Remote learning slightly decreased student performance in an introductory undergraduate course on climate change

Sattik Ghosh1,2, Stephanie Pulford1,4 & Arnold J. Bloom3

Public understanding about complex issues such as climate change relies heavily on online resources. Yet the role that online instruction should assume in post-secondary science education remains contentious despite its near ubiquity during the COVID-19 pandemic. The objective here was to compare the performance of 1790 undergraduates taking either an online or face-to-face version of an introductory course on climate change. Both versions were taught by a single instructor, thus, minimizing instructor bias. Women, seniors, English language learners, and humanities majors disproportionately chose to enroll in the online version because of its ease of scheduling and accessibility. After correcting for performance-gaps among different demographic groups, the COVID-19 pandemic had no significant effect on online student performance and students in the online version scored 2% lower (on a scale of 0–100) than those in the face-to-face version, a penalty that may be a reasonable tradeoff for the ease of scheduling and accessibility that these students desire.
Support for policies that address climate change depends on an educated populace and its comprehension of difficult scientific concepts. To forestall action on climate change, the government of the United States in 2017 removed hundreds of webpages about climate change from the websites of federal agencies and departments and scrubbed the term “climate change” from thousands of others. Only four years later after a new administration took office was this censoring reversed. Also troubling is that during this period some reliable sources of information became less suitable for educational purposes; for example, the Assessment Reports of the United Nations Inter-governmental Panel on Climate Change (IPCC) grew exponentially: the reports for Working Group I about the Physical Science expanded from 414 pages in 1990 to 3949 pages in 2021, for Working Group II about Impact and Adaptation from 296 pages in 1990 to 3675 pages in 2021, and for Working Group III about Mitigation from 438 pages in 1995 to 2913 pages in 2022 (Fig. S1). To address these issues, the National Science Foundation of the United States, as part of DUE 09-50396 “Creating a Learning Community for Solutions to Climate Change”, funded establishment of a nationwide cyber-enabled learning community to develop web-based curricular resources for teaching undergraduates about climate changes. One product of this project was a multi-disciplinary, introductory online course that is freely available to the public.

This course was pressed into broader service as schools struggled to provide online materials at the onset of the COVID-19 pandemic. Institutions of higher education received criticism for adopting such courses, largely based on the assumption that online instruction is inherently inferior to that delivered face-to-face. The issue has become whether the convenience and safety of online instruction outweighs the possibility of inferior learning outcomes for today’s undergraduates.

Although the pandemic infused topical urgency into this issue, it is hardly new. The efficacy of distance learning has been debated since the External Programme of the University of London first offered a correspondence course in 1858. Correspondence courses have historically been driven by equity concerns for working people and women who could not access colleges, yet they have historically been perceived as inferior to on-campus education.

Online learning opportunities experienced explosive growth with the advent of widespread internet access and expanded credentialed university programs. In the United States alone, enrollments in online college courses rose from 1.6 million students in 2002 to 6.9 million students in 2018. During 2018, 35.3% of undergraduates in the United States took at least one course online, and half of these students took online courses exclusively. This boom in online offerings coevolved with active learning and EdTech, and today’s online courses tend to be highly interactive, even when asynchronous or self-paced. Indeed, instructional design proponents often position today’s courses with either different subject matter, those taught by different instructors, or those having relatively small numbers of students. Because many of these studies are based on dissimilar courses, they have had no opportunity to isolate students’ enrollment decisions to a simple choice between an online and a face-to-face version, nor provide appropriate analysis to account for the potential effects of underserved groups’ preference for one format over the other.

It follows that prior pseudo-experimental studies have also been unable to examine the critical concern that underlies all comparisons of online and face-to-face courses: if a tradeoff does exist between a face-to-face course’s baseline educational outcomes and an online course’s extended accessibility, is the decrease in learning outcomes worth the attendant increase in accessibility? These tradeoffs have been imbued with new urgency because of the COVID-19 pandemic during which universities and students seek to make difficult decisions about how to ensure safe course access while optimizing learning outcomes during the disruption of unfettered public life.

