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Massive Open Online Courses as a Tool for Developing High-Level Engineering Expertise

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ABSTRACT

Online courses have become increasingly popular in education and professional development because of their user-friendliness, accessibility, and ability to provide specialized training beyond formal education for workforce preparation. We demonstrate the efficacy of using a Massive Open Online Course (MOOC) to teach specialized engineering concepts through the case study of a multi-body gravitational dynamics course; this topic is not typically taught in undergraduate courses but essential for specialized roles in aerospace engineering. Our use of MOOCs to bridge the knowledge gap between engineering education and practice represents a critical advance in tools for workforce preparation. Our MOOC, Designing the Moonshot, was released to the public in June 2021 and again in June 2022 as part of an international virtual event entitled OrbitCamp (originally called AstroCamp) where we collected data from a sample of 840 participants to study learning gains through pre-post testing and retention. Participant drop-off rates were steep (66% of participants did not complete the first module) but lower among men and those with higher degrees. Statistical analysis demonstrated that participants gained significant knowledge on the 12 (of 14 total) learning outcomes for which sample sizes were sufficient. Some of this knowledge was retained three months after OrbitCamp. These results support the use of MOOCs as a tool for furthering the expertise of the engineering workforce in highly specific domains.

Key words: Massive Open Online Classes (MOOCs), continuing education, knowledge gain

BACKGROUND

Undergraduate engineering education is designed to equip upcoming engineering practitioners with the expertise to navigate their roles in the workforce, but alone it is insufficient preparation for engineering practice. Curricula must make tradeoffs between breadth and depth, and as technical problems and technology both evolve so does the expertise needed by practitioners. Changes in professional practice are not immediately reflected in the curriculum, as new findings take considerable time to be published (Goodrum et al. 2001). Continuous education post-grad allows practitioners to remain current within their area of expertise or explore new areas of expertise and is a requirement of engineering licensing (Froehle, Phillips, and Murzi 2021). Massive Open Online Courses (MOOCs) offer one avenue for developing domain-specific expertise outside of or in supplement to formal education. MOOCs are open online courses available to unlimited participants typically characterized by self-paced and asynchronous content delivery through video lectures with little direct contact from an instructor. In this paper, we demonstrate the success of a MOOC as an intervention to build domain-specific expertise in trajectory design, specifically multi-body gravitational dynamics. The success of this MOOC serves as a proof of concept that supports the intentional use of MOOCs as part of the continuous education of engineers and advances our ability to support the engineering workforce.

Advantages of MOOCs

Since the first MOOCs offered at Stanford University in 2011 (Vardi 2012), the use of online modules has become increasingly common (Sezgin and Cirak 2020). A well-designed online course offers benefits such as user-friendliness (Zhou et al. 2020), the use of visualizations and online tools, and availability to anyone in the world with internet access (Iniesto et al. 2016). MOOCs also offer advantages that may not be available in traditional in-person lecture courses, such as accessibility and flexibility, while introducing information in ways that can be comprehended and retained similar to an in-person course (Moradi et al. 2018). Sharing resources on the internet allows for specialization in skills and topics that are newly relevant to a field of study (Goodrum et al. 2001).

The adaptability of MOOCs supports their use in teaching cutting-edge topics (Garrido and Koepke 2016; Sarma and Bonville 2021); they can serve as avenues for distributing updated knowledge in fast-changing fields. An online format allows the learner to set their own pace, complete knowledge checks and quizzes that ensure comprehension, and visualize concepts in software such as virtual reality (Deliktas 2011; Moradi et al. 2018; Iniesto et al. 2016). Online learning also offers flexibility and convenience to students that cannot otherwise attend an in-person class (Abdelmalak and Parra 2016; Powell, Roberts, and Patrick 2015), as pursuit of higher education often represents not only motivation to learn but also access to opportunity (Knutsen 2011; Rose 2013; Artino and Stephens 2009; Kyndt et al. 2015). An online course can take less time to complete than a semester-long university course (Pickard, Shah, and De Simone 2018) and allow individuals to more quickly gain specialized expertise to enter the workforce. Speedy expertise acquisition is particularly important in STEM fields. These fields are frequently advancing, making it necessary for practitioners to quickly attain new skills to succeed in their roles (Deming and Noray 2020). Completing a MOOC can give jobseekers a competitive advantage by demonstrating that they are hard-working, diligent, and better equipped to enter the workforce (Garrido and Koepke 2016).

The efficacy of online courses has been demonstrated across fields such as mathematics (Moradi et al. 2018) and biology (Thompson et al. 2010). A MOOC coupled with an in-person class can be more effective than an in-person class alone, as demonstrated by case studies in inorganic chemistry and English (Wang and Zhu 2019; Ahmed 2022). MOOCs also support knowledge retention, as demonstrated in a case study case in nursing (Pham et al. 2021). The asynchronous format of MOOCs allows for "mechanistic" learning, exploring, and tinkering with concepts in as much detail and as long as needed, which supports a higher likelihood of retaining knowledge for longer periods of time (Todd and Romine 2018). Students that learn concepts through diverse examples, such as the ones presented in well-designed online classes (Ally 2004), are more likely to retain those concepts than if they were just memorizing content (DeDecker et al. 2022).

In addition to the learning gains they provide, MOOCs can also lead to increased confidence in the ability to work in a professional setting (Zhou et al. 2020) and increased confidence levels (Sadi and Dağyar 2015) or self-efficacy (Zhou et al. 2020) in the corresponding domain of expertise. Self-efficacy refers to the belief that one can perform the necessary behaviors to be successful (Bandura, Freeman, and Lightsey 1999; Bandura and Adams 1977) and is subsequently closely related to confidence. A higher sense of confidence or self-efficacy for undergraduate students has been positively correlated with a desire to remain in the engineering field (Besterfield-Sacre, Atman, and Shuman 2009). Environments in which students feel confident promote persistence (Rittmeyer and Bayer 2008); an online format can relieve some of the normal stresses of classwork and boost confidence (Forsgren and Miller 2010), subsequently supporting persistence.

Critiques of MOOCs

The primary critique of MOOCs is their low completion rates, which is exacerbated by the dependence on self-regulated learning and the need for a stable internet connection as well as comfortable space to work.

Low completion rates are common among online courses (Panigrahi, Srivastava, and Sharma 2018, Hew and Cheung 2014), and often tied to the time or monetary cost (Pickard, Shah, and De Simone 2018). On average, 52% of participants that register for a MOOC never actually open the course materials, and the percentage of active participants steadily decreases in the first two weeks of a course (Reich et al 2019). In one case study of a calculus MOOC, only 5% of participants completed the course while approximately 40% of participants dropped out completely (Rothkrantz 2017).

