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16

17 **Abstract** (200 words):

18 Explicit emphasis on teaching science process skills leads to both gains in the skills themselves and,
19 strikingly, deeper understanding of content. Here, we created and tested a series of online, interactive
20 tutorials with the goal of helping undergraduate students develop science process skills. We designed
21 the tutorials in accordance with evidence-based multimedia design principles and student feedback
22 from usability testing. We then tested the efficacy of the tutorials in an introductory undergraduate
23 biology class. Based on a multivariate ordinary least squares regression model, students that received
24 the tutorials are predicted to score 0.824 points higher on a 15 point science process skill assessment
25 than their peers that received traditional textbook instruction on the same topic. This moderate but
26 significant impact indicates that well designed online tutorials can be more effective than traditional
27 ways of teaching science process skills to undergraduate students. We also found trends that suggest
28 the tutorials are especially effective for non-native English speaking students. However, due to a limited
29 sample size, we were unable to confirm that these trends occurred due to more than just variation in
30 the sampled student group.

31 Introduction

32 Science process skills are an important component of undergraduate biology curricula.

33 A primary goal of undergraduate biology education is to have students develop the ability to think like a
34 scientist. That is, students must develop the ability to ask and answer meaningful biological questions,
35 the core of scientific inquiry. To achieve this goal, students need to master an underlying set of skills
36 including the ability to ask a testable question, propose a hypothesis, design an experiment, analyze
37 data, draw conclusions from evidence and communicate findings. We refer to these skills as *science*
38 *process skills*. Recent reports by the American Association for the Advancement of Science [AAAS] (2009)
39 and other biology education leaders (Wright & Klymkowsky, 2005; Krajcik & Sutherland, 2010)
40 emphasize teaching these skills as a key goal in improving undergraduate education. Faculty also
41 overwhelmingly value these skills in their students, but traditionally neglect to include them in course
42 design due to a fear of losing time devoted to important subject content (Coil *et al.*, 2010). Here, we
43 offer an alternative approach to incorporating science process skills into course curriculum. We created
44 a series of interactive online tutorials that explicitly teach science process skills and supplement
45 classroom learning with minimal added effort from instructors.

46 Recent attempts at re-designing undergraduate biology courses show that placing an explicit
47 emphasis on science process skills leads to both gains in the skills themselves and, strikingly, greater
48 retention of subject content. Students who participated in a supplemental course at the University of
49 Washington that taught science process skills and other aspects of scientific culture earned higher
50 grades in introductory biology classes than their peers who did not participate in the course (Dirks &
51 Cunningham, 2006; Buchwitz *et al.*, 2012). Further supporting the benefits of learning science process
52 skills, students' scores on a science process skills assessment taken after the supplemental course
53 correlated with their introductory biology course grades. The connection between science process skills
54 and overall course grade underscores the impact of explicit instruction in science process skills. In
55 another example, students at Brigham Young University participated in a re-designed cell biology course
56 that placed explicit emphasis on data analysis, interpretation and communication. These students
57 showed improvement in both data analysis and conceptual problems during the course (Kitchen *et al.*,
58 2003). They also scored higher than students in the traditional content-focused cell biology course on
59 both analysis and recall problems. Other instructors have focused on using primary literature to
60 emphasize critical thinking and science process skills in redesigned courses. The CREATE method,
61 developed at the City University of New York, teaches the nature of science through a series of primary
62 research papers produced by a single research group covering a specific topic (Hoskins *et al.*, 2007).
63 Students use active learning approaches to apply science process skills like hypothesis generation,
64 experimental design, data analysis and scientific communication. This approach has yielded gains in
65 critical thinking, gains in experimental design, and improved student attitudes about science in a broad
66 range of postsecondary settings, from community colleges to graduate programs (Hoskins *et al.*, 2011;
67 Gottesman & Hoskins, 2013; Stevens & Hoskins, 2014; Kenyon *et al.*, 2016). While the well-defined
68 CREATE method has proven highly effective in most implementations studied, some instances show no
69 extra gains compared to other active, literature-focused pedagogies (Segura-Totten & Dalman, 2013) In
70 each of these examples, explicit instruction in science process skills led to greater facility with those
71 skills and better content learning in the subject area. Taken together, these results illustrate a clear
72 value in emphasizing science process skills for undergraduates.

73 **Barriers to teaching science process skills**

74 While the value of teaching science process skills becomes clearer every year, significant barriers still
75 prevent their incorporation into undergraduate curricula. Chief among the barriers is the time
76 commitment required for instruction. As any instructor knows well, time with students is limited and
77 instructors must allocate class time for maximum student benefit. This leads to the familiar debate
78 between covering as much subject material as possible versus a “more is less” approach that focuses on
79 skill development and inquiry while covering a narrower range of topics. Up to this point, most
80 incorporation of science process skills has focused on course-wide redesigns and long-term instruction,
81 as described above. These large-scale changes require significant investment of the instructor’s time and
82 re-allocation of class time. Other attempts at emphasizing science process skills have focused on their
83 integration into laboratory and research experiences, an option not available to all courses and
84 instructors (DeBurman, 2002; Shi *et al.*, 2011; Brownell *et al.*, 2015; Woodham *et al.*, 2016). Short of
85 these large changes, could smaller scale incorporation of science process skills instruction prove useful
86 to student learning? Little research has evaluated the effect of limited, stand-alone instruction in science
87 process skills.