In this study, we seek to dissect student choice, student outcomes, and the tradeoffs between online and face-to-face courses at a large research university, through a post-hoc pseudo-experiment. We analyzed student performance versus their attributes for 1790 undergraduates of the University of California at Davis (a public research university) who enrolled in either an online or face-to-face version of the introductory course about climate change (for a syllabus of the course see Table 1). Each demographic group had more than 100 students enrolled in the online and face-to-face versions (Fig. 1). Each year, both versions of the course were taught by a single instructor, thus, minimizing major confounding variables such as instructor bias, course design, content differences, and other aspects that might influence student choices and outcomes. Before the COVID-19 pandemic, we offered both versions of the course during eight Winter quarters and offered only the online version during six Spring quarters. In Winter and Spring quarters 2021, during the pandemic, we offered the course only online. For two concurrent course offerings in Winter 2019—one face-to-face and one online—and for COVID-19 pandemic-induced online course offerings in Winter 2021 and Spring 2021, we surveyed the students about their past experiences with online learning and how these
Table 1 Syllabus: global climate change SAS 25 (face-to-face) and 25v (online).

| Activity                  | Hours per week |
|---------------------------|----------------|
| Readings                  | 2.5            |
| Lectures: Live and Mini   | 3.0            |
| Discussion                | 1.0            |
| Quiz or Essay             | 1.5            |
| Exercise or Essay         | 4.0            |
| Total                     | 12.0           |

Textbook: Climate Change: Causes, Consequences, and Solutions. Free online at https://indd.adobe.com/view/7eafc24d-9151-4493-85d2-cb32fe5a2a51. Please read the simple directions on navigating through this textbook at How to Dance.

SAS 25v also requires: A headset (any combination of headphones and microphone), a webcam, high speed, reliable connection to the internet (DSL, cable, on-campus, etc.)

| Week | Topic                      | Video       | Reading      | Assignments |
|------|---------------------------|-------------|--------------|-------------|
| 1    | Intro to climate research | Lecture 1-3 | Chapt. 1     | Exercise 1  |
| 2    | History of Earth's climate| Lecture 4-7 | Chapt. 2     | Essay 1     |
| 3    | Causes of climate         | Lecture 8-11| Chapt. 3     | Exercise 2  |
| 4    | Climate models            | Lecture 12-17| Chapt. 4    | Essay 2     |
| 5    | Climate & biosphere       | Lecture 18-22| Chapt. 5 & 6| Exercise 3  |
| 6    | Transportation            | Lecture 23-27| Chapt. 7    | Essay 3     |
| 7    | Electricity & other sectors| Lecture 28-36| Chapt. 8 & 9| Exercise 4  |
| 8    | Climate change economics  | Lecture 37-42| Chapt. 10   | Essay 4     |
| 9    | Environmental law         | Lecture 43-46| Chapt. 11   | Exercise 5  |
| 10   | Culture & climate change  | Lecture 47-48| Chapt. 12   | Essay 5, Final |

Exercise Assignments: These should prepare you for writing the essay assignments. You will have one learning exercise due every other week and we will review your answers during discussion sections. These are typically 2 to 3 pages in length.

| Week | Topic | Topic | Reading | Assignments |
|------|-------|-------|---------|-------------|
| 1    | Climate Trends: Examine temperature graphs for climate change trends in Davis, CA | Lecture 1-3 | Chapt. 1 | Exercise 1 |
| 2    | How to Read a Scientific Article: Critically read and summarize a scientific article on a GCM | Lecture 4-7 | Chapt. 2 | Essay 1 |
| 3    | Climate Change and Species: Discover how polar bears are affected by climate change | Lecture 8-11 | Chapt. 3 | Exercise 2 |
| 4    | Carbon Footprint: Calculate your contributions to GHG emissions | Lecture 12-17 | Chapt. 4 | Essay 2 |
| 5    | Countries and Climate Change: Discover how the USA influences climate change actions | Lecture 18-22 | Chapt. 5 & 6 | Exercise 3 |