Drop-off rates also vary with gender, degree, and experience level of the participants themselves. Undergraduate students are more likely to drop off because of time pressures and the lack of tangible consequences for incompletion, whereas PhD recipients or practitioners are more likely to persist (Zheng et al. 2015; Milligan, Littlejohn, and Margaryan 2013). Historically underrepresented groups are over one and a half times more likely to drop out of an online STEM course compared to white males because of a lack of representation and imposter syndrome influencing feelings of self-efficacy (Flynn 2016; Ellis, Fosdick and Rasmussen 2016). In a case study of a computer science MOOC, 53% of women dropped the course by the second week compared to only 33% of men despite only small variations in performance scores (Duran, Haaranen, and Hellas 2020). High drop-off rates can be partially attributed to an absence of community and face-to-face collaboration (Cheng, Kulkarni, and Klemmer 2013; Prince, Felder, and Brent 2020) but can be reduced by facilitating opportunities for community and engagement for participants (Labarthem, Bachelet, and Bouchet 2016; Zheng, Rosson, Shih, Carroll 2015).

Participant's confidence, prior experience, and motivation are also large factors in the success and completion rates within a MOOC and online learning in general (Milligan, Littlejohn, and Margaryan 2013; Appana 2008; Muilenburg and Berge 2005) because of MOOC's reliance on self-regulated learning (Littlejohn et al. 2016). Engagement in online learning can be further limited by the cost of access to a computer or the internet and feasibility of having a space to work (Appana 2008; Muilenburg and Berge 2005).

Despite these limitations, the advantages of well-designed online courses (Ally 2004) support their use as a tool for continuous education. When specifically considering populations seeking to further advance their expertise in highly specific technical domains, many of these limitations (e.g., motivation) are less applicable. Subsequently, the use of MOOCs for continuous education in highly specific domains of technical expertise represents a large potential advance in workforce preparation.

Designing the Moonshot MOOC - an Advance in Continuous Education

We have created a highly technical MOOC on multi-body dynamics aimed at undergraduate students that represents an advance in tools for continuous education. Multi-body dynamics is an increasingly important topic in aerospace engineering, especially with NASA's Artemis Program (Guzzetti et al. 2017; OSTP 2022) aiming to return to the Moon, but it is not covered in undergraduate (or even some graduate) curriculum. Multi-body dynamics in this MOOC are focused on spacecraft trajectories (or pathways) with more than one gravitational body, such as the Earth and the Moon, effecting the spacecraft. Engineers entering the workforce therefore have a knowledge gap with respect to multi-body dynamics (Boardman, et al 2018). NASA has previously used a private online course to fill knowledge gaps of new hires for topics such as basics in astronomy and professionalism in engineering (Forsgren and Miller 2010). Similar knowledge gaps in areas such as data gathering and analysis, monitor processing, and systems evaluations reported among STEM graduate students (Jang 2016) highlight the persistent need for continuing and supplemental training that allow engineers, whether still in school seeking to gain a specialty or in the workforce requiring additional training in an area of expertise, to develop specialized skills and expertise in an easily accessible manner. MOOCs, such as the Designing the Moonshot MOOC developed here, represent one approach that advances the field's ability to address these gaps.

METHODS

Designing the Moonshot was released to the public in June 2021 as part of a two-week virtual "Astrocamp" and in June 2022 as "OrbitCamp" aimed at high-yield data collection. The rebranding to OrbitCamp was adopted to differentiate this event from other NASA initiatives. Moving forward, the two "camp" experiences will be referred to as OrbitCamp. During OrbitCamp participants were encouraged to complete the Designing the Moonshot course and participate in synchronous virtual events such as socials and webinars. Data from participants' answers were analyzed to determine if the course was successful in improving comprehension of astrodynamic topics in multi-body dynamics.

Designing the Moonshot was developed using best practices for online learning (Ally 2004) for a target audience of upper-level undergraduate students who had taken an introductory course on astrodynamics (i.e., two-body motion) and tested for public readiness through think-aloud studies in 2020-2021 before release (Kaiser et al. 2020; Busato et al. 2022). The think-aloud studies defined our best practices for MOOCs and informed the final design of Designing the Moonshot. These practices are described in detail in previous work (Kaiser et al. 2020; Busato et al. 2022). The course contains five modules, each with a topic of focus: 1) gravitational fields, 2) understanding chaotic behavior, 3) spacecraft orbits in a gravitational multi-body environment, 4) targeting and optimization, and 5) advanced topics. The modules target 14 learning objectives across these five topics. The course was hosted on a Canvas site by Auburn Online. Module content consisted of pre-quizzes, post-quizzes, video lectures, coding exercises with skeleton code, and an interview of a practicing expert on the module topic at the end (Kaiser et al. 2020). Designing the Moonshot was created to be autonomous, but the discussion boards were moderated during the two weeks of OrbitCamp. The total video length for each module ranged from 20 to 60 minutes with each individual video being less than 11 minutes as noted in best practices (Ahn and Bir 2018).

Participants and Recruitment

Participants were recruited through a variety of methods including personal emails to students at participating institutions, flyers on participating campuses, advertising through professional societies (American Institute for Aeronautics and Astronautics and American Astronautical Society), NASA contacts, and university faculty including aerospace engineering chairs. Eight hundred and forty participants over the age of 18 consented to participate in the study, 476 participants in 2021 and 364 in 2022. The online format supported geographically diverse participants from not only across the United States but also countries such as Italy, Turkey, India, Russia, and Japan. Participants self-identified as male (n = 606), female (n = 218), not listed (n = 3), or prefer not to answer (n = 13). Women are overrepresented in our sample (26%) when compared to the prevalence of women in aerospace engineering awarded bachelor's degrees in 2021 (15.9%, ASEE 2022). Our pool, however, includes participants not just with bachelor's degrees but from high school to graduate school and beyond, which may have given us access to a larger pool of women. Participants were primarily engineering students, ranging in experience from high school to graduate-level, but also included practicing professionals. The target audience, undergraduates, comprised 427 of the total consented participants (51%). Participants who completed the first pre-quiz and self-identified as male (n = 452) or female (n = 140) were classified into 1) pursuing or having a bachelor's degree, 2) pursuing a graduate degree, and 3) having a graduate degree (Table 1) based on responses to questions on what degree they are currently pursuing and their highest degree earned.

Table 1. Degree Level Categories based on Gender and Responses to Degree Currently Pursuing and Highest Degree Earned (n = 592).

Degree Level Categories	Response to Degree Pursuing and Highest Degree Earned	Male	Female
Pursuing or having bachelor's degree	Currently in High School	2	3
	Obtaining associate degree or Equivalent	0	5
	Pursuing a bachelor's degree	189	70
	Obtained their bachelor's degree and not currently pursuing another degree	28	3
	Total pursuing or having bachelor's degree	219	81
Pursuing a graduate degree	Have a bachelor's and obtaining Master's	80	21
	Have a bachelor's and obtaining Ph.D.	22	6
	Total pursuing a graduate degree	102	27
Having a graduate degree	Have a Master's/Ph.D. and pursuing another Master's	9	2
	Have a Master's/ Ph.D. and pursuing Ph.D.	44	13
	Have a Master's/Ph.D. and not currently enrolled as students	78	17
	Total having a graduate degree	131	32

Data Collection

Data were collected through Qualtrics survey software and the Canvas site. Demographic information such as age, nationality, and level of education were collected from each participant before the start of the course through a Qualtrics registration form. Course progression was tracked through Canvas. Progression data included pre- and post-quiz responses for each module. Three months after the camp ended (October 2021 and 2022) participants were sent a knowledge retention quiz through Qualtrics.

