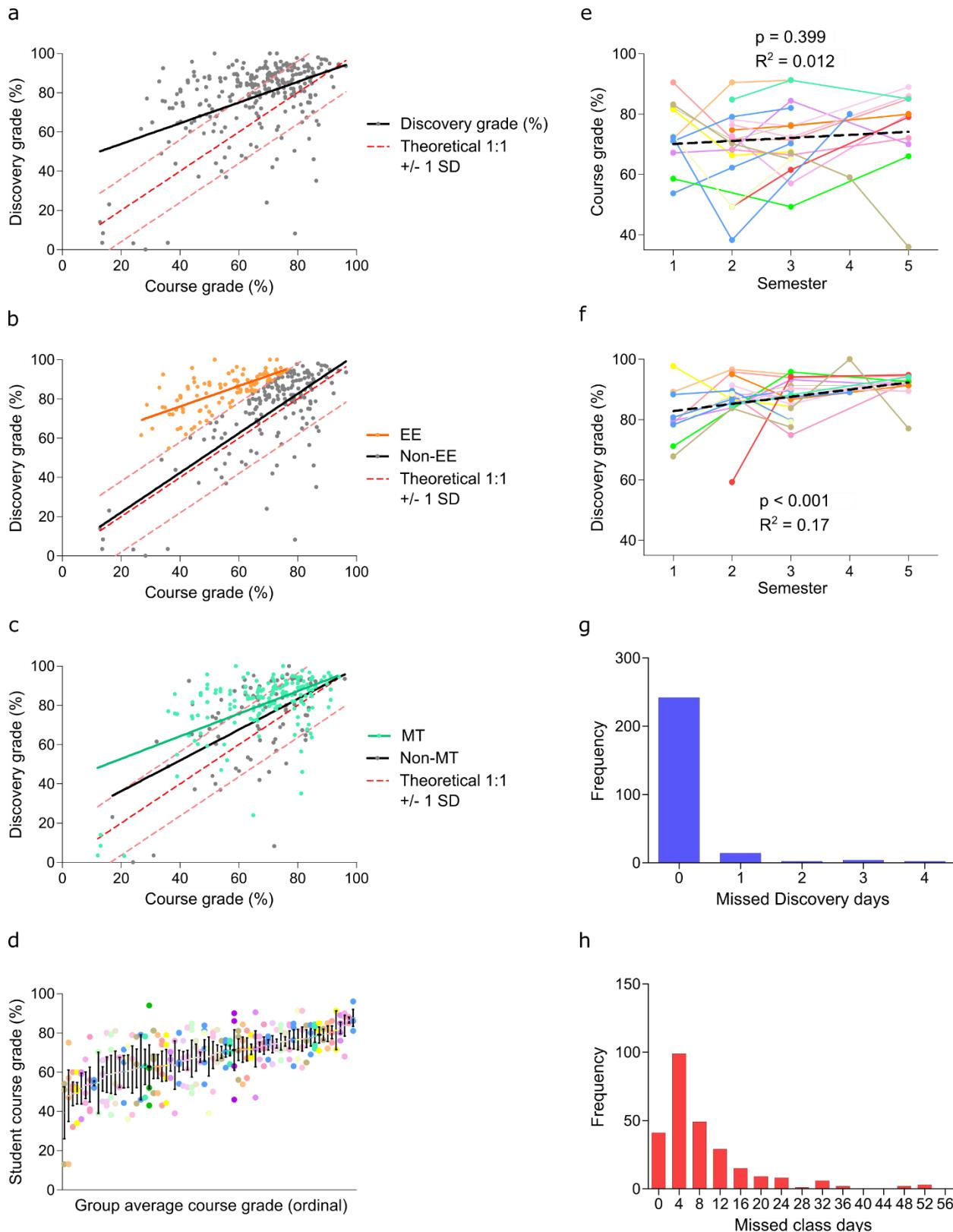
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471 **7 Figures**



