COVID-19 Pandemic Impacts on Student Learning in Undergraduate Mineralogy

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ABSTRACT

Online and hybrid instruction as a response to the coronavirus (COVID-19) pandemic presented specific challenges in geosciences due to the role of laboratory and field activities. We carried out a research study on student learning in undergraduate mineralogy at a large public research university in the United States over a 4-year period including pre-pandemic in-person instruction and during pandemic online and hybrid instruction. A total of 94 students participated in course activities and mixed-method surveys. Survey results indicated that during the pandemic, students entered the course with lower sense of belonging relative to pre-pandemic students. Despite challenges related to instruction and student learning since 2020, the pandemic did not necessarily produce worse learning outcomes for mineralogy students as measured by course assessments. Structured course delivery and opportunities for interaction can offset challenges resulting from global emergencies.

INTRODUCTION

The global coronavirus (COVID-19) pandemic required a rapid shift to online learning in Spring 2020 for all levels of education, including universities (Ali, 2020). This shift in teaching modality presented both opportunities and difficulties for faculty and students alike. While faculty needed to rapidly modify face-to-face materials for use in online contexts, students were faced with learning in isolation rather than in communities with other students. Both faculty and students gained proficiency in technology use as well as appreciation for the flexibility that became integral to successful teaching and learning during the height of pandemic isolation (Kohnke & Moorhouse, 2021). Many universities rose to the challenge the pandemic presented, enhancing access to synchronous and asynchronous technologies and offering training for faculty and students (Turnbull et al., 2021). Recent studies suggest university education has fundamentally changed, with much more focus on online and hybrid (a mix of online and face-to-face) instruction now than before the pandemic (e.g., Ashour et al., 2021). The pandemic also led to an important shift in how faculty integrate digital and physical learning resources with many courses retaining a hybrid format even as pandemic isolation waned (Singh et al., 2022). However, access to digital tools and technologies is inequitable, with some students unable to access online learning, particularly in countries in the Global South (OECD, 2020). This so-called "digital divide" was felt most strongly by students and faculty – in all nations – who were socioeconomically disadvantaged in terms of access to computers, internet, and software (Mula-Falcón et al., 2023; Roy & Brown, 2022) as well as for those who experienced disparities in technological preparedness (Eri et al., 2021).

While most faculty adapted to online communication tools for instantiating higher education classrooms, many struggled with the pivot from physical to digital delivery as well as implementing effective student assessment tools within the online space (Herodotou et al., 2022; Oliveira et al., 2021; Sedaghatjou et al., 2023). Many faculty felt that they were unable to effectively support students in online settings (Ramlo, 2021). Finally, faculty professional development in effective use of digital tools remains necessary even as higher education has shifted back towards physical classrooms (Romero-Hall & Jaramillo Cherrez, 2023).

Whether instruction and learning could easily move online during the pandemic was highly dependent on disciplinary teaching norms and student needs (Ramlo, 2021). Although online and remote teaching were actively developed and researched before the pandemic, many science, engineering and mathematics instructors had no experience with online teaching (Seaman et al., 2021). Within the sciences and related fields, some faculty struggled to move past traditional notions of what science instruction needed to look like for learning to occur. In one study of mathematics courses, instructors were seemingly unaware of challenges faced by students such as social isolation and lack of structured learning in the online context, or did not consider these challenges to be within their responsibility to address (Radmehr & Goodchild, 2022). In other spaces, faculty embraced a range of active learning tools available in online spaces that could enhance and encourage student engagement with content (Rossi et al., 2021). Faculty in environmental education reported mixed experiences with pandemic online learning (Nichols et al., 2022). Positives included enhanced access to experiences that became free or very low cost during the pandemic (i.e., conferences) to negatives such as needing more time to facilitate student engagement (Nichols et al., 2022).

Faculty and students alike were uncertain about how critical skills could be learned in an online setting. Some geoscientists felt laboratory and field skills could not be acquired online (Alías et al., 2023; Andrews et al., 2020) although virtual field trips and virtual laboratories offer digital opportunities were found to be effective even before the pandemic. For example, pre-pandemic studies indicated that online geoscience instruction using virtual tools was as effective as hybrid or in-person instruction (Becerra et al., 2015; Herodotou et al., 2018; Whalley et al., 2011). Post-pandemic studies of virtual field trips also suggest similar outcomes to in-person trips. Virtual field trips can open access to science more broadly and prepare for a future pandemic or other global emergency (Mercer et al., 2023).

Alangari (2022) points out the need for comparative studies of face-to-face and online instruction to better understand the affordances of each approach as well as the ways the two approaches can be blended into more effective hybrid instruction. The current study focuses on considering the efficacy of instruction before, during, and after the COVID-19 pandemic forced instruction to change into a completely online setting at the same time as students and instructors faced acute personal and professional challenges.

Undergraduate Mineralogy

This study focuses on undergraduate mineralogy as a specific context. Undergraduate mineralogy is essential preparation for geoscience majors and many environmental science majors, required in nearly all programs in the US as a gateway course to upper-level Earth materials and field courses (Benbow & Balanon, 2022; Grissom et al., 2015; Manzanares et al., 2023). This subject includes several skills considered key for geoscientists including identification of natural materials in the field and using laboratory equipment, and spatial reasoning for interpreting 3-dimensional crystal structures and their impact on physical and chemical behavior at many scales. 84% of US undergraduate mineralogy courses incorporate a laboratory component and 33% contain a field component (Benbow & Balanon, 2022).

When we transitioned to online teaching in response to the COVID-19 pandemic, we were two years into a study of impacts of student identity, affect, and spatial reasoning skills on performance in mineralogy and career trajectory. Having obtained pre-pandemic baseline data, we were given a unique opportunity to understand how course modality and global stress can impact learning.