Data were collected from a total of 24 assessment questions covering 14 learning outcomes across the five modules. The assessment questions and associated learning outcomes are listed in Table 2 (full question statements with answer choices are provided in Table 6 in the Appendix). Each module had two to eight assessment questions, and each of these questions was linked to one of 14 learning outcomes. The questions are numbered MXLOYα where "MX" corresponds to the module, "Y" the learning outcome in that module, and "α" is included if a learning outcome was assessed more than once, which occurred for seven of the 14 learning outcomes.

Participants' existing knowledge was captured through a required pre-quiz at the beginning of each module that consisted of all the assessment questions for that module. Module content was unavailable until the pre-quiz was complete, though participants could work through the modules in any order. As participants moved through the modules, they completed a series of 20 post-quizzes (seven in Module 1, three in Module 2, four in Module 3, three in Module 4, and three in Module 5) that included the assessment questions in Table 2.

Table 2. Assessment Questions and their Associated Learning Outcomes.

Number	Question	Learning Outcome
M1LO1	Like two-body motion, the Circular Restricted Three-Body Problem only produces orbits that are conics. (True/False)	Explain the difference between two-body and three-body motion
M1LO2A	In this module, how many elements are in a state vector?	Propagate three-body motion
M1LO2B	What is the CR3BP equation of motion for the y-hat direction using state space notation?	
M1LO2C	Which term completes the following CR3BP equation of motion?	
M1LO3	How do you convert a distance from dimensional units to nondimensional units?	Nondimensionalize equations of motion
M1LO4	Match the image to the correct coordinate frame.	Visualize the difference between Earth-fixed and Earth-Moon-fixed frames
M2LO1	Chaotic behavior within deterministic nonlinear dynamical systems arises from high sensitivity to…	Recognize chaotic behavior
M2LO2	If v is the particle velocity in the rotating frame, U^* is the pseudo-potential function, and JC is the Jacobi constant, then…	Explain the constant of motion in CR3BP
M2LO3A	Punctures on a Poincaré map are caused by…	Generate and interpret Poincaré maps (recognize structures in chaos)
M2LO3B	On a Poincaré map, puncture patterns that resemble a group of closed curves forming an island-like structure indicate…	
M3LO1	How can you locate the Lagrange relative equilibrium points in the circular restricted three-body problem?	Estimate the location of the Lagrange points
M3LO2A	In this module, which term better describes the process of generating a family of periodic orbits?	Compute (a subset) of periodic orbits
M3LO2B	In this module, what conditions in rotating frame coordinates do describe a perpendicular crossing of the x-axis? Consider planar dynamics when answering this question.	
M3LO2C	Which component of the initial state do we update when targeting perpendicular crossing with the algorithm presented in this module? Assume the initial state is expressed in rotating frame coordinates.	
M4LO1A	What is the size of the State Transition Matrix?	Create a state transition matrix
M4LO1B	Which of the following is NOT a property of the State Transition Matrix?	
M4LO1C	To find $\phi(t, t_1)$ we numerically integrate $\dot{x}$ and ϕ	
M4LO2A	Which of the following is NOT an assumption of the Single Shooting Method as discussed in this module?	Apply single-shooting to a trajectory
M4LO2B	How does the Single Shooting Method described in this module solve for an optimal trajectory?	
M4LO3A	Compared to the indirect method, the direct method...	Analyze different optimization schemes
M4LO3B	Compared to the collocation method, the shooting method of discretization...	
M4LO4	An optimization problem can be initialized by first solving a simpler problem and using the result as initial conditions.	Explain how to initialize an optimization problem
M5LO1A	Which of the following is NOT an aspect of mission planning?	State the functions of mission operations in active missions
M5LO1B	What does navigation and orbit control deal with?	

Three months after the end of OrbitCamp (October of 2021 and 2022), participants that had completed at least one module were sent a Qualtrics retention quiz based on their course progression. For example, if a participant completed the first three modules, they were sent a quiz that included the assessment questions from Module 1 to Module 3.

Data Analysis

After exporting data from Canvas and Qualtrics, each question was scored as correct (1) or incorrect (0). Three questions (M1LO4, M4LO3B, and M4LO4) had partial credit with a maximum score of 1 as participants had to complete two or three drop-down menus per question. Our analysis in R considered completion rates for gender and degree (chi-squared and Fisher's exact test), knowledge gained during the camp (Wilcoxon Signed-Rank test, also referred to as Wilcoxon test for paired samples, due to non-normally distributed sample), and knowledge retained after camp completion (Wilcoxon Signed-Rank test). The phi coefficient of association (referred to as association levels in results) was computed for chi-squared analyses (square root of chi-squared statistic divided by the sample size) to denote the strength of the association. An association of "no" denotes a nonsignificant result, a value less than 0.1 denotes "little" association, and a value between 0.1 and 0.3 denotes "low" association. A power analysis was completed using the WMWssp package in R (Happ, Bathke, and Brunner 2019). For completion results, a participant was considered to complete a module if they completed all assessment quiz questions for that module. To determine whether learning occurred across each module as a whole, we added up the correct answers for the questions across each module and performed a Wilcoxon Signed-Rank test.

RESULTS AND DISCUSSION

We ran analyses on module completion rates, participant quiz scores before and after module completion, and participant retention quiz scores. Within the demographic subsets in our sample, we only had sufficient sample sizes for analysis by gender and degree. Module completion rates were unsurprisingly low, with men and those with higher degrees more likely to complete all five modules. Quiz scores were higher after module completion, indicating knowledge gains, and some knowledge was retained three months after OrbitCamp ended.

Module Completion Rate

The drop-off rate for completion was steep across both years of OrbitCamp ($N = 840$) with 66% of participants ($n = 553$) dropping off prior to the end of Module 1 and only 6% of participants ($n = 52$) completing all five modules. Almost all participants moved through the modules sequentially, except for 19 participants in 2021 (4%) and 5 participants in 2022 (1.3%). Most of the participants who completed OrbitCamp non-sequentially (*n* = 16) skipped Module 3 or Module 4. Other undergraduate STEM MOOC courses have reported similarly low completion rates (Rothkrantz 2017). Completion rates are often tied to costs (Pickard, Shah, and De Simone 2018). The time cost for each module was on average around 40 minutes of videos plus additional time for coding exercises. Designing the Moonshot was free to the public so there were no financial losses or pressure for participants to complete the course, which can contribute to low completion rates (Zheng et al. 2015). Completion rates did vary by gender and degree with undergraduate students and women dropping off initially at faster rates than graduate students and men. Further insights into these gender and degree trends are provided in the next sections.