88

89 **Deficiencies of textbook-based instruction**

90 As often as not, students’ only exposure to science process skills comes as an assigned reading in the
91 first chapter of a science textbook. While noble in their intent, these readings often fail to engage
92 students. Students struggle to synthesize the large amounts of information presented in a textbook into
93 an organized framework. This occurs because the amount of processing required by the textbook
94 reading exceeds the capacity of students’ working memory, the amount of information a person is
95 capable of processing at a given time. In psychology terminology, this problem with textbook-based
96 learning is called cognitive overload (Mayer & Moreno, 2003). Static text and layout require readers to
97 devote a large portion of their cognitive load to aspects of the textbook other than the intended
98 content. It is common to find topics covered in one section referencing diagrams found on different
99 pages, forcing students to flip back-and-forth in order to match the text with its graphical
100 representation. The process of moving from page to page requires that the reader split their attention
101 and use what limited working memory they have to synthesize information found in two distinct areas.
102 Additionally, textbooks often overload students with too much information, making it difficult for them
103 to identify and focus on the information worth remembering. While high cognitive load is a common
104 problem for textbooks, not all textbooks are poorly designed. If designed correctly, textbooks can be as
105 effective at teaching students as alternative multimedia. Unfortunately, when it comes to science
106 process skills, this is more often the exception than the rule.

107

108 **Benefits of interactive digital instruction**

109 Many students opt out of reading the textbook and instead rely only on in-class lectures to help them
110 learn important topics covered in the course. How can instructor convince their students of the value of
111 pre-class learning? Resistance to learning outside of the classroom is being met with new ways of
112 engaging students. Online, multimedia-based learning is improving education by engaging students

113 through interactive multisensory learning. Harnessing the power of audio, visuals, text, animation and
114 user interactions, multimedia design capitalizes on a variety of ways to deliver information. Students are
115 able to receive and process information through two primary channels: audio and visual. By
116 simultaneously tapping into both channels students are capable of processing larger amounts of
117 information resulting in increased retention. By using this medium, instructors can effectively reduce
118 cognitive load for their students and enable quicker, better-retained learning (Mayer & Moreno, 2003;
119 Evans & Gibbons, 2007; Mayer, 2008; Domagk *et al.*, 2010). A multitude of examples show that online
120 multimedia learning not only helps students to improve their understanding of the concepts presented,
121 but also allows them to integrate new concepts with their existing knowledge base (Carpi, 2001; Carpi &
122 Mikhailova, 2003; McClean *et al.*, 2005; Silver & Nickel, 2005; Chudler & Bergsman, 2014; Goff *et al.*,
123 2017).

124

125 **Interactive digital modules created to teach science process skills**

126 This paper will outline best practices for creating useful and engaging multimedia based tutorials that
127 provide students with an alternative method of learning key material outside of the classroom. Using
128 these principles, we created a series of seven interactive digital modules, each addressing a different
129 science process skill and incorporated them into in a large enrollment introductory biology course. We
130 then assessed the tutorials' effect on students' ability to apply those skills compared to students that
131 received only traditional textbook-based instruction. Although we tailored our design strategy to online,
132 multimedia-based learning, instructors can, and should, be able to apply many of these same principles
133 to lecture based design as well.

134

135 **Tutorial Design**

136 **Tutorial Design Methods**

137 To create online tutorials, we used Articulate Storyline 2 software (Articulate Global, Inc.), with
138 VideoScribe software (Sparkol Limited, Bristol UK) to create animated whiteboard style videos. All
139 tutorial modules were administered as SCORM 2004 packages via Moodle learning management system,
140 version 3.0.

141

142 **Multimedia Design Principles**

143 Our online, science process tutorial was broken up into seven modules outlining the different steps
144 within the scientific process. Although we understand that science does not always progress linearly, we
145 designed these tutorials to be completed in a sequential order. Following the principle of backwards
146 design (Wiggins & McTighe, 2005), we first established a concrete set of learning objectives for each of
147 the seven modules (Supplemental Material). Each module covered two to five learning objectives guided
148 by Bloom's Taxonomy principles in order to promote higher-level, critical thinking and analytical skills
149 (Bloom *et al.*, 1956; Crowe *et al.*, 2008).

150 Once completed, these objectives became the roadmap that guided both the content as well as the
151 assessments. When choosing the format for the tutorial, we felt it important that our students
152 experience the process of scientific discovery firsthand. For many years, educational research has
153 supported the use of stories and case studies to teach and make a personal connection with science
154 students (Martin & Brouwer, 1991). Therefore, our science process tutorial follows the storyline of two
155 Nobel laureates, Dr. Barry Marshall and Dr. Robin Warren and their quest to discover the underlying
156 causes of ulcers. From reading primary literature to establishing experiments to analyzing and
157 presenting data, the goal of the online tutorial was to simulate the process of science through the lens
158 of two experienced researchers. Importantly, our online platform offered students an opportunity to
159 learn through interactive engagement rather than passive reading of text.