Thus, this study addresses the primary question: *How has student learning in undergraduate mineralogy been impacted, if at all, by the COVID-19 pandemic?* In this context, student learning is measured by performance on homework, laboratory activities, and exams. We focus on comparison between three groups of students taught Pre-COVID (2018, 2019) face-to-face, in COVID Year 1 (2020) online, and in COVID Year 2 (2021) both online and face-to-face (hybrid). Recognizing that multiple individual variables may mediate group differences, a secondary question considers: *In what ways, if any, do individual memory, spatial visualization, and affective variables mediate differences in learning across the three groups?* Finally, these quantitative results are contextualized based on Likert-type and open-ended surveys of student perceptions.

ABOUT THE COURSE

Research was situated in a 300-level (typically second or third year) mineralogy course serving 20-40 students per year. The course is required for and almost exclusively composed of geoscience and environmental science majors. In 2018 and 2019 (Pre-COVID), the course was held in-person with three 50-minute lecture periods per week plus a weekly 110-minute laboratory session (sections of up to 16 students). During 2020 (COVID Year 1), the course ran fully online, with one mandatory, synchronous 50-minute meeting per week over Zoom plus asynchronous lecture videos and exercises delivered over an online learning management system (DesireToLearn, hereafter referred to as D2L) and optional laboratory and office hour Zoom sessions. In 2021 (COVID Year 2), the course ran in a hybrid/flexible mode, with in-person labs (alternative online lab assignments available on request on an individual lab basis) and one mandatory synchronous 50-minute meeting in-person or online plus asynchronous lecture videos. Assessment also shifted weight from in-person exams before the pandemic to take-home assignments during the pandemic (Table 1).

At least once per week, lecture sessions included activities such as quizzes, demonstrations, or problem-solving sessions in small groups. Examples of materials from course assessments are shown in Figure 1. In-person classes (2018-2019) included one or more class periods working with block models to demonstrate and identify point group symmetry. For the online version of these classes, physical models were replaced by practice using virtual models in Euhedra software (Tislar, 2020). For the hybrid/flexible mode (2021), students chose whether to attend in-person or online and were offered both block models and software options for practice during class sessions. Assessments for the online version of the course (2020) included exercises using virtual models to identify symmetry in simulated objects. Homework assignments allowed for both formative assessment on practice attempts and summative assessment of the students' achievement on the final attempt. Laboratory assignments covered optical and hand sample mineral identification, analysis of X-ray diffraction and electron microprobe data, and phase diagrams. Laboratory assignments were delivered and graded by a teaching assistant.

Before designing the online version of the course, the instructor (Dorfman) participated in 5-day online training. Lessons included an introduction to online teaching and universal design for learning; backwards design, outcomes and structures; assessment (co-taught by Libarkin); engagement and interaction; and technology tools.

Many discipline-specific materials for online teaching of mineralogy and Earth materials were shared as part of a community effort in summer 2020 (Andrews et al., 2020). Online assignments were adopted from Virtual Field Trips (Arizona State University, n.d.), Earth Optics Mineralogy (Tramontano, 2015), Mineral ID Practical Online Study Guide (Brande, 2019), and Mineral Physical Properties and Identification lab (Harwood, 2017). Existing laboratory materials were adapted for online delivery by incorporating interactive content from the UK Virtual Microscope (The Open University, n.d.), Video Atlas of Minerals in Thin Section (Mazdab, 2015), and Sketchfab 3D model collections (West Virginia University, n.d.). Both before and during the period of instruction impacted by the pandemic, laboratory exercises employed software for visualizing crystal structures such as VESTA (Momma & Izumi, 2011).

In response to the constraints of online instruction and inspired by instructor training, we developed a semester-long project for the course to promote student interaction and engagement in the online mode and to develop communication skills, creativity, and higher-order thinking. The project was composed primarily of discussions hosted on D2L. The discussions largely replaced the exam component of the course assessments. In the second week of the semester, each student chose a mineral to study. Students submitted weekly posts to the D2L discussion boards in response to a writing prompt and commented on each other's posts. Discussion topics generally coordinate with the learning content in lecture/homework/lab for the week, for example: after learning about phase diagrams in class, students were asked to search scientific literature for a phase diagram that includes their mineral, and to apply what they had learned to describe what this diagram indicates about pressure-temperature-composition conditions of their mineral's stability. Some discussion topics address broader applications of mineralogy, for example: students were asked to research the price of their mineral, and its applications to human industry and daily life. At the end of the semester, students summarized their research. In the COVID Year 1, the summary was presented to the class in a medium of the student's choice (typically a recorded PowerPoint presentation but students also created watercolor art and a science fiction story). In COVID Year 2, the summary took the form of a scientific presentation-style abstract.

THEORETICAL FRAMEWORK

This research study draws from both cognitive science and socio-cognitive career theory. Following a study by Hambrick et al. (2012), this work considers the role working memory and spatial visualization play in mineralogy learning. Following that work, working memory is defined as the cognitive ability to retain and use information in the short term and can be related to cognitive processing of complex information. Spatial visualization is defined as the cognitive ability to imagine and manipulate multi-dimensional objects and information. Recognizing the importance of affective variables for learning, socio-cognitive theory (Bandura, 1986; Bong, 1999; Lent et al., 1994; Pugh et al., 2021) was also incorporated into the study with specific focus on self-efficacy, sense of belonging, academic career satisfaction, and academic goals. Self-efficacy is defined as "the belief that one can perform a novel or difficult tasks, or cope with adversity" (Schwarzer & Jerusalem, 1995). Sense of belonging is defined as "one's feelings of membership and acceptance" in a group of people, community, or environment (Good et al., 2012). Academic career satisfaction, a modified construct related to more general measures of career satisfaction (Greenhaus et al., 1990), is defined as the student's sense of accomplishment and progress in academic study (McCallum et al., 2018). Academic goals is a measure of students' motivation to achieve understanding and/or perform competitively (Elliot & McGregor, 2001). This work specifically recognizes the impacts of the pandemic in changing instruction, investigates if and how student performance in mineralogy changes as instruction changes, and considers any mediation resulting from cognitive, affective, and demographic independent variables.