Completion Rate by Gender

Drop-off rates were steep across both self-identified gender groups (Figure 1). The completion rate for men and women for all pre- and post-quizzes in Figure 1 is relative to the total population that completed the informed consent. By the first pre-quiz, 25% of men and 35% of women dropped off (first data point in the figure). Participants who did not select male or female (*n* = 16) are excluded from this analysis due to low sampling numbers.

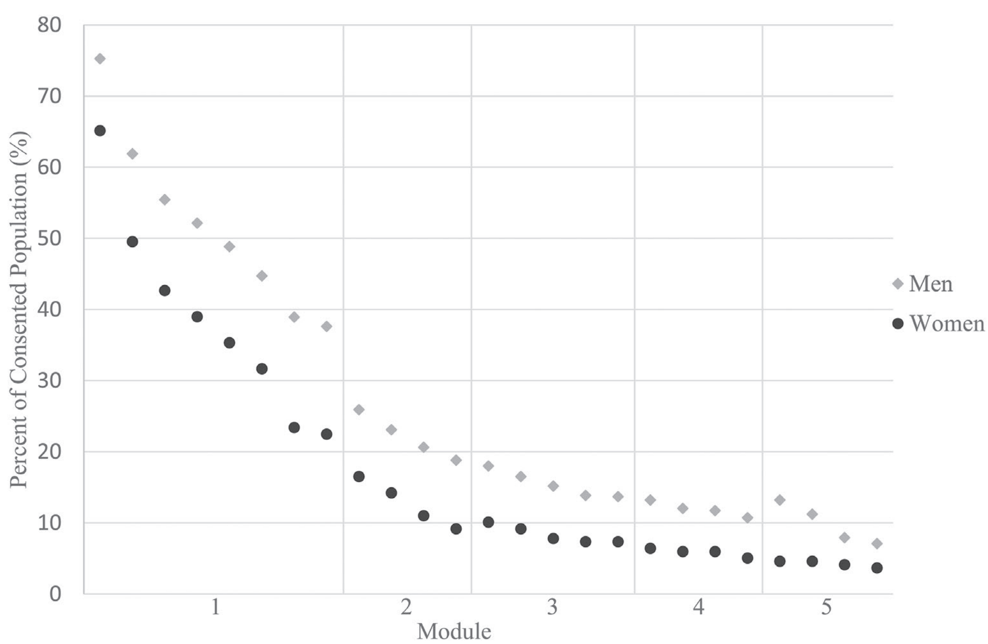

Figure 1. Completion rates for men and women on pre- and post-quizzes as a percentage of those who completed the informed consent.

Table 3. Module Completion Rates after Informed Consent across Gender (n = 824, df = 1).

Module	χ^2	p	Association $\sqrt{\frac{\chi^2}{n}}$
1	15.8	< 0.05	Low
2	10.2	< 0.05	Low
3	5.5	< 0.05	Little
4	5.5	< 0.05	Little
5	2.7	> 0.05	No

Women initially had a significantly higher drop-off rate than men, as demonstrated by the statistically significant, higher, completion rate for men in early modules (Table 3). The strength of the association between gender and completion rate based on chi-squared analysis decreases across modules and becomes non-existent by Module 5. Similar gender differences in drop-off rates are observed in other MOOCs (Duran, Haaranen, and Hellas 2020) and in in-person classes (Sanabria and Penner 2017; Ellis, Fosdick, and Rasmussen 2016). Women have been cited to drop out and report lower confidence even when their performance is higher than their male counterparts (Ellis, Fosdick, and Rasmussen 2016). While we did not measure confidence, it is a known contributor to MOOC completion rates (Milligan, Littlejohn, and Margaryan 2013), and the possibility of lower confidence among women could explain the drop-off rate differences.

Completion Rate by Degree Level for Men and Women

Participants with higher degrees tended to complete modules at a higher rate as indicated by the significant, low association between degree level and the completion rate (Table 4). Overall, those with or pursuing a graduate degree completed the modules at higher rates than those who were earning or had only earned a bachelor's degree (Figure 2). This trend is perhaps unsurprising

Table 4. Module Completion Rates after First Quiz across Degree Type (n = 482, df = 2).

Module	χ^2	p	Association $\sqrt{\frac{\chi^2}{n}}$
1	11.3	< 0.05	Low
2	13.4	< 0.05	Low
3	17.4	< 0.05	Low
4	14.6	< 0.05	Low
5	16.2	< 0.05	Low

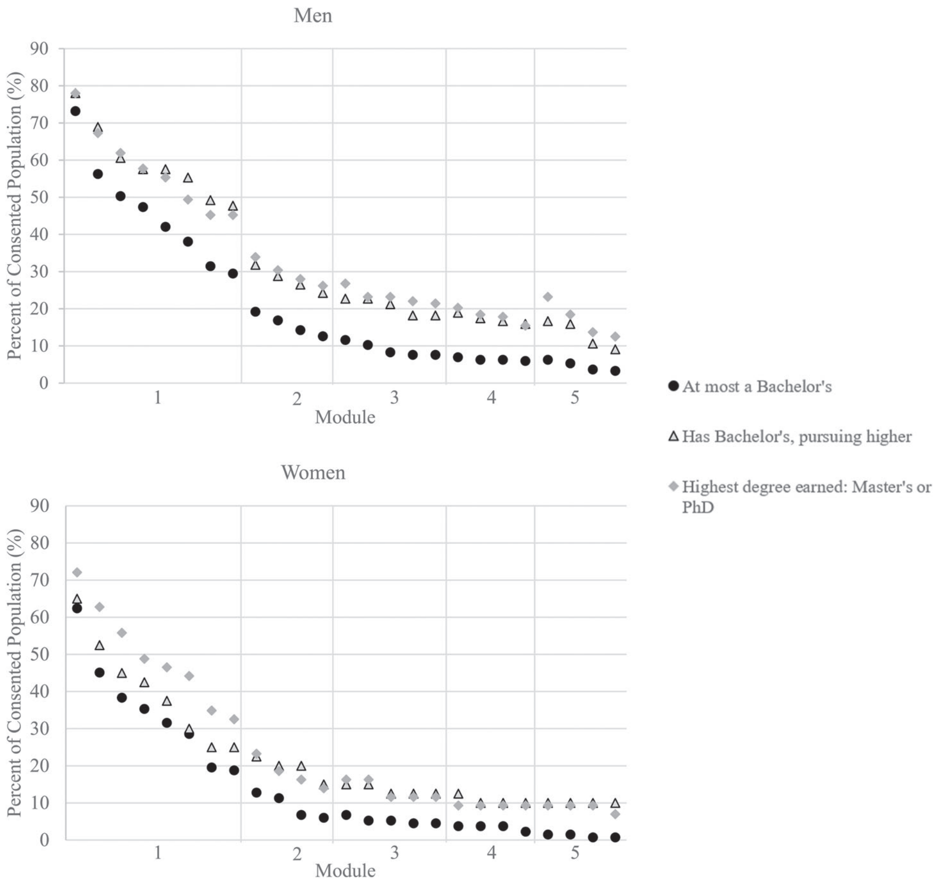

Figure 2. Quiz completion rate for men and women by degree as a percentage of those who completed the informed consent.

as pursuit of higher education can signal motivation (Artino and Stephens 2009), and motivation is one of the factors of self-regulated learning that influences MOOC completion rates (Milligan, Littlejohn, and Margaryan 2013; Appana 2008; Muilenburg and Berge 2005; Littlejohn et al. 2016). Undergraduate students approach online learning with different levels of self-determination and motivation compared to graduate students who exhibit more adaptability and report lower levels of procrastination (Artino and Stephens 2009). This motivation difference may explain why we see higher drop-off rates with those who have or are pursuing a bachelor's degree.