160 Having selected learning objectives and the overarching narrative structure for the tutorial, we next
161 turned to designing how the students would interact with the tutorial. A growing body of evidence
162 suggests that multimedia platforms, if properly designed, are effective tools for learning scientific
163 material. For each of the seven individual modules, we followed evidence-based principles of
164 multimedia design outlined, in large part, by Richard Mayer with special attention placed on the
165 coherency and redundancy principles (Mayer, 2008) (Supplemental Materials).

166 The coherency principle suggests limiting the use of visuals that do not support the overall learning
167 objectives of the project. Every item occupying the learning space increases cognitive load on the
168 learner. Therefore, to maximize learning gains and limit cognitive overload we carefully selected only
169 diagrams and text that support the learning outcomes of the scene. Close adherence to the coherency
170 principle was especially important for this tutorial because of the limited screen space. For each visual
171 scene presented to students, we were careful to limit written text. This approach especially relied on
172 narrated scenes, so that audible narration was not repeated by verbatim text, a concept that closely
173 aligns with the redundancy principle.

174 The redundancy principle strives to limit the use of printed text for a *narrated* graphic. In other words,
175 narration should describe an image rather than re-reading words on a screen. Simultaneous
176 presentation of words and narration can overload the user's working memory, making it harder to learn
177 the topic at hand. Instead, research suggests that it is better to replace the words with an image that
178 displays the narrated process .

179 Finally, to reduce cognitive load, we created a consistent user experience throughout the tutorial
180 (Mayer, 2008; Blummer & Kritskaya, 2009). A consistent navigation interface with clearly labelled
181 buttons allowed student to focus more of their mental capacity on the content presented. We also
182 included repeated prompts and signals that communicate to students what information is most
183 important, when a section is complete, what resources are available and when they are required to
184 make a decision. Approaches as simple as highlighting key words and using a consistent "NEXT" button
185 allow students to reduce extraneous processing.

186

187 **Tutorial Audience**

188 We designed our tutorials for undergraduate students with little or no background in the biological
189 sciences. Target populations included students majoring in biology, other science majors and students

190 majoring in non-science subjects. Because the tutorials address fundamental science process skills
191 through the lens of biology, they are appropriate for this broad audience. We also were interested in
192 designing the tutorials to aid students that are non-native English speaking (NNES) students. Interactive
193 and online learning methods can be especially useful for NNES students because they allow students to
194 control the pace of their learning, immediately repeat difficult material, and use visual representations
195 that do not depend on written text. Simulations and learning games are especially effective for NNES
196 students (Abdel, 2002). As such, we recognized the potential our tutorials hold for NNES students and
197 emphasized these elements in our tutorials to make them maximally useful.

198

199 **Tutorial Format**

200 In agreement with these design principles, each module followed a similar layout and students quickly
201 became familiar with the general types of slides: the introductory slide, the challenge questions and the
202 summary slides. The introductory slide was the first slide in each module (Figure 1A). On each
203 introductory slide, students watched a brief video that summarized previous modules and outlined
204 upcoming learning objectives. In accordance with the redundancy principle, we used whiteboard-style
205 animations to build the introductory videos (Türkay, 2016). In the videos, drawings appeared as the
206 narrator describes them, an approach that has been shown to increase student engagement (Guo *et al.*,
207 2014) and that allowed the viewer to take in related information through both the auditory and visual
208 channels simultaneously. Capitalizing on the use of both auditory and visual channels limited cognitive
209 overload and freed the learner to process and store larger amounts of information.

210 Following the introductory whiteboard video, an onscreen character greeted the student and introduced
211 the specific activities for that module. Personalizing interactions between an onscreen character and the
212 learner created a sense teamwork. The onscreen character in each module served to guide the storyline,
213 provided feedback, and prompted the students to think deeply about the learned material (Figure 1B-C).
214 In the module “Design an Experiment,” students were asked to help the researchers develop an
215 experimental outline for the project. As the students progressed through the module, they learned the
216 importance of selecting a model system, assigning proper treatment and control groups, and creating a
217 protocol. Challenge questions posed by the onscreen character during each of these steps pushed
218 students to think critically about typical problems faced at each step of the scientific process.

219 The tutorials were designed so that when students made choices or answered questions, they reflected
220 on why they chose their specific option and why the other options were better, worse or totally wrong.
221 For example, when selecting the treatment group for their experiments, students chose from four
222 different treatment options. In this scenario, students must select *and* justify the use of their selected
223 treatment. If students selected an incorrect treatment, they received specific feedback that helped
224 guide them to the correct answer (Figure 1C). This feature of the tutorials comports with research
225 indicating that explanatory or informed-tutoring feedback, which provides context and explanations for
226 why an incorrect choice is incorrect and a correct one is correct, is more helpful in the learning process
227 than feedback that is merely corrective (Moreno, 2004; Narciss, 2004).

