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Improving Spatial Visualization Training through Personalized Emails and Assignment Scaffolding

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Abstract

Spatial visualization, the ability to mentally rotate and manipulate 2D and 3D objects, is a critical skill for engineering and STEM majors. While the use of digital sketching tools, such as Spatial Vis, can help students develop spatial visualization skills, some students still show limited learning gains. Because these tools record detailed clickstream and performance data, they provide an opportunity to provide targeted support based on each student's behavior. This paper explores how assignment modifications and semi-automated personalized emails based on the clickstream data can impact student outcomes and motivation in a first-year engineering graphics course.

The following study was conducted with 286 students enrolled in a first-year Structural Engineering graphics course at UCSD. These students were divided into a control group (n = 137) and an intervention group (n = 135). The intervention group received an assignment set with additional questions and semi-personalized email messages encouraging persistence. Both the control and intervention assignment sets were selected so that students spent a similar amount of time completing them based on expected completion rates. Student outcomes were measured using clickstream data from the Spatial Vis software, pre- and post-spatial visualization tests (PSVT:R), and post-survey data on student engagement and motivation.

Results showed greater mean PSVT:R gains in the intervention group (25%) than in the control group (16%), although this difference was not statistically significant. Additionally, survey results showed that personalized emails improved student motivation and engagement. Specifically, 40% of students rated the emails as moderately improving their motivation, while 35% said emails greatly improved it. Finally, assignment difficulty, a metric derived from the number of hints, peeks, and attempts on an assignment, showed that intervention students experienced a decrease in overall assignment difficulty. These results showed that persistence was higher in the intervention group, meaning that students persisted through the assignment without relying as much on hints and peeks. Overall, the study shows that emails based on data from a digital platform and a modified assignment set can increase student motivation and decrease assignment difficulty. Additional research is needed to determine whether the results in this study are statistically significant and whether they are due more to the semi-personalized emails or more to the assignment scaffolding.

Background

Spatial visualization, or the ability to mentally rotate and manipulate 2-dimensional and 3-dimensional objects, is a critical skill for engineering and STEM majors [1]. Years of research have shown that spatial visualization ability predicts performance in Science, Technology, Engineering, and Mathematics (STEM) courses and careers [2][3]. Within engineering education specifically, students with stronger spatial visualization skills are more likely to earn higher grades and stay in the engineering major. In comparison, students with weaker spatial visualization skills, disproportionately women and underrepresented student groups, are at an elevated risk of dropping out of the major [1][4][5]. These findings have motivated calls from the National Research Council for programs that explicitly help develop spatial thinking skills as part of the STEM curriculum [3][6]. Luckily, spatial skills can be learned and are not static [1][7]. Instructional interventions ranging from short lessons to full classes have been shown to yield substantial gains on standardized measures such as the Purdue Spatial Visualization Test: Rotations (PSVT:R) [8], with large benefits for students with low spatial skills [1][7][9]. Sorby demonstrated that targeted spatial visualization courses can improve PSVT:R performance and reduce gender gaps in early engineering courses [7][8][9]. This work shows that spatial visualization training is a highly effective and opportune pathway for supporting students in STEM careers [2][3][7].

Improvements in educational technology have enabled new methods for providing spatial visualization education through digital sketching on smartphones, tablets, or computers [10][11]. The Spatial Vis touchscreen application allows students to complete sketch-based assignments with automatic grading and real-time feedback. When students make a mistake, they have the option to try the assignment on their own again or use a "hint" or "peek" feature for additional guidance [10][12]. The transition to digital sketching provides a wealth of clickstream data to study student learning further and improve outcomes[13]. For example, prior work quantified student persistence by the number of times a student retried an assignment on their own before opting for a hint or peek [14][15]. On average, implementing the Spatial Vis software in undergraduate engineering classes has led students to show significant improvements in their post-PSVT:R, with higher average gains among those who entered the class with low pre-PSVT:R scores (<70%). However, at a more granular level, a subset of students who entered with low pre-PSVT:R scores showed minimal or no gains. The research in this paper explores additional ways the wealth of information gathered in the Spatial Vis software can be used for educational research and student benefit in an attempt to increase learning gains, especially among the subset of students who start a class with low spatial visualization ability and do not substantially increase this ability while using the Spatial Vis software.

Research Approach

To improve students' learning gains in spatial visualization, two separate interventions were implemented:

- Students were sent a personalized email based to encourage increased persistence with the Spatial Vis assignments when appropriate.
- Increased scaffolding assignments were provided in certain lessons relating to challenging 3D rotations.