METHODS

A mixed-methods approach following an explanatory design was undertaken (Creswell, 2014). In this study, quantitative data collection and analysis were used to answer each of the two research questions. Follow-on qualitative data collection provided additional insight intended to explain the quantitative results. We begin by locating the researchers and research and follow with description of participants, surveys, course-based measures, and analysis approaches.

Locating the Research

This work was undertaken by a mineralogy professor (SD), a geoscience education researcher (JL), and two undergraduates majoring in education (SB) and neuroscience (NS). SD's formal research training is in mineral physics. JL is formally trained in geophysics and human dimensions scholarship. We undertake this work from a postpositivist and constructivist perspective, meaning knowledge is perceived not as a fixed entity, but rather as being supported by the strongest evidence and subject to change as new evidence becomes available. This work utilized a purposeful sample of students enrolled in SD's course "Mineralogy and Geochemistry" with human subjects approval (Study #00000421). Participants consented to their participation.

Participants

Data were collected across four years (2018-2021). As noted, 2018 and 2019 are pooled together as Pre-COVID, 2020 is COVID Year 1, and 2021 is COVID Year 2. Information about the research study and informed consent was provided to students at the beginning of each semester. In all, 94 students enrolled in a mineralogy course at a large public research university in the United States agreed to participate in voluntary surveys and interviews to assess the relationship between affect, spatial visualization, working memory, course performance, and course modality. Each student was assigned a code to de-identify data before analysis.

Of 94 students, 83-89 (88-95%) participated in each homework assignment and 91 (97%) completed the course including the final exam. 75 (80%) completed pre-semester affect surveys, while 53 (56%) completed the post-semester affect surveys. Spatial-visual and working memory assessments were administered to 78 students in the Pre-COVID: Face-to-Face and COVID Year 2: Hybrid groups. Of these, 59 students (76%) participated in spatial-visual and working memory assessments. 47 (50%) participated in anonymous mid-semester feedback surveys.

Finally, 40 students responded to a demographics survey containing questions on race, ethnicity, gender, sexual orientation, and disability status. Among respondents 19-27 years in age, 90% described themselves as White or multiracial including White, 8% as Black or multiracial including Black, and 8% as Asian or multiracial including Asian. Respondents were 52.5% men, 45% women, and 2.5% nonbinary; 25% identified as lesbian, gay, bisexual, pansexual, queer, or asexual. 17.5% of respondents also identified as disabled. At the beginning of the semester, students indicated differing career interests (National Science Foundation, 2015): 95% of students strongly agreed or agreed that future career interests include basic or applied research, while the least popular career directions were development (56%) and teaching (61%). Students' interests were generally unchanged post-instruction. In general, the demographic characteristics of the three groups were not demonstrably different.

Surveys

Participants completed multiple surveys at different times throughout the semester (Table 2 and references therein). Working memory tests (multiple-choice) were administered near the beginning of the semester. Multiple-choice measures of spatial visualization and Likert-type measures of self-efficacy, sense of belonging, academic career satisfaction, and academic goals were administered twice near the beginning and end of the semester. Spatial visualization and working memory were not measured during COVID Year 1. As an exploratory study that pivoted to analysis of COVID-19 impacts, we did not complete a power analysis of importance to the study presented here.

Surveys administered at the middle of the semester probed Self-Assessment of progress towards each of the course learning goals (Likert-type). In addition, surveys included open-ended written response questions on perceptions of material difficulty, interests, and general feedback. These surveys were submitted anonymously and reported in aggregate for each course year. In addition, a pre-semester question introduced in response to the pandemic (COVID Years 1 and 2) prompted students to reflect on how they were doing in general as well as any supports they might need.

Course-Based Measures

Three course-based measures were used to assess overall student performance in mineralogy: 1) homework, 2) laboratory, and 2) final exam. Homework and laboratory were each calculated as a mean average across all assignments while final exam was an overall score. These three measures were used instead of overall course grade since the course grade inputs differed slightly across the three groups; these three measures were nearly identical across time and thus best measures of "performance in mineralogy".

Homework assignments were administered through D2L as autograded, multi-attempt quizzes (mixed format: multiple-choice, fill-in-the-blank, matching) across all study years. Only the best attempt was scored. Most of these assignments were unchanged over the study period with the remaining minor changes reflecting modification of course content as modality changed.

Weekly laboratory assignments used a mixed format including multiple-choice, fill-in-the-blank, and open-ended quantitative and qualitative questions. Laboratory sessions were held in-person during face-to-face instruction Pre-COVID and in COVID Year 2. For the online version of the lab in COVID Year 1, one-third of assignments were online labs designed, developed, and hosted by other educators (Arizona State University, n.d.; Brande, 2019; Harwood, 2017; Tramontano, 2015), and the other two-thirds of the assignments were adapted from our in-person labs by replacing physical samples and microscope work with online materials (Mazdab, 2015; The Open University, n.d.; West Virginia University, n.d.). In COVID Year 2, students were offered the choice of in-person laboratory sessions or these online alternatives on a week-by-week basis.

Final exams were mixed format including fill-in-the-blank, open-ended quantitative and qualitative questions, and short essays. Final exams were administered in in-person, closed-book modality Pre-COVID. After the pandemic began in 2020, final exams were administered as open-book, take-home exams. While topical content was unchanged, the format of the exams changed in response to course instruction modality. In particular, the COVID Year 1 and 2 exams required students to engage with computer-based tools also used in the course instruction.

Analysis

Multiple-choice surveys for working memory and spatial visualization were scored as the number of correct responses minus the number of incorrect responses, with items with no response ignored. All other measures were calculated as means and standard deviations across all items.