SAS 25v also requires: A headset (any combination of headphones and microphone), a webcam, high speed, reliable connection to the internet (DSL, cable, on-campus, etc.)

| Exercise Assignments | Reading | Assignments |
|----------------------|---------|-------------|
| 4                   | Exercise 1 | Essay 1 |
| 8                   | Exercise 2 | Essay 2 |
| 9                   | Exercise 3 | Essay 3 |
| 10                  | Exercise 4 | Essay 4 |
| 11                  | Exercise 5 | Essay 5, Final |

Grading: Exercises (each 3% of the grade for a total of 15%), essays (each 8% of the grade for a total of 40%); deduct 5% of the grade per day for late assignments. Online Quizzes: one per week (each 1% of the grade for a total of 10%). Midterm: 25 Multiple choice questions and an essay about the greenhouse effect (10%); Final: 50 Multiple choice questions and an essay about what we should do, if anything, to address climate change (15%); Discussion section presentations and participation (each 1% of the grade for a total of 10%).

Results

Before the COVID-19 pandemic (2013 through 2020), we taught both the online and face-to-face versions of the course concurrently during Winter quarters and only the online version during most Spring quarters. During the pandemic in Winter and Spring quarters 2021, we taught only the online version of the course. We found no significant difference in the grades for students enrolled in the online version before and during the pandemic (Table S1); therefore, in a subsequent analysis that compared the grades between the online and face-to-face versions, we merged the data for Winter and Spring 2021 with earlier data from the online version from 2013 to 2020 (Table 2).

Overall, students performed poorer in the online version. Humanities students, Underrepresented Minorities (i.e., African Americans, American Indian/Alaska Native, Chicana/Latinx including Puerto Rican, and Pacific Islander including Native Hawaiian), and Seniors (i.e., students in their last year) received significantly lower grades than other students enrolled in either the online or face-to-face formats (Table 2). The factor that consistently had the largest influence on a student’s grade in this course was the student’s overall Grade Point Average (GPA) (Table 2, S1, S2, S3 and S5), demonstrating that students, who on average performed well in all their courses, performed well in this course. Students who spoke Mixed Languages at Home and those who were the First Generation to attend college received slightly higher grades than other students. Students from Low Income Families (i.e., annual family income of less than $80,000) received grades that did not differ significantly from other students.

One issue of concern is that students could choose which version they took in Winter quarters before the Covid pandemic: that is, assignment of a student to a treatment was nonrandom. Disentangling the influence of format selection on student performance from the influence of course format itself proved challenging. We took several approaches to account for the influence of format selection, and some of them indicated that
students’ choice of course format was a major factor in their grades (see Supplementary Materials: Format Selection).

When students could choose between course formats (Winter quarters before the pandemic), student demographics and average grades differed between formats. Students self-identifying as Women, seniors, and humanities majors disproportionately chose to enroll in the online version of the course (Fig. 1). Students during these quarters performed poorer in the online version, and notably humanities students and underrepresented minorities who enrolled in either the online or face-to-face formats received significantly lower grades than other students (Table S2).

One approach for disentangling the influence of student choice of format from those of course format was to conduct a well-controlled regression comparing the outcomes of students who chose the face-to-face version in the Winter quarters before the pandemic with those of students who took the course when only the online version was offered (i.e., Spring quarters before the pandemic). Total course grade (out of 100), when regressed on course format but performed worse in the online version on material that was independent of course format but performed worse in the online version on material.

Table 2 Regressions of course grade in an introductory, undergraduate course on climate change for all quarters.

| Variable                  | Model 1          | Model 2          | Model 3          |
|---------------------------|------------------|------------------|------------------|
| Intercept                 | 86.48***         | 87.83***         | 52.89***         |
| Online                    | -2.07***         | -1.99***         | -2.00***         |
| Mixed Lang. Home          | -0.12            | 1.98**           |                  |
| Non-English Home          | -0.96            | -0.02            |                  |
| Male                      | -0.75            | -0.12            |                  |
| Senior                    | -1.11            | -1.90**          |                  |
| Humanities                | -4.91***         | -5.80***         |                  |
| GPA                       | 11.54***         |                  |                  |
| URM                       | -4.09***         |                  |                  |
| Low Income                | -0.98            |                  |                  |
| First Gen                 | 1.34*            |                  |                  |

*For model 1, **P < 0.01, ***P < 0.001, and ****P < 0.0001.