Research suggests that semi-automated, performance-based messaging can improve student engagement and persistence by drawing students' attention to their behaviors and providing timely feedback and encouragement [16][17]. Little work, however, has examined how personalized email feedback based on software usage patterns and a modified assignment can be utilized to improve spatial visualization learning in a first-year engineering course. It is recognized that both interventions in this study could have an impact on student performance, and that it may be difficult to discern which intervention had the greatest impact. However, this approach was used to increase the likelihood of detecting a difference between the control and intervention groups, as the course is offered only once per year, limiting the number of trials possible within our study timeline.

The Structural Engineering 3 class, a freshman-level engineering graphics course, was randomly split into a control and intervention group based on their pre-PSVT:R scores. The details of the email and assignment interventions are described in the sections below.

This study was classified as human subjects research by the UCSD Institutional Review Board (#812291). All study participants gave informed consent before their data were utilized in this analysis.

Study Overview

The course used in this study is specifically designed to teach students spatial reasoning skills and the fundamentals of CAD, and to introduce the Design Process through a hands-on design project. Spatial visualization practice using the Spatial Vis software was assigned during the first five weeks of the quarter, while the team design–build project was introduced in week 4 and continued through week 10, which was the end of the term. In parallel, students completed CAD assignments in SolidWorks and AutoCAD.

Throughout the first five weeks of the quarter, students completed sketching assignments from the various Spatial Vis lessons as a part of the required coursework. Within Spatial Vis program, students were graded on a point system represented by "stars," with each assignment worth 3 stars. Completing an assignment marked "required" by the program without taking a peek or a hint earned students the full three stars. If a hint was used, the student lost one star; if the student peeked at the solution, they lost two stars; and if a student did not complete the assignment, they would receive zero stars. The option to request a hint or peek was displayed following every failed attempt. Taking a hint allowed students to view only the lines in their submitted sketch that were correct, while peeks allowed them to see the full solution. Stars missed on required assignments could be made up by completing optional assignments. Each bonus star was earned by completing an assignment that was not required in the same lesson without using a hint or peek. A small portion of the total class grade also consisted of completing weekly reflections surrounding class and Spatial Vis software experiences.

In week 1, students completed the pre-PSVT:R test. In week 2, they were tasked with assignments from the Introduction, 2D Rotations, and Iso Cubes lessons. In week 3, they were required to complete assignments in the Ortho Cubes, 2D to 3D, and Slopes and Curves lessons. In week 4, they were required to complete assignments in the Flat Patterns and Rotations about 1 Axis lessons. In week 5, students were assigned the Rotations about 2 axes and Assembly lessons (depending on whether they were assigned to the control or intervention group, which is described further below). Finally, students completed the PSVT:R "post test" during the last week of the term. Throughout the quarter, grades for both the Spatial Vis and PSVT:R assignments were posted for students. The number and type of required assignments varied by group, but the total estimated time to complete all required assignments was the same for both groups.

Throughout the course, the Spatial Vis software stored performance data for each student: use of hints and peeks, number of attempts, time on tasks, drawing accuracy, and stars earned. Data from the Spatial Vis software collected in a prior implementation of this class were used to design the revised assignment set, and data collected from students each week were used to implement the email intervention described below.

Research Design and Group Assignment

A total of 286 structural engineering students were enrolled in the course. Of these, 276 consented to have their data used for research, and each completed at least one feedback form that was included in the sample. All of these students completed the pre-PSVT:R at the beginning of the term. The pre-PSVT:R is a 20-minute, 30-question, timed multiple-choice assessment of spatial visualization skills in rotations, administered via the Canvas learning management system [8]. Students were categorized into Low pre-PSVT:R (scores less than or equal to 70%), Mid pre-PSVT:R (between 70% and 90%), and High pre-PSVT:R (greater than or equal to 90%). These categories were informed by prior work by Sorby, who reported that students below 70% would benefit from spatial visualization training [18]. Within each of these 3 categories, students were randomly assigned to the control or intervention group. The randomization was used to ensure that the distribution of initial PSVT:R scores was similar across both the control and intervention groups. After randomizing, 135 students were assigned to the intervention group and 137 to the control group.

Assessment of Spatial Visualization Learning Gains

The PSVT:R can result in capped results, with some students completing all 30 questions correctly or having minimal errors. These students have very little or no room to increase their PSVT:R score in the post-test. Accordingly, rather than focusing on absolute gains in the PSVT:R test, we defined a new metric, Opportunity Captured, using Equation (1):

$$Opportunity\ Captured\ = \frac{PostTS - PreTS}{30 - PreTS} \quad (1)$$

where PreTS and PostTS are the pretest and posttest scores (out of 30) from the PSVT:R standardized test, respectively. This metric was used to gauge improvement on the PSVT:R, as it represented the proportion of possible improvement on the PSVT:R that the student had realized. If students received a perfect score on pre-PSVT:R, they would automatically receive a 100% for opportunity captured, so the denominator would not go to zero.