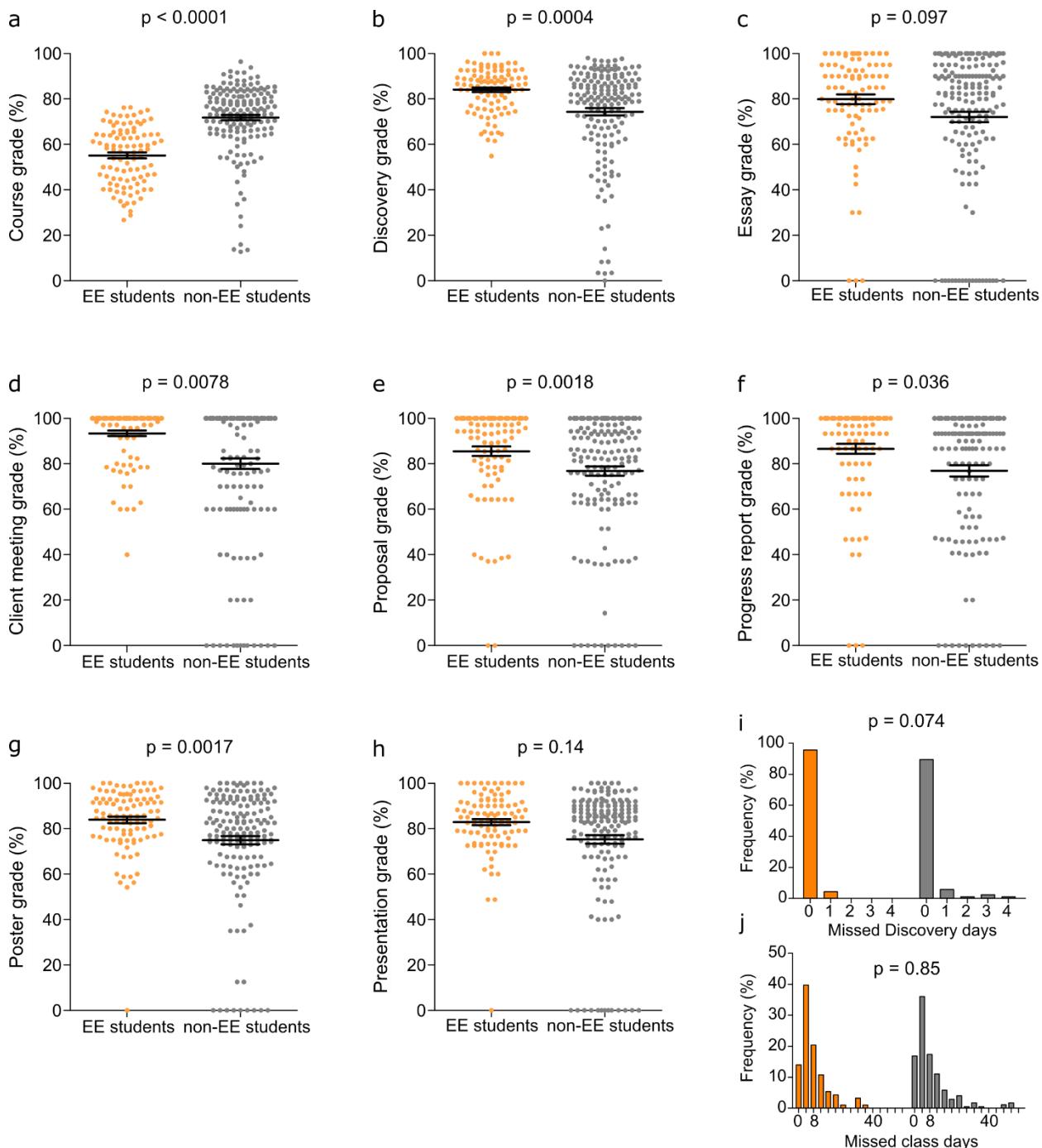
473 **Fig 1. Structure and rationale underlying the *Discovery* framework.** The general program concept (blue
474 background; *top left*) highlights a global research topic examined through student dissemination of subject specific
475 research questions, yielding multifaceted student outcomes (orange background; *top right*). Each program term
476 (semester workflow, yellow background; *bottom panel*), students work on program deliverables in class (blue),
477 iterate experimental outcomes within university facilities (orange), and are assessed accordingly at numerous
478 deliverables in an inquiry-focused learning model (**S3 Appendix III**).