Men and women of similar degree types had no difference in completion rates, but gender differences did emerge when each group was considered separately. Our population was majority men, so it is unsurprising that the completion results for men mirror the overall population. Men with higher degrees completed the modules at higher rates than men pursuing or only having a bachelor's

Table 5. Module Completion Rates after First Quiz across Degree for Men (n = 374, df = 2).

Module	χ^2	p	Association $\sqrt{\frac{\chi^2}{n}}$
1	9.8	< 0.05	Low
2	10.1	< 0.05	Low
3	14.4	< 0.05	Low
4	10.0	< 0.05	Low
5	11.1	< 0.05	Low

degree for all five modules with a significant, low association between degree level and completion rate (Table 5). Women, on the other hand, completed all the modules at the same rate regardless of degree type, except for the final module where women with or pursuing higher degrees completed the module at significantly higher rates (7 of the 8 women who completed the fifth module had or were pursuing higher degrees, $p < 0.05$, Fisher's exact test).

When looking at differences in drop-off rates across degree types within each gender, the higher drop-off rate of men at lower degree levels may be explained by lack of motivation (Tanaka 2022) and less experience in self-learning (Milligan, Littlejohn, and Margaryan 2013; Zheng et al. 2015). Male students have been documented as exhibiting higher amotivation (lack of motivation) and learned helplessness compared to female students in project-based learning (Tanaka 2022). This finding, taken together with Milligan's prediction factors of motivation, prior knowledge, and confidence (2013), may explain the significant, low association difference between men of lower and higher degrees. In contrast, female students' higher intrinsic motivation and self-determination (Tanaka 2022) may result in what we see as few differences between women's drop-off rates by degree.

Participant Knowledge Gained during OrbitCamp

Participant knowledge did increase during OrbitCamp. We had a sufficient sample size for pre-quiz/post-quiz analysis of 20 of the 24 assessment questions, which addressed 12 of our 14 learning objectives. A Wilcoxon Signed-Rank Test indicated that post-quiz scores were statistically different from and higher than pre-quiz scores in all 20 cases (Table 8 in Appendix). These results indicate statistically significant learning gains from completing the modules and suggest that the intervention was successful (Figure 3).

The four questions without enough power for the analysis (M3LO1, M4LO1A, M4LO1C, and M4LO4) covered three learning objectives. For M3LO1 (estimate Lagrange points), 71 of 123 participants answered the pre-quiz question correctly and 83 of 123 participants answered the post-quiz question

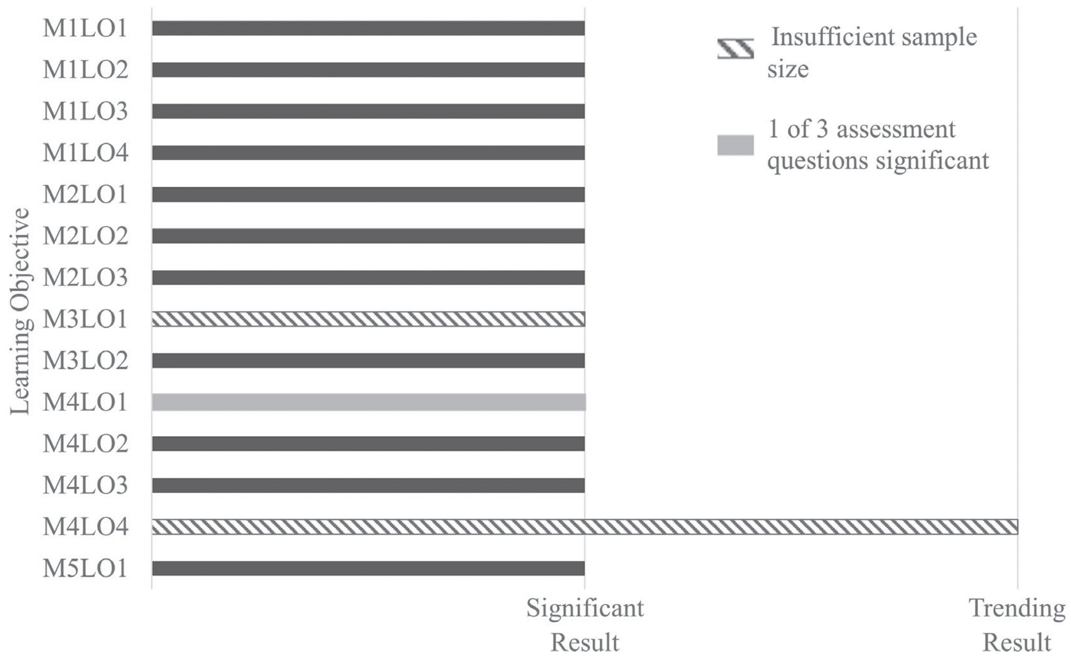

Figure 3. Statistical significance in learning gains by learning objectives.

correctly. M3LO1 was determined to be poorly written upon review, so revisions to the question are needed to better assess M3LO1. M4LO1 (creating a state transition matrix), was assessed three times; M4LO1B had enough power and showed significant differences between the pre- and post-quiz results with significantly higher post-test results. For M4LO1A and M4LO1C, over 80% of the 87 participants got the pre-quiz question correct while over 90% got the post-quiz question correct. This result indicates that the population had high prior knowledge about M4LO1A and M4LO1C suggesting that the questions may have been too simple. The high percentage of correct answers on M4LO1A and M4LO1C taken with the significant and higher difference for M4LO1B led us to determine that participants achieved M4LO1. For M4LO4 (initialize an optimization problem), 73 of 77 answered the pre-quiz questions correctly while all 77 answered the post-quiz correctly again suggesting high prior knowledge and an overly simple question. As this was the only question that addressed M4LO4, we cannot determine whether participants achieved how to initialize an optimization problem from the MOOC. These results further underscore the importance of online course design (Ally 2004) as despite careful design and testing not all questions supported assessment.