Revised Assignment Set

The control group was assigned the same assignment set that was used in prior offerings of this course, which is referred to as “curated mid-load” in the Spatial Vis teacher interface. This assignment set required students to complete 147 of the 292 available assignments in the overall software. The revised assignment set for the intervention group was constructed to provide more scaffolding for problems that students had more difficulty with. From the assignments with increased scaffolding were identified using data collected during a previous offering of this course. Assignments were ranked based on the statistical relationship between the stars earned and Opportunity Captured, with a focus on low- and medium-performing students. From the data, three lessons appeared to have the highest correlation to performance on the PSVT:R assessment: Slopes and Curves, Rotations about 1 Axis, and Rotations about 2 Axes. From these lessons, twelve assignments were identified as having the strongest correlation with Opportunity Captured and were then added to the required assignments for the intervention group.

To maintain overall workload balance, in terms of expected overall time to complete the homework, between the control and intervention groups, 18 assignments that contributed the least to the Opportunity Captured metric were removed from the required intervention assignment set. Specifically, two required assignments were removed from 2D Rotations, two from Iso Cubes, one from Ortho Cubes, one from 2D-to-3D, one from Flat Patterns, and all eleven required assignments from the Assembly lesson. The end result was an intervention group with 141 required assignments out of the 292 available to students, 6 fewer than in the control group. For both groups the overall expected homework time using Spatial Vis was 5 hours and 19 minutes.

Email Intervention Procedures

In addition to the scaffolded assignment, the students in the intervention group could receive a semi-personalized email message each week based on their Spatial Vis performance. Three types of emails were utilized: praise emails for students who completed all assignments without hints or peeks, reminder emails for students with incomplete required assignments, and encouragement emails to reduce the use of hints and peeks.

At the end of each week, data from the Spatial Vis software was exported and processed with a MATLAB script. For the required lessons in that week, the script would calculate the mean and standard deviation of the hints and peeks used and the number of incomplete assignments. Students whose hint or peek usage exceeded approximately 2 standard deviations above the weekly mean (e.g., greater than six hints or 4 peeks or a combination such as 5 hints with one peek) were flagged as students for "high hint utilization" emails, while students with any incomplete required assignments were flagged for "incomplete" email reminders. Any students who completed the required lessons without hints or peeks were sent a praise email.

Email lists were created and sorted in Excel tables, and the professor sent personalized emails (with the student names) via a mail merge program. The emails emphasized persistence, productive struggle, and the support resources available to them, as seen in the appendix. Additionally, it referenced students' recent Spatial Vis software activity as a reason for the check-in email. The email process was iterative across weeks 2 through 4 of Spatial Vis usage, with logic to avoid sending the same email to a student (e.g., a student receiving a praise email twice will receive two different praise emails). Additionally, for students who repeatedly utilized high/hints and peeks, the emails were designed to escalate from the "use fewer hint" emails to emails suggesting they go to office hours.

Assignment Difficulty Metric

To compare assignments based on how challenging they are to complete, a difficulty metric was developed that combines three measures. The values for these measures were collected across all submissions and are defined as follows:

1. a = Median number of Attempts, calculated based only on submissions from students who did not request a hint or peek on that assignment.
2. s = Mean number of **S**tars missed
3. f = Percent of students who failed to complete the assignment on the first try.

For each assignment and each measure ($k \in \{a, s, f\}$), a standardized score z_k was computed using Equation (2).

$$z_k = \frac{x_k - \mu_k}{\sigma_k} \qquad (2)$$

where x_k is the raw value of that assignment, μ_k is the mean of measure k across all assignments, and σ_k is the corresponding standard deviation.

The overall Assignment Difficulty score is the sum of the three standardized components as shown in Equation (3):

$$Assignment\ Difficulty = z_a + z_s + z_f \qquad (3)$$

A larger value of this combined score indicates a more difficult assignment.

Results and Discussion

Data Analysis Procedures

From the Spatial Vis software, the following variables were extracted for each student and assignment: number of attempts, first-attempt correctness, number of hints used, and number of peeks used. These variables were then aggregated for each student and used to analyze outcomes between the control and intervention groups and to examine correlations between behaviors within the Spatial Vis software and PSVT:R gains. Independent-sample tests were conducted to compare differences in Opportunity Captured, total stars earned, hint utilization, and peek utilization.