All statistical analyses were carried out in SPSS 29. Factor analysis determined the relationship between three course assessments (homework, laboratory, final exam); see Rigor and Trustworthiness section below for details. Based on this analysis, an average course performance measure was calculated. Mean and standard deviation are reported for each of the three study groups and at the beginning and end of semester as appropriate (Table 3). To answer the primary question, Kruskal-Wallis tests (one-way ANOVA on ranks) for comparing non-parametric samples of unequal size was performed on the three course-based measures and the course performance aggregate. To answer the secondary question, correlation analysis for all 94 participants was performed to consider relationships between cognitive and affective variables. Based on significant or near-significant correlations, a regression analysis was performed to understand the impact of individual variables in mediating group outcomes for average course performance. Variables were commuted to z-scores prior to regression.

Rigor and Trustworthiness

Rigor in quantitative data was established through use of previously validated surveys (Table 2). We take the prior use and publication of these surveys, including evidence of validity and reliability, as evidence of the rigor of quantitative data. The outcome variable of course performance was measured by scores on course assessments in the form of homework, laboratory assignments, and the final exam. Relative to measuring an individual latent variable such as knowledge, course assessments are created for instructional purposes and are generally recognized as having low rigor. In the context of this study, these assessments are used to measure the outcome of course performance only – no claims are made about individual knowledge or skills.

Individual course performance assessments were all significantly correlated at $p<.001$: homework to laboratory ($r(94)=.75$); homework to final exam ($r(91)=.59$); laboratory to final exam ($r(91)=.55$). Given this, exploratory factor analysis was conducted on the three course assessment measures to determine appropriateness of calculating an average measure. The data set met the minimum conditions necessary for factor analysis, with a final sample size of 91 after listwise deletion of incomplete responses. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.710, above the 0.7 value recommended for factor analysis. Bartlett's Test of Sphericity was significant (χ^2 (3) = 87.9, $p<0.001$). Given these data, exploratory factor analysis using the maximum likelihood approach was performed. Analysis based on eigenvalues ≥1.0 and scree plot suggested one factor. This one factor – labeled average course performance – was retained. This single factor explains 59% of the variance in the three assessments. Factor loadings were over 0.7 for all items. Finally, a Cronbach's alpha measure of internal consistency of 0.81 was calculated. Taken together, these results suggest that the three assessments are highly related and an effective measure of "mineralogy performance".

Open-ended survey responses were analyzed inductively. Carefulness in qualitative analysis was established through iterative coding and discussion between the three authors (O'Connor & Joffe, 2020 and references therein). One author (NS) initially coded response text via inductive thematic content analysis (Patton, 2002), with iterative discussion of emergent codes with one author (SD) until an agreed upon coding schema was developed. A third author (JL) subsequently reviewed these codes and provided feedback, with minor revisions to the overall coding scheme. This approach of iterative development and review of qualitative codes ensured trustworthiness in the coding process. Overall, qualitative data were used to explain quantitative findings. Two authors (SD, JL) further reviewed codes to identify relationships between inductive codes and quantitative constructs.

RESULTS & DISCUSSION

Quantitative Findings

Relative to group differences considered in question 1 (*How has student learning in undergraduate mineralogy been impacted, if at all, by the COVID-19 pandemic?)*, we report on surveys and course-based measures, including overall descriptive statistics, correlations between variables, and statistical differences across three groups (Pre-COVID, COVID Year 1, COVID Year 2). Further regression analysis provides evidence for evaluating the mediating effects of individual variables addressed in question 2.

Working memory and spatial visualization scores were similar across Pre-COVID and COVID Year 2. Participants demonstrated working memory levels as expected of a late teenage population (Table 3). Spatial visualization scores for both Pre-COVID and COVID Year 2 post-scores and Pre-COVID pre-scores align with values observed in other studies (e.g., Hambrick et al., 2009). Low scores were observed for the pre-assessment implemented early in the COVID Year 2 semester. As in previous observations before the pandemic (Ozdemir, 2010), we observe slight improvement in block rotation spatial ability over the semester mineralogy course in the Pre-COVID group, but no significant change in cognitive spatial ability overall despite a larger study group. In COVID Year 2, spatial visualization scores are also constant or improve over the semester, especially for block rotation, but only 8 students completed both pre- and post-assessments and no significant difference on non-parametric tests was observed in spatial visualization ability over the semester between Pre-COVID and COVID Year 2.

Survey data do not demonstrate significant differences in student affect between study groups or between pre- and post-surveys. Self-efficacy, sense of belonging, academic career satisfaction, and academic goal averages (scores of 1-4) ranged from 1.9 to 2.4 across all implementations. Since 1 is the strongest level, these values correlate to moderately strong levels of each construct (Table 3) with little to no change end of semester.

Course performance is interpreted as the average of three course assessments (homework average, laboratory average, final exam) (Table 3). Average course performance ranged from 69.5 (COVID Year 2) to 75.4 (COVID Year 1). Homework ranged from 72.0 (COVID Year 2) to 82.3 (COVID Year 1), laboratory from 69.8 (COVID Year 2) to 82.7 (Pre-COVID), and final exam from 64.8 (Pre-COVID) to 71.6 (COVID Year 1). Average final exam scores were higher for COVID Year 1 and COVID Year 2 relative to Pre-COVID group (Figure 2), and students in the COVID Year 1 were most likely to underperform on the final exam relative to homework scores. The minimum final exam scores for COVID Years 1 and 2 were also lower than the minimum for Pre-COVID group, resulting in an overall slightly broader distribution. Laboratory assignment scores (Figure 3) followed a different pattern, with similar distributions in Pre-COVID and COVID Year 1 but a lower average observed for the COVID Year 2 where students completed primarily in-person labs but could replace these with online assignments on request.