Discussion
This study offers both methodological and topical insights. We identified differences in outcomes between course formats using well-controlled regression analyses of various subsets of the data. The performance of a student in this course depended most strongly on the overall Grade Point Average of the student (Table 2, S1, S2, S3, and S5), indicating that this course required proficiency in the same skills as other college courses.

The outcomes of the students who only had an option of the online format (i.e., Spring quarters before the pandemic) did not differ significantly from those of the students who selected the face-to-face version in Winter quarters before the pandemic (Table S3). Perhaps our most illuminating findings were that differences in outcomes between formats were significant for the writing assignments and exams, but not the quizzes. We hypothesized that because the quizzes were based entirely on online material, online students would not be disadvantaged. This proved to be the case (Fig. 2). Poorer participation through lower
events, year-abroad programs, or social distancing are well served by an online format.

Materials and methods
Table 1 provides the syllabus for the course. During Winter quarters 2013 through 2015 and 2017 through 2020, the primary instructor (A. J. Bloom) taught both the online and face-to-face versions concurrently, whereas in Winter 2016, a second instructor (Dr. Margaret Swisher-Mantor) taught both versions. The primary instructor taught only the online version during Winter quarter 2021 and Spring quarters of 2013, 2014, 2015, 2017, 2018, and 2021.

All elements of the course are available for free at https://www.climatechangeourse.org/, including a free multi-media textbook at https://indd.adobe.com/view/7eac24d-9151-4493-85d2-cb3fe5a2a51 that is regularly updated. Before 2016, a printed version of the textbook was available for purchase (23). The course covered the (a) physical sciences (history of Earth’s climate, causes of change, and predictions), (b) biological consequences (direct effects of rising CO2, global warming, precipitation changes, and ocean acidification), (c) technological mitigation and adaptation, (transportation, electricity generation, buildings, and geoengineering), and (d) social sciences (economics, law, and social change). Lecture materials were available in 48 short (less than 15 min) videos or presented two times per week in live lectures of 50-minute duration that were streamed live over the internet or posted as videos on the course website on the same day. Students—be they enrolled in the online or face-to-face version of the course—had access to the lecture materials in all forms. Students had a weekly mandatory, 50-minute discussion section that met either synchronously online via video conferencing (Adobe Connect or Zoom) with up to 15 students per section or a choice of 8 different meeting times or face-to-face with up to 25 students per section with a choice of 4 different meeting times.

Assessments of the students included (a) weekly quizzes drawn randomly from a pool of about 50 questions available as a practice quiz in the multi-media textbook, (b) participation in the weekly discussion sections based mostly on attendance, (c) weekly written assignments that alternate between exercises and exercises, (d) a proctored midterm exam with 25 multiple choice questions including those from the same question pools as the weekly quizzes and a few from the lectures and one essay question in which a student explained the greenhouse effect, and (e) a proctored final exam with 50 multiple choice questions including those from the same question pools as the weekly quizzes and a few from the lectures and one essay question in which a student explained what they would do, if anything, about climate change and why they would choose this course of action.

We predicted that performance on quizzes would not differ between students in the online and face-to-face versions of the course because the quizzes are based entirely on the textbook, whereas performance on the other assessments would be more dependent on course format because these rely more on information in lectures and discussion sections.