228 Lastly, once the student selected the correct answer, we used a consistent format to summarize the
229 question and responses. This interactive slide let students review their correct answer and each of the
230 incorrect answers, including explanations about how each answer fit with the larger concept. In pilot

231 studies, students found the guided feedback very useful for helping them break down complicated
232 material into single units of information. Additionally, we found that asking students to justify their
233 selection forced students to think critically about the question at hand instead of randomly selecting an
234 answer.

235 Students are better able to engage with multimedia tutorials when they can track their progress and see
236 how close to finishing they are. Some tutorials display the percent complete or the total number of
237 slides. For our tutorial, we created a test tube graphic to represent progress in the tutorial. The test-
238 tube also served a second purpose, to show students the learning objectives for that module. As
239 students complete learning objectives, the test tube fills up (Figure 1D). At the end of the tutorial, the
240 student finishes with a full test tube that displays all of the learning objectives (Figure 1E). This visual
241 tracking method also allows students to “collect” test tubes for all seven modules in the tutorial,
242 creating a game-like incentive that engages students (Figure 1F). Based on student feedback, students
243 appreciated the ability to track their progress through the tutorial.

244 As mentioned, the test tubes served a second purpose as a way for students to explicitly see the
245 learning objectives for the current module. Upon completing a module, students saw the full test tube
246 with each learning objective filled in (Figure 1E). Each learning objective was as a clickable item that led
247 to a small review activity on that topic. Along with this end of module review, students were always able
248 to review test tubes and learning objectives from previously completed modules by clicking on a
249 consistent icon in the corner of the tutorial screen. This approach requires that students actively seek
250 out necessary information, referred to as “pulling” information. This design strategy was repeated
251 throughout the tutorial as a way to further engage students and give them a sense of control as they
252 work through the tutorial. By using the test tube format, the modules clearly articulate learning
253 objectives and offer a convenient way to revisit previous material.

254 **Usability testing**

255 After the initial design, we refined our tutorials based on usability testing. Because students experienced
256 the tutorials on their own time and without direct input from the instructor, it was imperative that the
257 tutorials were easy to use, engaging, accessible to students of all abilities, and met our intended learning
258 objectives. To reach these goals, we collaborated with the University of Minnesota Usability Lab. The
259 usability lab provides a physical space to observe a person using a product or design in real time and a
260 process to help improve the effectiveness and accessibility of that product based on those observations.
261 During this process, we met with a usability expert from the lab, determined testing goals, conducted
262 focus groups with undergraduate students, evaluated the results, and decided on specific improvements
263 to the tutorials that addressed identified problems. We chose to focus on improving navigation,
264 optimizing information placement, and determining whether tutorial content was properly challenging
265 for undergraduate students. Students selected for participation were observed as they attempted to
266 complete the “Design an Experiment” tutorial module, immediately followed by a debriefing interview
267 with the usability expert. During the testing session, we directly observed students via a one-way mirror,
268 their computer screen via simulcast, and their eye movements via eye-tracker camera and software. We
269 tested tutorials in this way with six undergraduate students, including both biology majors and non-
270 majors, and native English speakers and non-native English speakers.

271 During usability testing, we found that students were most engaged by concise delivery of information
272 with emphasis placed on key concepts (e.g. bold, italics, or color), extremely consistent visual markers

273 for navigation, and immediate feedback for wrong answers to challenge questions. As expected, the
274 level of difficulty, as measured by in tutorial assessment questions, was higher for students who were
275 majoring in subjects outside of the sciences. Lastly, we found that distinct aspects of the tutorials
276 engaged non-native English speakers. Consistent layout and visual design were important for easy
277 navigation. We suspect that this design allowed students to spend less cognitive energy decoding the
278 instructions and navigation, and to focus more on absorbing content from the tutorials. Along similar
279 lines, non-native English speakers also specifically appreciated repeated presentation of key ideas and
280 optional chances to review those important concepts. We incorporated all of these observations into
281 the design strategy for the final version of the tutorials (see Supplemental Material for specific
282 feedback).

283

284 **Research study**

285 **Design**

286 To investigate the effectiveness of our online science process skills tutorials, we conducted a quasi-
287 experimental study in a large format introductory biology course for students majoring outside biology
288 in spring of 2017 at the University of Minnesota, a large public research institution in the Midwest of the
289 United States (Figure 2). Without prior knowledge of this study, students enrolled in one of two sections,
290 each with the same instructor. One section was assigned the tutorials as an out-of-class activity to
291 supplement textbook reading over the first two weeks of the course, the “online tutorial” group
292 (n=118). Student completion of the tutorials was high: 93% of enrolled students completed at least
293 three out of five tutorials and 88% of enrolled students completed all five tutorials. The other section
294 was assigned only out-of-class textbook reading covering similar subject material over the same two
295 weeks, the “textbook reading” group (n=118). For reasons of fairness, students in the textbook reading
296 group were given access to the online tutorials following the experimental period and assessment.
297 Students were incentivized to complete the tutorials with a small amount of homework credit (low
298 stakes). The University of Minnesota Institutional Review Board deemed this study exempt from review
299 (Study Number: 1612E01861).