For assessing learning across each module as a whole, all five modules had enough power to complete the analysis and showed learning gains through post-quiz scores that were statistically different and higher than pre-quiz scores (Table 7 in Appendix). Overall, participants gained knowledge after completing the modules, supporting the use of MOOCs or similar online courses for high-level expertise development (Moradi 2018; Thompson 2010; Deliktas 2011; Lam and Annetta 2012; Wang and Zhu 2019) to advance engineering education and practice.

Analysis by gender reveals that the overall results during the camp (pre-quiz and post-quiz comparison) are mirrored for men (since our sample population was primarily male) with significantly different and higher post-quiz scores for all questions with the same four questions (Figure 3, M3LO1, M4LO1A, M4LO1C, and M4LO4) not having enough power for analysis (Table 9 in Appendix).

For women, only six questions (M1LO2A, M1LO2B, M1LO3, L2LO1, L2LO2, M5LO1B) covering five learning outcomes (Table 10 in Appendix) had sufficient power; post-quiz results were significantly higher in all six cases (same as the men). Four outcomes (M1LO1, M2LO3, M3LO1, and M4LO4) were not significant. For these outcomes, more than half of the participants correctly answered the pre-quiz question, and with the exception of M1LO1 (59% correct on the post-quiz), over 75% correctly answered the post-quiz questions. The remaining analysis was limited by sample size.

We also considered if differences in learning gains existed between men and women. We only had enough power for M1LO1 among cases where there was a significant difference in learning across genders (z = 4576, p = 0.0028) and men did significantly better on the post-quiz (z = 4576, p = 0.0014). Except in this one case, we cannot say if there is a difference in learning gains between men and women, but we can say that both groups learned independently. These independent learning gains demonstrate that this MOOC supported both men and women in gaining knowledge about multi-body dynamics in the short term as observed in other studies (Stolk, Gross, and Zavstavker 2021, Duran 2020).

Participant Knowledge Retained from OrbitCamp

Retention results are both more varied and more limited by low response rates. Response rates were 16% for Modules 1 and 2 (45 of 283 and 22 of 138 participants who completed post-quizzes, respectively), 18% for Module 3 (18 of 101 participants), 13% for Module 4 (11 of 85 participants), and 17% for Module 5 (9 of 52 participants). Chi-squared or Fisher's exact tests indicated that in all but one case, M4LO1C (p < 0.001, Fisher's exact test), the retention quiz respondents are representative of the camp population when considering the difference in the answer frequencies of the pre- and post-quizzes. In the case of M4LO1C, the limitation in retention analysis is furthered by this question not having enough power, but the learning outcome is assessed two other times allowing us to still capture outcome-level retention. In considering retention, we measure both from after camp (post-quizzes) and before (pre-quizzes) to capture additional nuances in retention.

Knowledge retention from before camp had five questions, all in Modules 1 and 2, with enough power to assess a difference, and demonstrated a significant improvement between the pre-quiz and retention quiz: M1LO1($z = 416$, $p < 0.001$), M1LO2A ($z = 577.5$, $p < 0.001$), M1LO2B ($z = 276$, $p < 0.001$), M1LO3 ($z = 542.5$, $p < 0.001$), and M2LO1 ($z = 253$, $p < 0.001$). These statistically significant differences indicate that participants not only gained knowledge during the camp but also retained a significant amount of knowledge three months later. Little or no difference in responses between post-quiz and retention quiz represents full knowledge retention after OrbitCamp; this was the case for 17 assessment questions (representing 11 of the 14 learning outcomes). Only two questions, M1LO2C (z = 0, p < 0.001) and M1LO4 (z = 14.5, p < 0.001) had enough power to interpret statistically significant post-quiz to retention quiz results, and the results indicated significant loss of knowledge from post quiz to retention quiz. Both M1LO2 and M1LO4 had significant learning gains during the camp. M1LO2 also had significant learning gains from pre-quiz to retention quiz suggesting that participants only lost some of the knowledge gained during the camp in the three months after. For M1LO4, participants appear to have reverted to pre-quiz knowledge levels.

The five questions (M1LO3, M3LO2C, M4LO2A, M4LO2B, M4LO3B) that had statistically significant differences but insufficient power between the post-quiz and retention quiz all had a decrease in the number of correct responses from the post-quiz. Participants still retained some knowledge as evidenced by the higher number of correct responses compared to the pre-quiz in all but M4LO2B where participants again reverted to pre-quiz knowledge levels.

Learning loss is inevitable over time (Ebbinghaus 1966) with around only a third of knowledge retained after one year (Custers 2010). Similar results for learning gains retained after course completion have been seen in other MOOCs and education in general (Todd and Romine 2018), but there is also evidence for knowledge continuing to increase after a MOOC if practitioners are using the material in their roles (Pham et al. 2021). Subsequently, while our retention results were limited by sample size, we have strong reason to believe that the use of MOOCs for highly specialized expertise development is an important advance in continuing education as the target audience are students or practitioners who will directly use the material in their current or future roles.

CONCLUSION AND FUTURE WORK

Our findings about knowledge gain support the use of MOOCs as an advance for developing high-level expertise among engineering practitioners. During the OrbitCamp experience, participants showed significant learning gains on all learning objectives for which sufficient power was available for analysis. While results on retention were variable and limited by low response rates resulting in insufficient power, we have reason to believe that participants engaging in such a MOOC for professional development would retain knowledge gained by using it in their professional roles.

Future work with a sample population of students or practitioners who intend to use the MOOC content in their roles could shed further light on the importance of content use and relevance to retention. Future work could also directly investigate influences of motivation and confidence on completion rate. A larger sample size would support more robust analysis, but, recognizing that response rates are a persistent problem, a mixed-methods study design incorporating interviews with participants may provide a richer data set. Designing the Moonshot remains publicly-accessible and free, supporting both the continuous education of anyone seeking to gain further expertise in multi-body dynamics as well as future research on use of MOOCs for developing high-level expertise.

As the field of engineering continues to advance at increasing rates, continuous education focused on the development of high-level expertise becomes increasingly important. A well-designed MOOC can bridge the inevitable knowledge-gaps that will arise for engineering practitioners as the field evolves or their roles change. The success of Designing the Moonshot supports MOOCs as an advance in engineering education that can be leveraged to address these gaps in knowledge.

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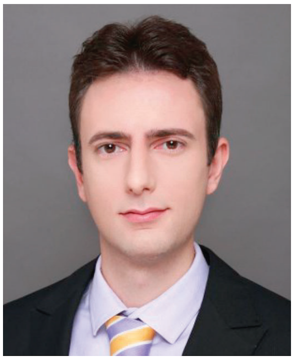

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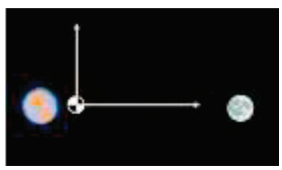
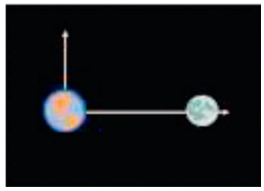
APPENDIX

Assessment Questions

The assessment questions with answer choices are listed in Table 6.