Statistics. We fit the three models using an ordinary least squares linear regression (function lm) implemented in R version 4.0.3 (R Core Team, 2013):

Model 1: \[ G_i = b_0 + b_1(\text{Format, or Covid}) + e_i \]
Model 2: \[ G_i = b_0 + b_2(\text{Format, or Covid}) + b_3\text{MixedLang} + b_4\text{NoneEngLang} + b_5\text{Male} + b_6\text{Senior} + b_7\text{Humanities} + e_i \]
Model 3: \[ G_i = b_0 + b_2(\text{Format, or Covid}) + b_3\text{MixedLang} + b_4\text{NoneEngLang} + b_5\text{Male} + b_6\text{Senior} + b_7\text{Humanities} + b_8\text{GPA} + b_9\text{URM} + b_{10}\text{LowIncome} + b_{11}\text{FirstGen} + e_i \]

where \( G_i \) is the grade for student \( i \) on a 0 to 100 scale. In these models, the variable of interest is Format (a binary indicator coded as 1 for the online format and 0 for the face-to-face format) or Covid (a binary indicator coded as 1 for the course offerings in 2021 and 0 for the previous years). The coefficient \( b_1 \) represents the marginal effect of the online course format or pandemic on grade. Model 1 yields a \( b_1 \) value that represents the unconditional difference in mean student grade between the online and face-to-face versions of the course or the difference in mean student grade during the pandemic and before the pandemic. This value is an offset from \( b_0 \), which represents the mean student grade in the face-to-face format or before the pandemic. Models 2 and 3 yield \( b_1 \) values that represent the difference in mean student grade between the online and face-to-face versions of the course or the difference in mean student grade during and before the pandemic after accounting for demographic makeup and for previous academic achievement of the students in each format or each time period.

The function lm calculated (a) ordinary least squares estimates of the coefficients (for COVID, Online, Mixed Lang. Home, Non-English Home, Male, Senior, Humanities, URM, Low

![](https://www.nature.com/commsev)
Income, and First Generation designated to be 0 or 1 and for GPA which varied between 0 and 4) with standard errors, (b) $t$ values for the Wald test of the hypothesis $H_0: \beta_1 = 0$, and (c) the associated $P$ values. A $P \leq 0.05$ was considered significant.

**Reporting summary.** Further information on research design is available in the Nature Research Reporting Summary linked to this article.

**Data availability**

All materials for the course including the multi-media textbook are publicly available for free. Student grades and demographic information in the United States are confidential according to the FERPA (Federal Educational Rights and Privacy Act; https://www2.ed.gov/policy/gen/gcl/ipco/ferpa/index.html). One can provide such data to the public only if aggregated for large groups (e.g., > 10 students). The authors judged that a dataset for large groups would duplicate the information already presented in Table 2, and $P \leq 0.05$ was considered significant.

Received: 24 March 2022; Accepted: 25 July 2022; Published online: 06 August 2022