300

301 **Measures**

302 While recent studies in undergraduate education have focused on ways to improve scientific literacy
303 and proficiency, the ability to test the effectiveness of these interventions is limited. To date, very few
304 formative assessments designed to gauge science process skills have been validated, and those that
305 have, are geared towards assessing K-12 students. Therefore, due to the lack of validated assessments,
306 we chose to modify a well-accepted science process skills assessment tool known as the Integrated
307 Process Skills Test, or TIPS II (Burns *et al.*, 1985). Modified versions of TIPS II have been successfully used
308 to assess science process skills in high school seniors, a population of students very similar to our own
309 (Kazeni, 2005). Rather than design and validate a new assessment tool we chose to select questions
310 from TIPS II for our assessment.

311 The fifteen-question assessment was designed to assess five different categories of science process skills
312 including graphing and interpreting data, identifying variables, stating hypotheses and selecting

313 operational definitions (Supplemental Material). To populate each category in our assessment we
314 selected only the questions from TIPS II with the highest item discrimination index (as reported in
315 Kazeni, 2005), a statistical measure that distinguishes between high performing and low performing
316 examinees for a given assessment. The average item discrimination index of questions selected from
317 TIPS II was 0.4, well above the acceptable range (>0.3 ; Bass *et al.*, 2016). Student scores on these fifteen
318 TIPS II items were averaged to create the main outcome variable in this study.

319 The ability to apply science process skills was assessed in both the online tutorial and textbook reading
320 groups at the same point in the semester, after instruction was complete, using our modified TIPS II test.
321 Student participation in the assessment was high for both groups: 98/118 for the online tutorial group
322 and 112/118 for the textbook reading group.

323 **Data**

324 The total pool of study participants was 54.3% female and 45.7% male, with a median age of 20.34
325 years. The respondents were 0.5% American Indian, 8.7% Asian, 6.6% black, 2.9% Hispanic, 15.8%
326 international, and 65.3% white. They were 3.6% first-year students, 40.6% sophomores, 32.0% juniors,
327 and 23.9% seniors, and 18.3% were listed as non-native English speaking (NNES) students. 74.2% of
328 participants were non-science majors.

329 Because participants were not randomly assigned to the online tutorial and textbook reading groups, it
330 was important to establish comparability of the two groups on the available exogenous variables, which
331 included aptitude variables (composite ACT score, GPA) and demographic variables (ethnicity, sex, age,
332 major, NNES status). We ran appropriate group comparison tests and determined that the two groups of
333 participants were statistically equivalent on all aptitude and demographic variables, with the exception
334 of age: the mean age in the online tutorial group was slightly higher than the mean age in the textbook
335 reading group (20.55 vs 19.88, $p = .008$).

336 **Analysis and Results**

337 We constructed a multivariate ordinary least squares regression model to predict participants'
338 performance on our outcome variable of interest, namely score on the modified TIPS II test. For this
339 model, casewise diagnostics were generated and examined to locate outliers in the data set, defined as
340 cases with standardized residuals greater than 3.3. This procedure revealed three outliers for the
341 dependent variable. On inspection, these cases were not otherwise anomalous, so they were retained in
342 the data set. Variance inflation factor (VIF) statistics were also generated to check for multicollinearity
343 among the predictor variables. In no case was the VIF statistic greater than 1.135, far from the common
344 cut-off of 4, so multicollinearity did not appear to be a problem in the data set. The Durbin-Watson
345 statistic of 2.346 indicated very little auto-collinearity in the data.

346 The model included just three predictor variables (GPA, NNES status, and treatment group); no other
347 demographic variables were significantly related to TIPS II score. The model was highly significant ($p <$
348 $.001$) and accounted for a small-to-moderate amount of the variation in TIPS II score with an R^2 value of
349 $.403$, adjusted $R^2 = .140$.

350 The covariate GPA was significantly related at the $p < .05$ level to TIPS II scores ($t = 2.799$, $p = .006$), as
351 was the main treatment of interest, being in the online tutorial group ($t = 2.600$, $p = .010$). The predictor

352 variable representing NNES status was negatively associated with TIPS II scores, but it was not
353 statistically significant ($t = -1.164$, $p = .246$).

354 Given the results displayed in Table 1, we can conclude that for each unit increase in a student's GPA,
355 we can expect more than a 1-point increase in that student's TIPS II score. Similarly, being in the online
356 tutorial group was associated with a 0.824 point increase in a student's TIPS II score, while holding other
357 variables in the model constant. The pooled standard deviation for the TIPS II score variable was 1.99, so
358 the effect size for GPA was moderate to large (almost 60% of a standard deviation), while the effect size
359 for being in the online tutorial group was moderate (over 40% of a standard deviation).