Correlations across variables indicate several significant relationships. Only significant relationships are reported. Early and late spatial visualization scores correlate significantly, $r(35)=.80$, $p<.001$. The four affective variables exhibited significant correlation across pre and post implementations: self-efficacy ($r(46)=.64$, $p<.001$), sense of belonging ($r(46)=.59$, $p<.001$), academic career satisfaction ($r(46)=.59$, p<.001), and academic goals (r(46)=.62, p<.001). Sense of belonging at start of semester appears lower for the online cohort relative to face-to-face and hybrid groups (Figure 4), but the difference does not reach statistical significance. Change in self-efficacy positively correlated with change in academic satisfaction (r(46)=.30, p=.041) and sense of belonging (r(46)=.30, p=.035) (Figure 4). Change in sense of belonging also correlated with change in academic satisfaction (r(46)=.44, p=.002). Average Course Performance correlated negatively with late academic satisfaction (r(53)=-.32, p=.020). Correlations approaching significance were also observed between Average Course Performance and early academic satisfaction (r(75)=-.22, p=,054) and late sense of belonging (r(53)=-.32, p=,020). No other significant relationships are observed.

As noted, student performance - overall and on different course assessments - was significantly correlated, and some significant differences were observed between Pre-COVID, COVID Year 1, and COVID Year 2 instructional groups. A Kruskal-Wallis test indicated no significant difference for Average Course Performance across the three groups (p=0.357). Analysis of differences across individual assessments indicated Homework also exhibited no significant differences (p=0.218). Final Exam scores approached significant difference across the three groups, χ^2 (2) = 5.42, p=0.067. Laboratory scores were significantly different across the three groups, χ^2 (2) = 15.4, p<.001.

Question 2 (*In what ways, if any, do individual memory, spatial visualization, and affective variables mediate differences in learning across the three groups*?) was probed through regression analysis of independent variables as explanatory for variance in Average Course Performance. Regression was carried out in three steps. Placement in study group was included in the first step. The second step considered three affective variables (late, self-efficacy, academic goals, sense of belonging) as well as academic satisfaction. The third and final step considered cognitive variables (working memory, late spatial visualization). All variables were z-scores except for group. None of the regression models were significant, with p-values between 0.200 and 0.499.

Taken together, quantitative results probing the impact of group placement and cognitive and affective variables on student performance in mineralogy suggest: 1) COVID-19 had little impact on student performance and 2) affective and cognitive individual differences played little role in determining individual student performance in the mineralogy course. Multiple other studies have documented the impact of the global pandemic on students (e.g., Eri et al., 2021; Ramlo, 2021; Rapanta et al., 2021) and the predictive relationship between cognitive and affective variables and student performance (e.g., Bong, 1999; Lent et al., 1994; McConnell & van Der Hoeven Kraft, 2011; Pugh et al., 2021). Given this documented impact, we further consider additional data related to student and instructor experiences.

Contextualizing quantitative results with student perceptions

Likert-type responses to anonymous self-assessment of progress with respect to syllabus learning goals were similar across Pre-COVID and COVID Year 1. A small increase in perceptions of progress in COVID Year 2 may reflect low survey response rate (13 out of the 24 participants that year) and self-selection. On a Likert scale from 1 (“learned a lot!”) to 5 (“learned nothing”), the average response across all goals is reported in Table 3 (Self-Assessment). The trend of similar values between in-person and online groups and higher values for hybrid/flexible group was observed consistently for all learning goals, whether the skill/topic was obviously connected to in-person instruction in the lab (e.g. mineral identification in hand specimen, thin section and with other analytical techniques) or not (e.g. using software and online tools for understanding chemistry and crystallography). The largest positive shift in self-assessment of learning from COVID Year 1 to COVID Year 2 was observed in the skill “find, read and understand relevant scientific literature on geological materials," which was practiced almost exclusively online as part of the discussion-based research project developed for the online version of the course. However, these differences in students' anonymous self-reported perception of learning were not significant and align with the overall finding that course performance was similar across all three groups.

Qualitative survey data do indicate differences between the experience of students in face-to-face (Pre-COVID), online (COVID Year 1), and hybrid (COVID Year 2) modality groups. An overview of codes resulting from thematic analysis of open-ended surveys is presented in Table 4. These results provide insight into impacts of the pandemic outside of the classroom.

Students were most likely to discuss their emotions in the pre-semester survey administered during the pandemic, which was also the only survey that directly asked students how they were doing. At the beginning of the fully online semester, most students (10/15) shared negative emotions including fear, anxiety, overwhelm, sadness, helplessness, and anger, but the same number responses included statements of hope for the future. Negative student emotions included coursework-related concerns such as fear of missing deadlines and managing workload, sadness about missing out on campus life, and a broader sense that "we're all living in a downward spiral." The following year at the beginning of the hybrid semester, positive feelings and gratitude for the return to in-person learning were the most common responses to the pre-semester survey (10/18), although stress and fear were still common (7/18). Both positive and negative comments addressed transition and change. Positive comments expressed an optimistic outlook, noting improvement in circumstances relative to the previous year and hope for normalcy. Several comments about anxious emotions centered on instability, i.e., a sense that "things can always change in the matter of seconds."

Students in the online and hybrid modalities were conscious of their motivation and expressed a variety of reasons why they wanted to study. Several students were concerned that they felt less motivation relative to their memory of in-person school and wanted in-person learning as reason to "leave the house." Students felt motivation to "learn about what I love," to pursue a career that is the "reason I am going to college," and related to a general desire for self-improvement. Students reported circumstances during the pandemic that varied widely: while some students shared hardships such as poor home working environment and losses of loved ones, others stated they were doing fine or focused responses on typical concerns about balancing schoolwork with other priorities. Small sample size and lack of similar data in the Pre-COVID group hampers significant analysis of the intersection between external stressors, motivations, and students' identities.

For many students, connections with classmates and instructors suffered during the pandemic. Before the pandemic, 23% of students commented on a positive connection with instructors that was helpful to their learning (Figure 5). Only 13% of students in online and hybrid modalities made similar comments, suggesting it was more difficult for students to form meaningful relationships with the lab and lecture instructors while learning remotely. At the beginning of the online and hybrid semesters, students were concerned that they would struggle to find friends and study partners in class. Several students described classroom friendships as linked to relationships outside the classroom. Barriers to meeting other students include transfer status and lack of clubs and on-campus extracurricular activities. Even if students felt isolated, several students commented that they "think that a lot of people are in the same boat as me," indicating a sense of belonging in a student community.