479



481 **Fig 2. Student aggregate performance in *Discovery* and identification of subsets.** (a) Linear regression of student
482 grades reveals a significant correlation ($p = 0.0009$) between *Discovery* performance and final course grade less the
483 *Discovery* contribution to grade, as assessed by educators. The dashed red line and intervals represent the theoretical
484 1:1 correlation between *Discovery* and course grades and standard deviation of the *Discovery*-course grade
485 differential, respectively. (b & c) Identification of subgroups of interest, Exceeds Expectations (EE; $N = 99$, *orange*)
486 who were $\geq +1$ SD in *Discovery*-course grade differential and Multi-Term (MT; $N = 174$, *teal*), of which $N = 65$
487 students were present in both subgroups. (d) Students tended to self-assemble in working groups according to their
488 final course performance; data presented as mean \pm SEM. (e) For MT students participating at least 3 semesters in
489 *Discovery*, there was no significant correlation between course grade and time, while (f) there was a significant
490 correlation between *Discovery* grade and cumulative semesters in the program. (g & h) Histograms of total
491 absences per student in (g) *Discovery* and (h) class (binned by 4 days to be equivalent in time to a single *Discovery*
492 absence).

493

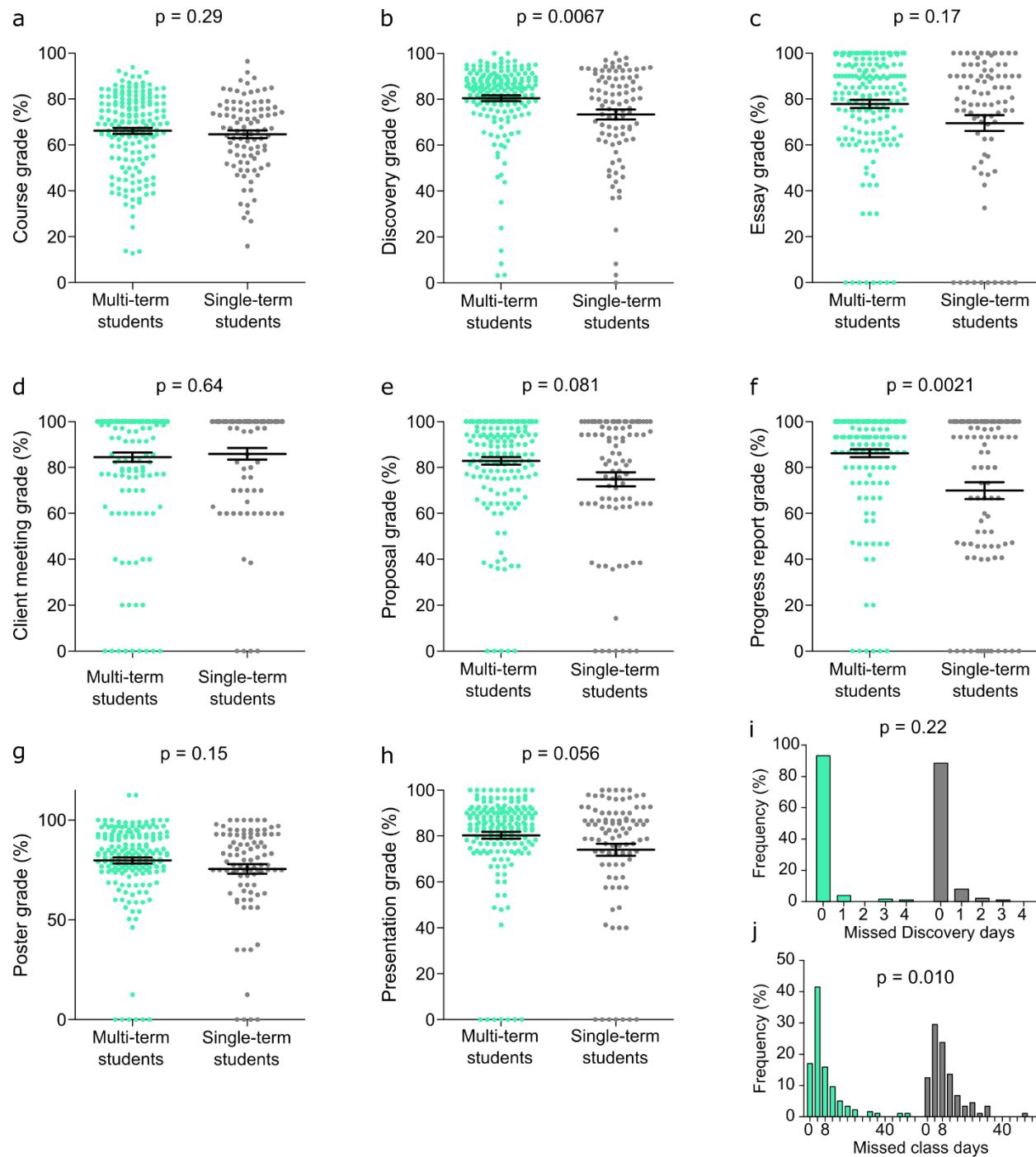


494

495 **Fig 3. Performance of exceeds expectations student subset.** The “Exceeds Expectations” (EE) subset of students
 496 (defined as those who received a combined *Discovery* grade ≥ 1 SD (18.0%) higher than their final course grade)
 497 performed (a) lower on their final course grade and (b) higher in the *Discovery* program as a whole when compared
 498 to their classmates. (d-h) EE students received significantly higher grades on each *Discovery* deliverable than their

499 classmates, except for their (c) introductory essays and (h) final presentations. The EE subset also tended (i) to have
500 a higher relative rate of attendance during *Discovery* sessions but no difference in (j) classroom attendance. N = 99
501 EE students and 169 non-EE students (268 total). Grade data expressed as mean \pm SEM.