Table 6. Question statement and multiple-choice answers.

Name in Paper	Question	Answer Choices
M1LO1	Like two-body motion, the Circular Restricted Three-Body Problem only produces orbits that are conics.	True False
M1LO2A	In this module, how many elements are in a state vector?	3 6 9 1
M1LO2B	What is the CR3BP equation of motion for the direction using state space notation?	$\ddot{y} = dS(5) = -2S(5) + S(2) - \left(\frac{1-\mu}{r_{13}^3}\right)S(2) - \left(\frac{\mu}{r_{23}^3}\right)S(2)$ $\ddot{y} = dS(5) = -2S(4) + S(2) - \left(\frac{1-\mu}{r_{13}^3}\right)S(2) - \left(\frac{\mu}{r_{23}^3}\right)S(2)$ $\ddot{y} = dS(5) = -2S(4) - S(2) - \left(\frac{1-\mu}{r_{13}^3}\right)S(2) - \left(\frac{\mu}{r_{23}^3}\right)S(2)$ $\ddot{y} = dS(5) = 2S(5) + S(1) - \left(\frac{1-\mu}{r_{13}^3}\right)S(1+\mu) - \frac{\mu(S(1)-(1-\mu))}{r_{23}^3}$
M1LO2C	Which term completes the following CR3BP equation of motion?	$-\frac{\mu}{r_{23}^3}S(3)$ $\frac{\mu}{r_{23}^3}S(3)$ $-\frac{\mu}{r_{23}^3}S(2)$ $2S(4) - S(2) - \frac{\mu}{r_{23}^3}S(1)$
M1LO3	How do you convert a distance from dimensional units to nondimensional units?	Multiply by l^* Divide by l^* Divide by m^* Multiply by t^*
		 Select from a drop-down menu: • Fixed Coordinate Frame • Rotating Coordinate Frame •

Name in Paper	Question	Answer Choices
M1LO4	Match the image to the correct coordinate frame. (Partial credit awarded)	 Select from a drop-down menu: • Fixed Coordinate Frame • Rotating Coordinate Frame
M2LO1	Chaotic behavior within deterministic nonlinear dynamical systems arises from high sensitivity to	Constant State Large Variations Small Variations
M2LO2	If v is the particle velocity in the rotating frame, U^* is the pseudo-potential function, and JC is the Jacobi constant, then…	$JC = U^* - v^2$ $JC = 2U^* - v^2$ $JC = 2U^* - v$ $JC = U^* - v$
M2LO3A	Punctures on a Poincaré map are caused by	Trajectories that crosses the surface of a section Trajectories on the surface of section By the initial states selected by the user Only random noise
M2LO3B	On a Poincaré map, puncture patterns that resemble a group of closed curves forming an island-like structure indicate	Quasi-periodic motion Periodic motion Chaotic motion Nothing
M3LO1	How can you locate the Lagrange relative equilibrium points in the circular restricted three-body problem?	I search for the stationary points of an appropriate potential function I search for points where the net gravity force is null Search for the points where velocity is zero They can't exist if the spacecraft is orbiting
M3LO2A	In this module, which term better describes the process of generating a family of periodic orbits?	Continuation Identification Correction
M3LO2B	In this module, what conditions in rotating frame coordinates do describe a perpendicular crossing of the x-axis? Consider planar dynamics when answering this question.	y = 0 and $\dot{x} = 0$ ONLY y = 0 Y = 0 and $\dot{y} = 0$ ONLY $\dot{x} = 0$

Name in Paper	Question	Answer Choices
M3LO2C	Which component of the initial state do we update when targeting perpendicular crossing with the algorithm presented in this module? Assume the initial state is expressed in rotating frame coordinates.	$\dot{y}$ $\dot{x}$ y x
M4LO1A	What is the size of the State Transition Matrix?	3x3 6x6 9x9 1x1
M4LO1B	Which of the following is NOT a property of the State Transition Matrix?	$\phi(t_3, t_1) = \phi(t_3, t_2)\phi(t_2, t_1)$ $\phi(t_1, t_1) = I$ $\phi(t_3, t_2) = \phi(t_2, t_1)$ $\phi(t_1, t_2) = \phi^{-1}(t_2, t_1)$
M4LO1C	To find $\phi(t, t_1)$ we numerically integrate $\dot{x}$ and ϕ	True False
M4LO2A	Which of the following is NOT an assumption of the Single Shooting Method as discussed in this module?	$t_2 - t_1$ is fixed We target both and $\underline{r}_d(t_2)$ and $v(t_2)$ $\delta\underline{r}(t_1) = 0$ $\underline{r}_d(t_2)$ is fixed
M4LO2B	How does the Single Shooting Method described in this module solve for an optimal trajectory?	By pushing the error to zero By minimizing the time of the maneuver By maximizing the time of the maneuver
M4LO3A	Compared to the indirect method, the direct method… (Partial credit awarded)	Select one of each pair: Pair 1: • First discretizes then optimizes • First optimizes then discretizes Pair 2: • Is less accurate • Is more accurate Pair 3: • Is harder to pose and solve • Is easier to pose and solve
M4LO3B	Compared to the collocation method, the shooting method of discretization… (Partial credit awarded)	Select one of each pair: Pair 1: • Is function approximation • Is simulation based
		Pair 2: • Has simple control and/or no path constraints • Has complicated control and/or path constraints
M4LO4	An optimization problem can be initialized by first solving a simpler problem and using the result as initial conditions	True False

Name in Paper	Question	Answer Choices
M5LO1A	Which of the following is NOT an aspect of mission planning?	Creating activity timelines
		Coordinating science, trajectory, and engineering plans
		The daily managing of activities
		Creating contingency plans
M5LO1B	What does navigation and orbit control deal with?	Establishing communication links with the spacecraft
		The location of a spacecraft and the planning maneuvers
		The daily managing of activities
		Coordinating science, trajectory, and engineering plans

Pre-Quiz to Post-Quiz Analysis

The analysis results across each module for all participants and separately for men and women are in Table 7. Analysis results for each question separately for all participants are in Table 8, for men in Table 9, and for women in Table 10.

Table 7. Pre-quiz to post quiz analysis by module.

			Pre-Quiz		Post-Quiz			
Population	**Module**	***n***	***M***	***SD***	***M***	***SD***	***z***	***p***
All	1	283	0	0	0.399	0.491	190	<0.001
	2	138	0	0	0.703	0.459	0	<0.001
	3	101	0.149	0.357	0.535	0.501	109	<0.001
	4	77	0	0	0.610	0.491	28.5	<0.001
	5	52	0.019	0.139	0.712	0.457	0	<0.001
Men	1	228	0	0	0.425	0.495	16	<0.001
	2	114	0	0	0.693	0.463	0	<0.001
	3	83	0.157	0.366	0.530	0.502	69	<0.001
	4	65	0	0	0.600	0.494	10.5	<0.001
	5	43	0.023	0.152	0.721	0.454	0	<0.001
Women	1	49	0	0	0.286	0.456	39	<0.001
	2	20	0	0	0.750	0.444	0	<0.001
	3	16	0.125	0.342	0.563	0.512	4.5	<0.001
	4	11	0	0	0.636	0.505	3	<0.001
	5	8	0	0	0.625	0.518	0	<0.001

Legend
Insufficient power
Significant
Trending

Table 8. Pre-quiz to post-quiz analysis for all participants.