Both before the pandemic and after the shift to online/hybrid learning, students described struggles with specific topics such as identifying minerals and applying optical microscopy to thin sections as well as cognitive skills such as spatial visualization and memorization, but engagement in and struggles with content were impacted by the course modality. Before the pandemic, the most interesting topic according to students was optical mineralogy and microscopy. The majority of the in-person lab time was dedicated to hands-on work with microscopes. During the pandemic, online or hybrid learners had less opportunity to work directly with microscopes, and instead used interactive virtual microscopes (The Open University, n.d.) and static images. Students in these cohorts were less likely to be interested in optical mineralogy relative to other course content (Figure 6). During online and hybrid semesters, students were also more likely to report that the most difficult content in the course is mineral identification and optical mineralogy (Figure 6). We infer that lower interest and higher difficulty are related to the anticipated instructional challenges entailed with training laboratory hand sample observation and microscopy skills in an online modality.

Instructional changes in response to the pandemic may have been effective in reducing stress and promoting community. Students were less likely to comment about the difficulty of the pace and workload during the pandemic, even though lectures and homework assignments covered the same content (Figure 5). Online recorded lectures allow students more control over pace and facilitate review. Previous studies carried out before the pandemic support the effectiveness of recorded lectures in student learning and high student satisfaction with this mode of consuming lecture content (Russell et al., 2016; Wieling & Hofman, 2010; Zhang et al., 2006). Students may have experienced less anxiety about learning all of the material without the pressure of the series of closed-book exams (Tewksbury, 1996). Increased assessment weight towards online, multiple-attempt homework and addition of the discussion-based project also allowed students to control their own work pace and schedule. The discussions encouraged students to interact with each other and follow their interests. Comments about the discussion-based research project in anonymous surveys included “hope that they are incorporated during GLG 321 classes even after COVID-19 is gone,” and “I actually like the discussions (after I get done writing them) because I like to write about something new and I don't really have a lot of time to read/write about new stuff outside of class.” Students also reported particularly appreciating topics in this project such as the uses and importance of minerals in diverse cultures. The organizational structure of the course website developed after training in remote instruction received positive comments as well. The importance of clear communication in successful online teaching has also been emphasized in pre-pandemic education research (Powell, 2003).

Despite the sense of community developed in the research project discussions, interaction and engagement labs suffered in the online modality. When in-person, students tended to collaborate on laboratory assignments with the same group of 2-4 students over the entire semester, without instructor intervention. In the online modality, this laissez-faire approach did not encourage connection between students. The instructor (SD) observed no consistent lab partnerships in COVID Year 1. While in-person labs require in-person attendance, online labs were available for students to complete asynchronously. Zoom sessions for explanation, help, and collaboration on lab materials saw low attendance, typically ~50%. Attendance at these Zoom sessions correlated with successfully completing labs and more students in COVID Year 1 failed to submit lab assignments than during in-person Years. This relationship between lack of attendance and non-completion of assignment continued in the hybrid modality.

LIMITATIONS

Purposeful, convenience samples are inherently limited in their ability to draw conclusions that are generalizable to a larger population. This study was carried out at a single large public research university in the US Midwest with a predominantly white population. Small sample size and limited diversity of the participant group limited investigation of the effects of diverse student identities on experiences in the course. Pre-semester surveys did not ask open-ended questions about student affect and circumstances for the pre-pandemic baseline group. Across the lifespan of the project, the introduction of COVID-19 itself resulted in a necessary shift in research focus. This shift meant we were unable to conduct a priori analyses, such as power analysis. Similarly, the study was not designed to investigate the impact of COVID-19 on student outcomes. Rather, the design of this research emerged from the study already being undertaken. As such, some variables of importance to the study of COVID-19 impacts were not collected in the pre-COVID years and thus comparison was not possible. A small number of students participated in both pre- and post-testing. This limited ability to draw conclusions from quantitative data and may introduce a bias in which types of students self-selected into the study. The research team also introduced potential limitations to the work and its generalizability through decision-making around study directions. The decision was made to focus on collection of survey rather than interview or focus group data. This survey data provided both quantitative measures that could be used for pre/post comparison and qualitative open-ended responses that contextualized those comparisons. Certainly, this approach limited our ability to pinpoint exactly why individual students were engaged or disengaged in the course or experienced positive or negative outcomes. In addition, retrospective discussion of open-ended responses with individual students might have provided insight beyond that gained through coding. Future studies of pandemic impacts could benefit from richer qualitative approaches.

IMPLICATIONS

Most pandemic learning research – focusing on difficult personal circumstances – predicts a decrease in student learning and performance during 2020 and 2021 (e.g., Eri et al., 2021; Ramlo, 2021; Rapanta et al., 2021). Our experience with undergraduate mineralogy indicates that average learning outcomes reflected by course performance did not necessarily suffer during the pandemic. An improvement in final exam scores in the online and hybrid groups relative to pre-pandemic face-to-face groups was observed in this study. Differences in student ability and affect cannot explain exam score differences, suggesting that instructional differences may be related to the similar or improved average learning outcomes in the pandemic cohorts.

In general, instructional changes resulting in reduced difficulty of assessments and/or more effective instruction may be related to improvement in academic performance as measured by course assessments. The content of the final exam remained much the same between the face-to-face and online/hybrid groups. The mode of the exam changed from a closed-book, timed exam to an open-book, take-home exam. The take-home exam incorporated more open-ended questions and required students to use software skills practiced in the course. Our finding of little difference in course performance across the pre- and syn-COVID years aligns with published work. For example, pre-pandemic educational research has documented similar performance of in-person and distance learning students in exams covering the same content (Werhner, 2010).