360

361 **Results for NNES Students**

362 One sub-population of interest in this study was the group of students identified as non-native English
363 speaking (NNES) students, so additional analyses were performed to examine the effects of the online
364 tutorials on this group. There were some indications in the data that the online tutorials may have
365 benefited NNES students to a greater degree than they benefited students who were native speakers of
366 English, but low subgroup N rendered these indications unclear.

367 First, we asked whether being in the online tutorial group improved the TIPS II scores of NNES students
368 more than it improved the scores of other students. The answer was, nominally, yes (Figure 3). Among
369 native speakers, being in the online tutorial group helped (mean difference 0.731, $p = .025$). However,
370 among NNES students, being in the experimental group helped *more* (mean difference 1.308, $p = .311$).
371 The latter difference is over $\frac{1}{2}$ of a standard deviation and is much larger than the difference between
372 the scores of tutorial and textbook native English speakers, but it does not test significant because of
373 low N in the NNES group (20 total).

374

375 Second, we noted that NNES students had average TIPS II scores that were significantly lower than the
376 scores of native English speakers (10.15 vs 11.23, $p = .030$). So we asked whether being in the online
377 tutorial group helped NNES students to *close the gap* between themselves and native speakers. Again,
378 the answer was, nominally, yes (Figure 4). The difference in average TIPS scores between native
379 speakers and NNES students was 1.21 points in the textbook reading group ($p = .101$), while in the
380 online tutorial group the difference was just about half of that, 0.633 points ($p = .255$).

381

382 **Discussion**

383 We created a series of online, interactive tutorials with the goal of helping undergraduate students
384 develop science process skills. We designed the tutorials in accordance with evidence-based multimedia
385 design principles and student feedback from usability testing. Based on a multivariate ordinary least
386 squares regression model, students who received the tutorials are predicted to score 0.824 points
387 higher on a 15-point science process skill assessment than their peers that received traditional textbook
388 instruction on the same topic. This moderate but significant impact indicates that well designed online
389 tutorials can be more effective than traditional ways of teaching science process skills to undergraduate

390 students. We also found trends that suggest the tutorials are especially effective for NNES students.
391 However, due to a limited sample size, we were unable to confirm that these trends occurred due more
392 than just variation in the sampled student group.

393

394 **Strategies for student engagement**

395 A preponderance of evidence shows that active learning improves student learning compared to
396 traditional lecture approaches (Freeman *et al.*, 2014). Here, we show that even on a very limited scale, a
397 switch from traditional textbook reading to include a more active approach results in improved learning.
398 To achieve this, we designed the tutorials to maximize interaction and engage students in multiple ways
399 in our tutorials. First, the nature of the multimedia-driven, interactive format increases interactivity
400 compared to textbook reading. While completing the tutorial, students are required to make decisions
401 and those decisions shape how the rest of the tutorial proceeds. Multiple sensory channels are engaged
402 in complimentary ways when students see images, hear narration and use computer interfaces to
403 interact with the virtual environment. Each of these features creates opportunities for student
404 engagement. While not every aspect might engage a particular student, the multiple levels of
405 engagement increase the likelihood that one of those elements will grab and keep a student's attention
406 during the tutorial.

407 We also chose to use a continued narrative across the modules in the tutorial to create a human
408 connection with students. Our storyline focused on the connection between stomach ulcers and the
409 bacteria *H. pylori* and the story of how two scientists, Robin Warren and Barry Marshall made that
410 discovery in the 1980s. We used familiar settings, like a doctor's office and library, specific characters,
411 and a medical mystery to create personal connections with students. We suspect that by connecting the
412 scientific method to a human story, students were able to engage more quickly and deeply with the
413 presented skills. While students appreciated the story, it was unclear whether they preferred a more
414 cartoonish or realistic presentation style. Casual feedback from students covered all perspectives from
415 appreciation to distaste for our animation-based style, but NNES students clearly favored the cartoon
416 style. This is consistent with other research that shows schematics are more effective at teaching
417 biological mechanism than realistic images (Scheiter *et al.*, 2009). Comparing different levels of realism
418 would make an area excellent future investigation.

419 Lastly, we maximized student engagement by offering frequent, specific feedback and opportunity for
420 reflection. We offered feedback in real time as students made choices, after challenge questions and at
421 the end of each module. We found that students appreciated a consistent format for feedback and were
422 able to focus on their thought process and reasoning when presented with a standardized feedback
423 interaction. We also found that feedback needed to be specific. During usability testing, we observed
424 that when the tutorial provided targeted feedback explaining why each of wrong answers were wrong,
425 students stayed more engaged and were more comfortable with the presented concepts at the end of
426 the tutorial. Lastly, we gave students a chance to revisit and modify their ideas. This was especially
427 evident in the "Propose a Hypothesis" module where the tutorial guides students to revise their
428 hypothesis to make it more scientifically sound. These types of interactions provide both engagement
429 and opportunity for formative assessment by the student.