502

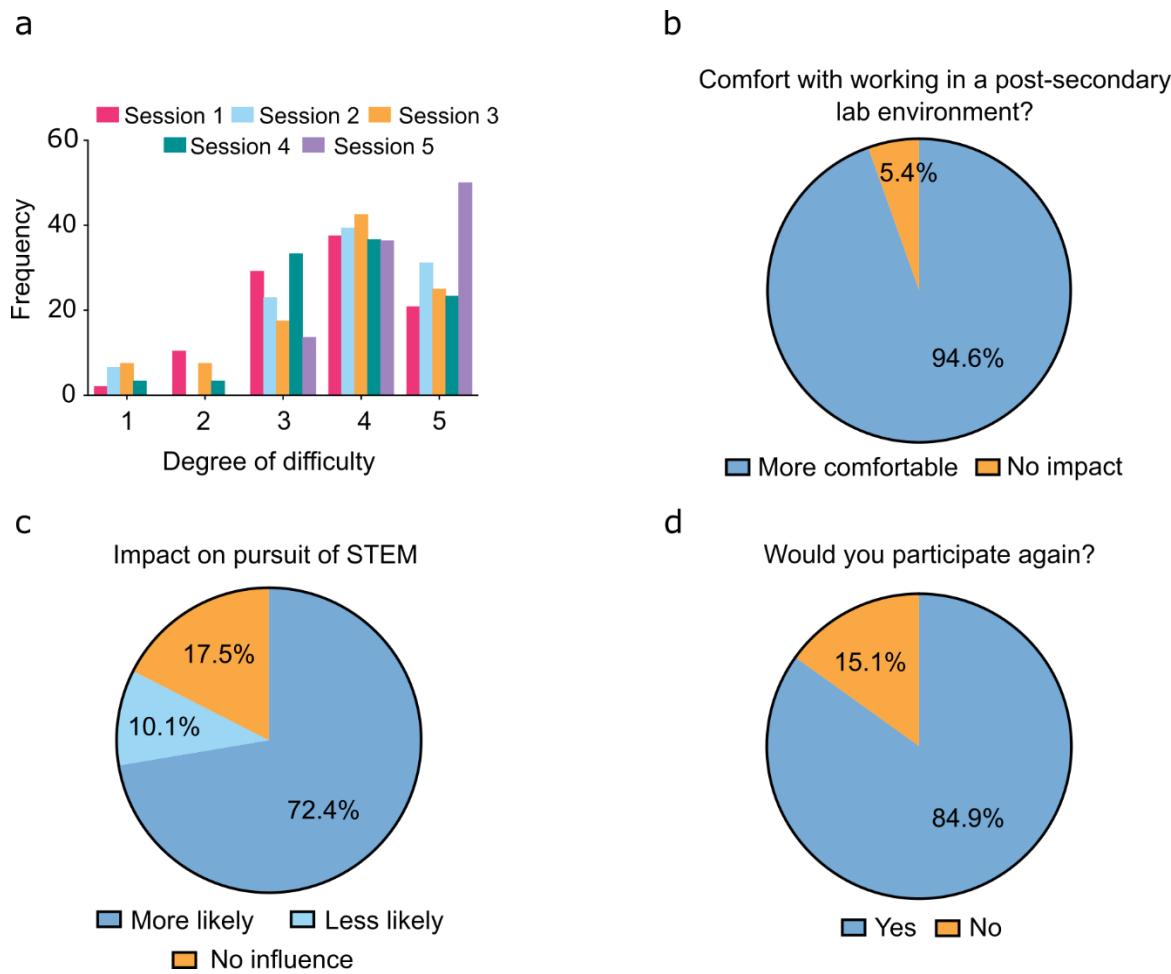


503

504 **Fig 4. Performance of multi-term student subset.** The “multi-term” (MT) subset of students (defined as having
 505 attended more than one semester of *Discovery*) demonstrated favourable performance in *Discovery*, (a) showing no
 506 difference in course grade compared to single-term students, but (b) outperforming them in final *Discovery* grade.

507 Independent of the number of times participating in *Discovery*, MT students did not score significantly differently
508 on their (c) essay, (d) client meeting, or (g) poster. They tended to outperform their single-term classmates on the (e)
509 proposal and (h) final presentation, and scored significantly higher on their (f) progress report. MT students showed
510 no statistical difference in (i) *Discovery* attendance, but did show (j) higher rates of classroom attendance than
511 single-term students. N=174 MT instances of student participation (76 individual students) and 94 single-term
512 students. Grade data expressed as mean \pm SEM.

513



515 **Fig 5. Student survey responses following participation in *Discovery* programming.** (a) Histogram of relative
516 frequency of perceived *Discovery* programming academic difficulty ranked from not challenging (1) to highly
517 challenging (5) for each session demonstrated the consistently perceived high degree of difficulty for *Discovery*
518 programming (total responses: 223). (b) Program participation increased student comfort (94.6%) with navigating
519 lab work in a university or college setting (total responses: 220). (c) Considering participation in *Discovery*
520 programming, students indicated their increased (72.4%) or decreased (10.1%) likelihood to pursue future
521 experiences in STEM as a measure of program impact (total responses: 217). (d) Large majority of participating
522 students (84.9%) indicated their interest for future participation in *Discovery* (total responses: 212). Students were
523 given the opportunity to opt out of individual survey questions, partially completed surveys were included in totals.

524

525

526 **8 Supplementary Materials**

- 527 S1 Appendix I: Sample teaching materials for one representative term of *Discovery*
- 528 S2 Appendix II: Entrance and exit student surveys for program assessment of *Discovery*
- 529 S3 Appendix III: Mark breakdown for student assessment in *Discovery* programming