Instruction also changed due to the instructor (SD) training in online pedagogy and universal design for learning (UDL). UDL training inspired and guided changes in assessments, particularly the creation of the online discussion-based research project. Before the COVID-19 pandemic, the majority of the summative assessment in the course took the form of closed-book exams; afterwards, multiple formative assessments were incorporated. During the pandemic, online activities replaced active in-class work with lab partners and instructor feedback. The online course needed to help students to feel connected to the class and interested in studying without the pressure of imminent exams. Both goals to foster online interaction and create engaging open-book assessments motivated the development of the research project submitted as a series of online discussions, similar to other efforts to move from exams to open-ended assessments (e.g., Tewksbury, 1996). The research projects on topics of student choice allowed the course to incorporate learning goals in writing, research skills, ethics, and societal context of Earth materials. Participation of nearly all students in the project each week supports the effectiveness of the project in engaging students. The project requires higher-order thinking skills including application of chemistry and crystallography concepts to students' chosen mineral and evaluating research sources. We speculate that because students were required to respond with comments on two other posts each week for full credit, they saw each other's research and felt validated by peer feedback and connected to the class community. Every student also received weekly feedback from the instructor, providing opportunities to correct misconceptions about science content, identify areas for improvement in science writing, and develop a relationship with the instructor towards future recommendation letters. This project has continued to be part of the course. Overall, we feel that the project succeeded in the goal of keeping students engaged and may have helped mitigate negative effects of the pandemic on student learning.

We predicted student affect (i.e. connection to course, sense of belonging) would decrease due to pandemic-related challenges, particularly constructs related to interaction with instructors and fellow students such as sense of belonging. Survey results indicated that during the pandemic students were more likely to enter the course with a lower sense of belonging and were more likely to express fearful emotions. The average scores on labs decreased in 2021, and course instructors observed that approximately a third of the hybrid class fell more than one week behind in laboratory and homework assignments. An increase in the number of student absences and failure to submit laboratory assignments in both online and hybrid groups relative to in-person group did not correspond to a decrease in student affect measured by surveys post instruction. The 2021 (hybrid) cohort reported an increase in self-assessed learning progress relative to the 2020 (online) cohort that did not correspond to an increase in average student performance on homework, labs, or final exam. We infer that students may have overestimated their progress towards learning goals in 2021 due to preference for in-person learning and/or optimism after the fully remote pandemic year, underestimating the continued impact of pandemic challenges on their academic performance.

However, the similar affect scores obtained from survey data for face-to-face, online, and hybrid groups support the effectiveness of online pedagogy in sustaining students' engagement and satisfaction with and connection to the class despite pandemic challenges. Although some content was less engaging when delivered online, we think that students redirected effort to other content areas and skills, resulting in overall success in meeting course objectives. Discussion-based research projects with wide-ranging topics addressing the relevance of minerals to people and communities address a common complaint that mineralogy is mostly memorization and "stamp-collecting"; i.e., overly focused on covering a large, varied collection of content without evaluation of importance or context. Projects of choice allow students to individually engage with content that feels personally meaningful (Kokotsaki et al., 2016; Yamzon, 1999). Students also appreciated guidance in selecting project topics which may mitigate a sense of overwhelm and choice paralysis (Harmer & Stokes, 2016). Student interactions on the weekly posts include frequent positive feedback—from students to each other as well as from instructor to students—that may have boosted the overall morale and engagement of the class. Grading and responding to the weekly discussion posts also provided an opportunity for weekly interaction between the instructor and each individual student. This activity thus served not only as a mechanism for practice and assessment of content and skills learning, but also was an important part of student and instructor engagement that may have supported student performance in homework and exams in an online/hybrid learning environment. Interaction through the project may have fostered sense of belonging.

The mineralogy course described here is part of a broader trend of adoption of hybrid or blended modalities in the wake of the pandemic (e.g., Ashour et al., 2021; Singh et al., 2022). The shift to remote learning spurred the development of new, high-quality online resources which support hybrid and blended learning in mineralogy. Students view these resources more positively in a blended environment than they do during fully online instruction (Engel et al., 2023). The qualitative data in our study also indicated that students exhibited generally more optimistic outlook in 2021 relative to 2020; were excited to take part in in-person activities; and also appreciated flexible structure supported by online resources.

CONCLUSIONS

Course performance measures compared between cohorts of students before and during the global COVID-19 pandemic in a mineralogy course at a large public research university in the United States show no significant decrease in average course performance, but an increase in the range and standard deviation of course performance outcomes. Although students approached learning during the pandemic with lower sense of belonging and strong emotions including fear, on average students' performance did not suffer. We find that no other differences between cohorts explain the resilience of the student population to pandemic stressors. Intentional course design and structured delivery can support student success in in-person, hybrid, and online modalities. One university-related outcome of the pandemic was the necessity for instructors, including the lead author, to engage in training around course design. The lead author will continue to employ lessons learned about universal design and formative assessment in courses moving forward and regardless of modality.

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TABLES

Table 1 Course assessment structure for 2018-2021.

Activity weight in course	Pre COVID (in-person)	2020 (COVID Year 1, online)	2021 (COVID Year 2, hybrid)
Exams	55%	15%	20%
Labs	25%	25%	25%
Participation/lecture activities	10%	5%	10%
Homework	10%	20%	20%
Project discussions and project	[none]	35%	25%

Table 2 Constructs used in the current study.