430

431 **Potential Uses for Tutorials**

432 In this study, we used our online tutorials as an out-of-class assignment, but they could be employed in
433 a variety of situations. We also created the tutorials with the intention that both the narrative content
434 and the learning goals associated with science process skills could be adapted to suit individual
435 instructor's needs. In fact, we tweaked several learning objectives before our study to better align the
436 tutorial with the instructor's other activities and materials. This included modifying language and
437 omitting one previously produced module entirely. We see this flexibility as a strength of the tutorial
438 format. Unlike textbook and other static material, the instructor is free to modify these tutorials to meet
439 their needs.

440

441 **Impact on broader student learning and NNES students**

442 One major strength of explicit science process skill instruction is the enhanced student learning in other
443 facets of undergraduate biology education, including content retention (Kitchen *et al.*, 2003; Dirks &
444 Cunningham, 2006; Ward *et al.*, 2014). Unfortunately, in this study, we were not able to reliably assess
445 the tutorial's impact on student learning other than specific gains in science process skills. We look
446 forward to extending our assessment to other facets of student learning. Similarly, based on our design
447 decisions, student feedback during usability testing, and assessment trends, we suspect that the
448 tutorials are especially helpful for NNES students. Better support for this idea, would require a more
449 targeted intervention involving larger numbers of NNES students. As modern biology deepens its
450 international connections and international students continue to enroll at English speaking universities,
451 we hope that the online tutorial format will provide a strong instructional tool to help minimize gaps
452 between native English speaking and NNES students.

453

454 **Supplemental Material**

455 Supplement 1: Principles of Multimedia design

456 Supplement 2: Tutorial Learning Objectives

457 Supplement 3: Usability testing results

458 Supplement 4: Assessment questions

459 Supplement 5: Descriptive statistics for individual assessment questions

460

461 **Accessing the Tutorials**

462 All seven of our tutorial modules can be accessed in HTML5 format at
463 (<https://sites.google.com/umn.edu/btltutorials>). For LMS-compatible files or to discuss modifying
464 modules for your use, please contact the authors.

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471

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586

587

588 **Figure Legends**

589 **Figure 1: Example screenshots from ‘Experimental Design’ interactive tutorial.** Interactive tutorials
590 were designed using consistently formatted interactions. These included module introductions (A),
591 challenge questions (B), and specific feedback (C). Tutorials also include test tube graphics that allow
592 students to track their progress through each module, review individual learning objectives (D), review
593 entire modules (E) and review their progress through the entire tutorial (F). The test tube rack
594 containing test tubes for all completed modules is accessible at any time during the tutorial by clicking
595 on the small rack icon in upper right corner of the tutorial interface. This allows students easy access to
596 review past content and track progress.

597

598 **Figure 2: Experimental design.** Students enrolled in parallel sections of the same introductory biology
599 course were given two weeks to complete either the online tutorials or textbook reading. At the end of
600 the two weeks, a 15 question quiz assessed students’ science process skills.

601

602 **Figure 3: Mean scores for science process skills assessment after textbook (red) or online tutorial**
603 **(purple) assignment.** Comparison highlights difference between instructional approaches for native and
604 non-native English speakers.

605

606 **Figure 4: Mean scores for science process skills assessment among native and non-native English**
607 **speakers.** Comparison highlights the difference between the two groups when given textbook reading or
608 online tutorials.

609

610

611

612

Regression Results: TIPS II Scores	
Cumulative GPA	1.133** (.405)
Online tutorial group	0.824* (.317)
NNES status	-0.552 (.474)
Constant	7.374*** (1.352)
N	151
Adjusted R²	0.14
F Test	7.146***

Table 1 Ordinary least squares regression, with TIPS II score as dependent variable. Cell entries are unstandardized beta coefficients with standard errors in parentheses. *p < .05, **p < .01, ***p < .001

A

Submit a bug

DESIGN AN EXPERIMENT

DRAMATIC DISCOVERIES: ULCERS & H.PYLORI

CURRENTLY THEORIES... (ALTHOUGH NOT PROVEN)

SPICY! ACIDIC H.PYLORI MODEL ORGANISMS

DR. ROBIN WARREN DR. BARRY MARSHALL

(Video length: 1 minute)

CLICK HERE TO START!

BEGIN

B

Submit a bug

DESIGN AN EXPERIMENT

Select the **BEST** Experimental Treatment for your experiments

Water + H. Pylori Soda Water Water Soda Water + H. Pylori

Hover over for more information!

Submit

Each tube represents a possible treatment we can give our **EXPERIMENTAL** mice. Remember, the experimental mice are the mice we hypothesize will develop ulcers when treated.

OK!

bioRxiv preprint doi: <https://doi.org/10.1101/153015>; this version posted June 22, 2017. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC-ND 4.0 International license.

C

Submit a bug

Soda water is acidic and this sample may induce the formation of ulcers. The problem is using this sample does not align with your hypothesis.

Remember, you are testing the effects of *H. pylori* and its ability to induce the formation of ulcers in mice.

Go back and select a sample that better aligns with your hypothesis.

TRY AGAIN

EXPERIMENTAL mice. Remember, the experimental mice are the mice we hypothesize will develop ulcers when treated.