**References**

1. Bloom, A. J. Climate Change: Causes, Consequences, and Solutions, https://climatechangeonlinecourse.org/ (2022).
2. Simpson, M. & Anderson, B. History and heritage in open, flexible and distance education. *J. Open Flexible Distance Learn.* 16, 1–10 (2012).
3. Bettinger, E. & Loeb, S. Promises and pitfalls of online education. *Evidence Speaks Reports* 2, 1–4 (2017).
4. Protopassitis, S. & Raum, S. Does online education live up to its promise? A look at the evidence and implications for federal policy. *Center for Educational Policy Evaluation* (2019).
5. Allen, I. E. & Seaman, J. Changing Course: Ten Years of Tracking Online Education in the United States. (Babson Survey Research Group and Quahog Research Group, LLC, 2013).
6. De Brey, C., Snyder, T. D., Zhang, A. & Dillow, S. A. Digest of Education Statistics 2019 (NCES 2021-009). 55th edn (National Center for Education Statistics, Institute of Education Sciences, U.S. Department of Education, 2021).
7. Crews, T. B., Wilkinson, K. & Neill, J. K. Principles for good practice in undergraduate education: Effective online course design to assist students’ success. *J. Online Learn. Teach.* 11, 87–103 (2015).
8. Grant, M. R. & Thornton, H. R. Best practices in undergraduate adult-centered online learning: Mechanisms for course design and delivery. *J. Online Learn. Teach.* 3, 346–356 (2007).
9. McGee, P., Windes, D. & Torres, M. Experienced online instructors: beliefs and preferred supports regarding online teaching. *J. Comput. Higher Educ.* 29, 331–352 (2017).
10. Greenhow, C. & Galvin, S. Teaching with social media: evidence-based strategies for making remote higher education less remote. *Inf. Learn. Sci.* 121, 513–524 (2020).
11. Kaupp, R. Online penalty: The impact of online instruction on the Latino-White achievement gap. *Journal of Applied Research in the Community College* 19, 3–11 (2012).
12. Kizilec, R. F. & Halawa, S. in Proceedings of the Second (2015) ACM Conference on Learning@ Scale. 57-66.
13. Means, B., Toyama, Y., Murphy, R., Bakia, M. & Jones, K. Evaluation of Evidence-Based Practices in Online Learning: A Meta-Analysis and Review of Online Learning Studies, http://www2.ed.gov/rschstat/eval/tech/evidence-based-practices/finalreport.pdf (2010).
14. Jaggars, S. & Bailey, T. Effectiveness of fully online courses for college students: Response to a department of education meta-analysis. (Community College Research Center, New York, NY, 2010. http://files.eric.ed.gov/fulltext/ED512277.pdf).
15. Xu, D. & Jaggars, S. S. Performance gaps between online and face-to-face courses: Differences across types of students and academic subject areas. *J. Higher Educ.* 85, 633–659 (2014).
16. Amro, H. J., Mundy, M.-A. & Kupczynski, L. The effects of age and gender on student achievement in face-to-face and online college algebra classes. https://files.eric.ed.gov/fulltext/ED5105678.pdf (2015).
17. Johnson, H. P., Mejia, M. C. & Cook, K. Successful online courses in California’s community colleges. 24 (Public Policy Institute, 2015).
18. Wladis, C., Conway, K. & Hachey, A. C. Using course-level factors as predictors of online course outcomes: a multi-level analysis at a US urban community college. *Stud. Higher Educ.* 42, 184–200 (2017).
19. Bettinger, E. P., Fox, L., Loeb, S. & Taylor, E. S. Virtual classrooms: How online college courses affect student success. *Am. Econ. Rev.* 107, 2855–2875 (2017).
20. Faulconer, E. K., Griffith, J., Wood, B., Acharya, S. & Roberts, D. A comparison of online, video synchronous, and traditional learning modes for an introductory undergraduate physics course. *J. Sci. Educ. Technol.* 27, 404–411 (2018).
21. Faulconer, E. K., Griffith, J. C., Wood, B. L., Acharya, S. & Roberts, D. L. A comparison of online and traditional chemistry lecture and lab. *Chem. Educ. Res. Pract.* 19, 392–397 (2018).
22. Hart, C. M. D., Friedmann, E. & Hill, M. Online course-taking and student outcomes in California community colleges. *Educ. Finance Policy* 13, 42–71 (2018).
23. Spencer, D. & Temple, T. Examining students’ online course perceptions and comparing student performance outcomes in online and face-to-face classrooms. *Online Learn.* 25, 233–261 (2021).
24. Mead, C. et al. Online biology degree program broadens access for women, first-generation to college, and low-income students, but grade disparities remain. *PLOS ONE* 15, e0243916 (2020).
25. Bloom, A. J. Global Climate Change: Convergence of Disciplines. (Sinauer Assoc., 2010).

**Author contributions**

Conceptualization: A.J.B., S.G., S.P. Methodology: A.J.B., S.G. Funding acquisition: A.J.B., S.G. Writing—original draft: A.J.B. Writing—review & editing: A.J.B., S.G., S.P.

**Competing interests**

The authors declare no competing interests.

**Additional information**

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-022-00506-6.

**Correspondence**

and requests for materials should be addressed to Arnold J. Bloom.

**Peer review information** Communications Earth & Environment thanks Aldo Bazan-Ramirez and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Heike Langenberg and Clare Davis.

**Reprints and permission information** is available at http://www.nature.com/reprints

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s) 2022