		Pre-Quiz		Post-Quiz			
Learning Objective	***n***	***M***	***SD***	***M***	***SD***	***z***	***p***
M1LO1	293	0.352	0.478	0.724	0.448	6050	**<0.001**
M1LO2A	283	0.176	0.382	0.951	0.217	819	**<0.001**
M1LO2B	283	0.163	0.370	0.731	0.444	1440	**<0.001**
M1LO2C	283	0.541	0.499	0.848	0.360	1365	**<0.001**
M1LO3	280	0.082	.274	0.937	0.244	668	**<0.001**
M1LO4	347	0.513	0.492	0.842	0.364	817.5	**<0.001**
M2LO1	176	0.028	0.167	0.977	0.150	0	**<0.001**
M2LO2	154	0.175	0.382	0.987	0.114	64	**<0.001**
M2LO3A	138	0.696	0.462	0.957	0.205	117.5	**<0.001**
M2LO3B	138	0.5	0.502	0.746	0.437	441	**<0.001**
M3LO1	123	0.577	0.496	0.675	0.471	253.5	0.526
M3LO2A	112	0.518	0.502	0.830	0.377	115	**<0.001**
M3LO2B	101	0.683	0.468	0.941	0.238	31	**<0.001**
M3LO2C	101	0.366	0.484	0.911	0.286	93	**<0.001**
M4LO1A	87	0.805	0.399	0.920	0.274	6.5	**0.005**
M4LO1B	87	0.030	0.274	0.931	0.255	121.5	**<0.001**
M4LO1C	87	0.828	0.380	0.931	0.255	36	**0.031**
M4LO2A	85	0.2	0.402	0.882	0.324	97.5	**<0.001**
M4LO2B	85	0.635	0.484	0.977	0.153	0	**<0.001**
M4LO3A	77	0.584	0.237	0.892	0.267	327	**<0.001**
M4LO3B	77	0.604	0.338	0.890	0.264	189.5	**<0.001**
M4LO4	77	0.948	0.223	1	0	0	*0.072*
M5LO1A	52	0.058	0.235	0.75	0.437	19.5	**<0.001**
M5LO1B	52	0.039	0.194	0.962	0.194	0	**<0.001**

Table 9. Pre-quiz to post-quiz analysis for men.

		Pre-Quiz		Post-Quiz			
Learning Objective	*n*	*M*	*SD*	*M*	*SD*	*z*	*p*
M1LO1	236	0.322	0.468	0.754	0.432	3529.5	**<0.001**
M1LO2A	228	0.171	0.377	0.974	0.160	285	**<0.001**
M1LO2B	228	0.180	0.385	0.75	0.434	930	**<0.001**
M1LO2C	228	0.579	0.495	0.860	0.348	712.5	**<0.001**
M1LO3	271	0.071	0.257	0.946	0.227	264	**<0.001**
M1LO4	140	0.522	0.494	0.856	0.349	493	**<0.001**
M2LO1	125	0.021	0.145	0.979	0.145	0	**<0.001**
M2LO2	114	0.168	0.375	0.984	0.126	52.5	**<0.001**
M2LO3A	114	0.675	0.470	0.965	0.185	84	**<0.001**
M2LO3B	100	0.491	0.502	0.746	0.437	286	**<0.001**
M3LO1	92	0.57	0.498	0.66	0.476	176	0.108
M3LO2A	83	0.503	0.503	0.837	0.371	105	**<0.001**
M3LO2B	83	0.687	0.467	0.940	0.239	26	**<0.001**
M3LO2C	73	0.398	0.492	0.928	0.261	49	**<0.001**
M4LO1A	73	0.822	0.385	0.932	0.254	5.5	**0.013**
M4LO1B	73	0.055	0.229	0.945	0.229	34	**<0.001**
M4LO1C	71	0.822	0.385	0.918	0.277	32	*0.076*
M4LO2A	71	0.211	0.411	0.901	0.300	54	**<0.001**
M4LO2B	65	0.634	0.485	0.972	0.167	0	**<0.001**
M4LO3A	65	0.590	0.241	0.892	0.277	231.5	**<0.001**
M4LO3B	65	0.569	0.341	0.885	0.276	124	**<0.001**
M4LO4	65	0.939	0.242	1	0	0	*0.072*
M5LO1A	43	0.070	0.258	0.767	0.428	16.5	**<0.001**
M5LO1B	43	0.047	0.213	0.953	0.213	0	**<0.001**

Legend
Insufficient power
Significant
Trending

Table 10. Pre-quiz to post-quiz analysis for women.

		Pre-Quiz		Post-Quiz			
Learning Objective	***n***	***M***	***SD***	***M***	***SD***	***z***	***p***
M1LO1	51	0.510	0.505	0.588	0.497	262.5	0.499
M1LO2A	49	0.225	0.422	0.837	0.373	78	**<0.001**
M1LO2B	49	0.061	0.242	0.653	0.481	34	**<0.001**
M1LO2C	49	0.367	0.487	0.837	0.373	45	**<0.001**
M1LO3	77	0.104	0.307	0.896	0.307	66	**<0.001**
M1LO4	69	0.5	0.485	0.783	0.416	40	**<0.001**
M2LO1	31	0.032	0.180	0.968	0.180	0	**<0.001**
M2LO2	24	0.167	0.381	1	0	0	**<0.001**
M2LO3A	20	0.75	0.444	0.9	0.308	3	0.233
M2LO3B	20	0.5	0.513	0.75	0.444	10	0.110
M3LO1	20	0.6	0.503	0.8	0.414	3.5	0.129
M3LO2A	17	0.647	0.493	0.765	0.437	0	0.346
M3LO2B	16	0.625	0.5	0.938	0.25	0	**0.037**
M3LO2C	16	0.25	0.447	0.813	0.403	6	**0.008**
M4LO1A	13	0.769	0.439	0.846	0.376	0	1
M4LO1B	13	0.231	0.439	0.846	0.376	13	**0.024**
M4LO1C	13	0.846	0.376	1	0	0	0.346
M4LO2A	13	0.154	0.376	0.769	0.439	5.5	**0.013**
M4LO2B	13	0.615	0.506	1	0	0	**0.037**
M4LO3A	11	0.576	0.216	0.879	0.225	8.5	*0.054*
M4LO3B	11	0.773	0.261	0.909	0.202	8	0.299
M4LO4	11	1	0	1	0	0	NA
M5LO1A	8	0	0	0.625	0.518	0	0.037
M5LO1B	8	0	0	1	0	0	0.005

Legend
Insufficient power
Significant
Trending