D

Submit a bug

Design an Experiment:

Learning Objective 3 Completed!

SUMMARY: Include Controls

Scientific controls are a **treatment group** to which you compare your experimental group. Ideally, this group differs from the experimental group by only one **variable**.

In this case that variable is H. pylori.

In your studies, giving water to your mice as a control allows you to "control" for the effect of *H. pylori* on ulcer formation.

NEXT

E

Submit a bug

THE SCIENTIFIC PROCESS:

COLLECT & ORGANIZE DATA

Gather, represent and interpret data that...

Uses basic statistics

Correctly labels graph Axes and includes units

Uses appropriate graphs to display data

Averages replicates

Is presented in graphs and tables

BACK

F

Submit a bug

THE SCIENTIFIC PROCESS:

TUTORIAL REVIEW

Primary Literature

Testable Questions

Hypotheses

Experimental Design

Collect & Organize Data

Analysis & Conclusions

Communicate & Discuss

Benefits & Outcomes

“Online Tutorials” group
class section 1
n=98 students

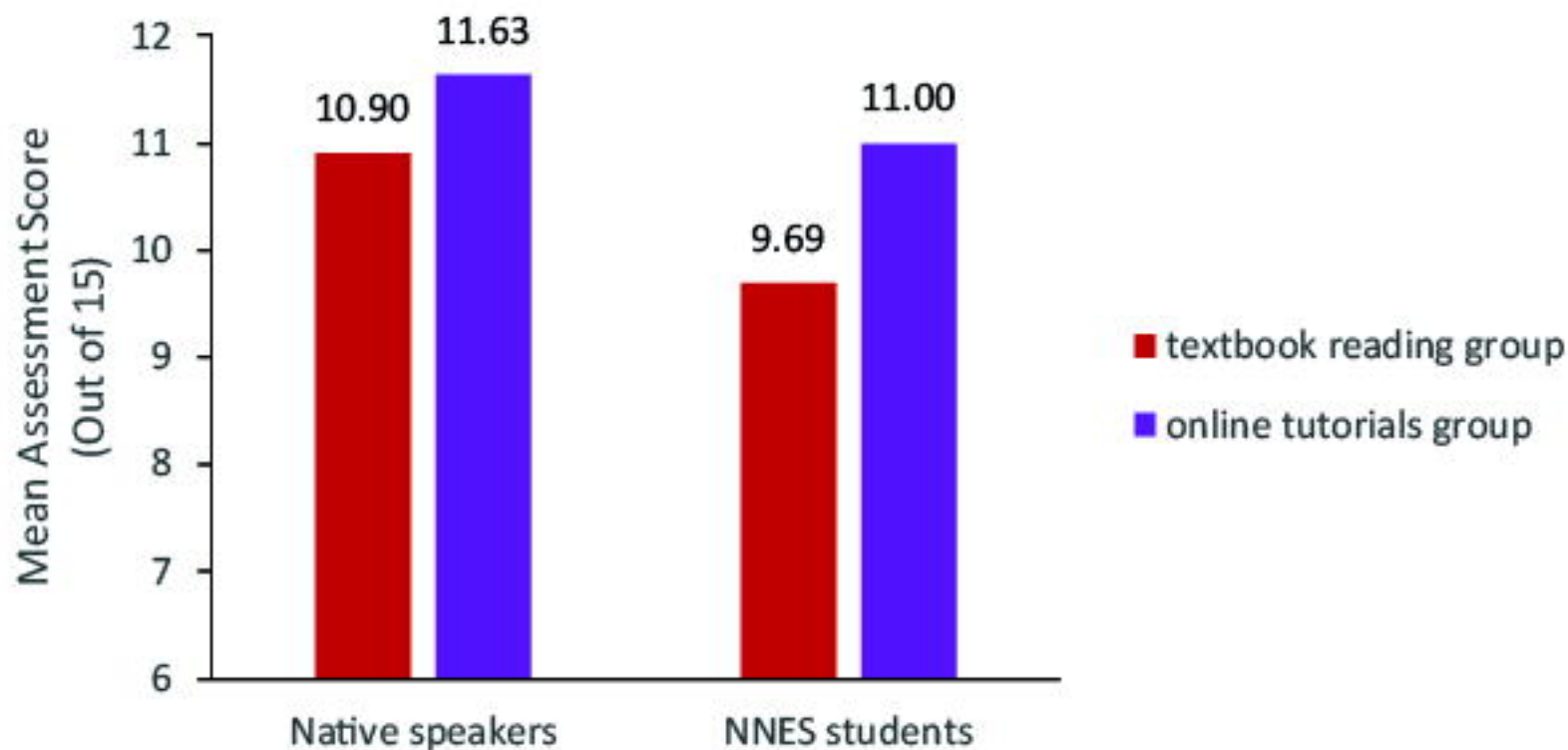


“Textbook Reading” group
class section 2
n=112 students



**Science Process Skills
assessment**

Online tutorials help all students, but especially NNES students



Online Tutorials help NNES students 'catch up' to native English speakers