Construct	Measure	Type**	Timing	Modality
[†]Working Memory	Shape Memory Test (Ekstrom et al., 1976)	TF	Week 3	In-person
[†]Spatial Visualization	Average of three measures: Paper Folding (Ekstrom et al., 1976) Block Rotation (Guay, 1976) Visual Penetration (Titus & Horsman, 2009)	MC	Weeks 3 and 13	In-person
Self-Efficacy	*General Self-Efficacy Scale (Schwarzer & Jerusalem, 1995)	L	Weeks 1 and 14	Online
Sense of Belonging	*Sense of Belonging (Good et al., 2012)	L	Weeks 1 and 14	Online
Academic Career Satisfaction	Academic Career Satisfaction (McCallum et al., 2018)	L	Weeks 1 and 14	Online
Academic Goals	Academic Goals (Elliot & McGregor, 2001)	L	Weeks 1 and 14	Online
Course Performance (outcome variable)	Average of three measures (this study): Homework Average, Laboratory Average, Final Exam Score	Score	Throughout semester	Online, in-person
Course Perceptions	This study	L, OE	Weeks 1 and 8	Online

[†]Not administered in 2020. *Prompt or items modified for mineralogy. **TF=True/False; MC=Multiple-choice; L=Likert-type; OE=open-ended

Table 3 Averages, standard deviations, and number of responses for quantitative measures for students completing early and late surveys. See Table 2 for additional information about measures, timing, and other measurement characteristics.

Construct	Pre-COVID: Face-to-Face (54)		COVID Year 1: Online (16)		COVID Year 2: Hybrid (24)	
Timing	Early	Late	Early	Late	Early	Late
Working Memory	20.1±8.5 (44)	---	---	---	18.9±8.8 (10)	---
Spatial Visualization	14.6±14 (44)	17.2±16 (34)	---	---	5.7±9.2 (15)	11.7±9.4 (10)
Self-Efficacy	2.0±.38 (42)	2.0±.46 (30)	1.9±.50 (14)	2.1±.40 (10)	1.9±.31 (19)	2.0±.41 (13)
Sense of Belonging	2.1±.47 (42)	2.2±0.50 (30)	2.4±.27 (14)	2.2±.58 (10)	2.0±.52 (19)	1.9±.54 (13)
Academic Career Satisfaction	2.2±.45 (42)	2.2±.58 (30)	1.92±.40 (14)	2.1±.62 (10)	2.1±.41 (19)	2.2±.40 (13)
Academic Goals	2.0±.50 (42)	2.0±.45 (30)	2.20±.32 (14)	2.0±.34 (10)	2.1±.38 (19)	2.3±.30 (13)
Self-Assessment	---	2.3±0.3 (31)	---	2.65±.16 (9)	---	1.8±.2 (7)
Homework Average	---	77.1±20 (54)	---	82.3±19 (16)	---	72.0±24 (24)
Laboratory Average	---	82.7±15 (54)	---	73.9±24 (16)	---	69.8±21 (24)
Final Exam	---	64.8±14 (53)	---	71.6±22 (15)	---	69.6±19 (23)
Average Course Performance*	---	70.4±16 (54)	---	75.4±20 (16)	---	69.46±23 (16)

Averages ± standard deviation (number of responses). *Average of Homework, Laboratory, and Final Exam measures.

Table 4: List of codes assigned to anonymous free-response pre- (COVID year 1 and 2) and mid-semester (all years) surveys with examples.

Code	Related construct assessed in quantitative surveys	Description of code	Example
Identity, affect, and personal circumstance			
Emotions	Academic satisfaction	Sadness, happiness, stress, anxiety	“I am a little afraid for this semester, I'm not going to lie.”
Motivation	Academic goals	Goals or desire for self-improvement	“I am motivated to get back to the student I was before.”
Classroom connection	Sense of belonging	Connection or interaction with fellow students and instructors	“Due to everything being online I feel like it will be harder to make connections with my fellow students and professors.”
Extracurricular	Career goals, Demographics, Sense of belonging	Friends, family, home life, work, internships, clubs	“My main friend group is outside of the university.”
Identity	Demographics	Personal identity including age, nationality, major, group membership	“I am 23, turning 24 in October.”
Course structure and delivery			
Pace/load	Academic satisfaction	Amount of content and expectations	“I wish things were taken a little more slow. I feel like I (and others) get sort of left behind and have to play catch up.”
Course setting	Academic satisfaction	Field, laboratory, classroom, or online learning environment	“I actually really learned a lot from the field trip.”
Structured learning	Academic satisfaction	Instruction vs. exploration, guided review and practice	“Include more examples in lecture slides with written out explanations.”
Course organization	Academic satisfaction	Deadlines, organization of course website, communication	“I am afraid of missing deadlines.”
Content and learning goals			
3D	Academic goals, Spatial Visualization	Symmetry, crystal structures	“Grasping the 3D picture of minerals on a macroscopic scale.”

Minerals	Academic goals	Physical properties testing and identifying minerals	“I love lab a lot with being able to figure out a mineral.”
Optics	Academic goals	Optical physics and thin section microscopy	“Looking at the minerals in thin section really amazes me”
Chemistry	Academic goals	Crystal chemistry, compositions, reactions	“Chemistry has always been difficult to me.”

FIGURE CAPTIONS

Figure 1: Examples of spatial tasks from course assessments in mineralogy. Students were asked to A: identify 3-dimensional symmetry operations and symmetry groups in images (rotoinversion). B: use Miller notation to describe planes and lines ((211)) and C: interpret this and similar images, where SiO_4 units are represented as blue tetrahedra and all other atoms and bonds as balls and sticks, to identify the silicate structure type (sheet silicate).

Figure 2: Histograms of average final exam scores during 2018-2019 (in-person), 2020 (online), and 2021 (hybrid).

Figure 3: Histograms of average laboratory scores across all assignments during 2018-2019 (in-person), 2020 (online), and 2021 (hybrid).

Figure 4: For individual de-identified students, averages of survey responses to questions assessing self-efficacy, academic satisfaction and sense of belonging constructs at end of semester vs. beginning of semester plotted with 1:1 line.

Figure 5: Histograms of numbers of student responses to open-ended anonymous survey questions in the mineralogy course coded as negative/needs improvement in “pace/load” and “course structure” and positive/working well in “classroom connection”, “course setting,” and “course organization” for in-person and online/hybrid modalities

Figure 6: Histograms of numbers of coded student responses to open-ended anonymous survey questions, “Which topic is the most difficult” and “Which topic is the most interesting” in the mineralogy course for in-person and online/hybrid modalities.