An independence test was used to determine whether there were differences between the control and intervention groups for the class as a whole and for initial performance subgroups (low, medium, and high pretest scores). For these analyses, MATLAB was used to perform a t-test to determine whether the means of two groups are significantly different, given the data's variability and sample size. Key p-values were independently validated in Excel to ensure accuracy.

The t-test analysis and additional data analysis allowed for the evaluation of whether the combined intervention of emails and a new assignment set was associated with a difference in student engagement and learning outcomes.

Spatial Vis and PSVT:R Performance

In the control group (Table 1), students completed on average 523 stars, or 115.5% of the total required stars (higher than 100% provided extra credit). This indicated substantial utilization of the optional assignments to recover missed stars. Students who scored in the low group on the initial PSVT:R showed higher average hint and peek usage (5.41 and 2.62, respectively) and lower Opportunity Captured (22%) than the mid-group students, who exhibited lower average hint (2.2) and peek (0.51) usage and the largest Opportunity Captured (30%). High group students in the control group had the lowest hint usage (1.33 on average) and the largest mean Opportunity Captured (-20%), consistent with ceiling effects on PSVT: R gains for initially strong students in the class, and possibly that students did not try as hard on the test at the end of the quarter when the main project assignment was due.

Table 1. Spatial Vis Performance of Control Students

	Number of Students	Average Hint Usage for All Assignments	Average Peek Usage for All Assignments	Average Total Stars	Percent Total Stars Of Required	Average Pre Test PSVT:R	Average Post Test PSVT:R	Opportunity Captured PSVTR
All Students	137	3.64	1.6	523.22	118.50%	20.72	22.66	16%
Low PSVT:R	69	5.41	2.62	494.35	112%	15.75	18.70	22%
Mid PSVT:R	41	2.2	0.51	550.17	124%	24.17	26.00	30%
High PSVT:R	27	1.33	0.63	556.07	126%	28.19	27.70	-20%

In the intervention group (Table 2), overall persistence was higher than in the control group, and students earned 545 stars (129% of the required stars) and used slightly fewer hints and peeks (3.19 and 1.50, respectively) than control students. Compared to the control group, intervention students in the low, mid, and high pretest subgroups generally performed better. However, mid-pretest intervention students showed slightly lower total stars completed and marginally higher peek usage than their control counterparts, and these differences were very small. High pretest PSVT:R students in the intervention earned the highest percentage of required stars and, on average, completed 602 stars, or 142% of the required stars. Yet high-pretest students in the intervention still demonstrated a (-7%) decrease in Opportunity Captured, further reflecting the limited room for improvement on the PSVT:R for these initially high-performing students.

Table 2. Spatial Vis Performance of Intervention Students

	Number of Students	Average Hint Usage for All Assignments	Average Peek Usage for All Assignments	Average Total Stars	Percent Total Stars Of Required	Average Pre Test PSVT:R	Average Post Test PSVT:R	Average Opportunity Captured PSVT:R
All Students	135	3.19	1.5	545.84	129%	20.68	23.39	25%
Low PSVT:R	68	4.16	2.25	523.93	124%	15.66	19.96	32%
Mid PSVT:R	40	2.95	0.78	544.88	128%	24.15	26.10	35%
High PSVT:R	27	1.11	0.7	602.48	142%	28.19	28.02	-7%

Comparisons using independent-samples t-tests showed that the intervention tended to use slightly fewer hints and peeks and to have higher Opportunity Captured on the PSVT:R (Table 3). However, none of these differences were statistically significant. For all students, hint usage did not differ significantly between groups ($p = 0.57$, $r = 0.03$), nor did peek usage ($p = 0.21$, $r = 0.01$) or Opportunity Captured ($p = 0.29$, $r = -0.05$). Subgroup analyses by pretest PSVT:R revealed a similar pattern with effect sizes for Opportunity Captured. The effect with the strongest statistical significance favored the intervention group among low-pretest students ($p=0.087$, $r=-0.15$) for Opportunity Captured, but these differences did not reach the conventional significance threshold of 0.05. This data can also be seen in Figures 1 and 2, which present it as a box-and-whisker plot.

Table 3. Comparison of Spatial Vis Performance between Intervention and Control Groups

	Hint Usage		Peek Usage		Opportunity Captured PSVTR	
	p-Values	r-Values	p-Values	r-Values	p-Values	r-Values
All Students	0.57	0.03	0.21	0.01	0.29	-0.05
Low PSVT:R	0.37	0.08	0.2525	0.04	0.0873	-.15
Mid PSVT:R	0.43	-0.09	0.38	-0.10	0.668	-0.05
High PSVT:R	0.7	0.05	0.88	-0.02	0.7162	-0.05

Figure 1. Comparison of Control and Intervention Groups: Hint and Peek Usage

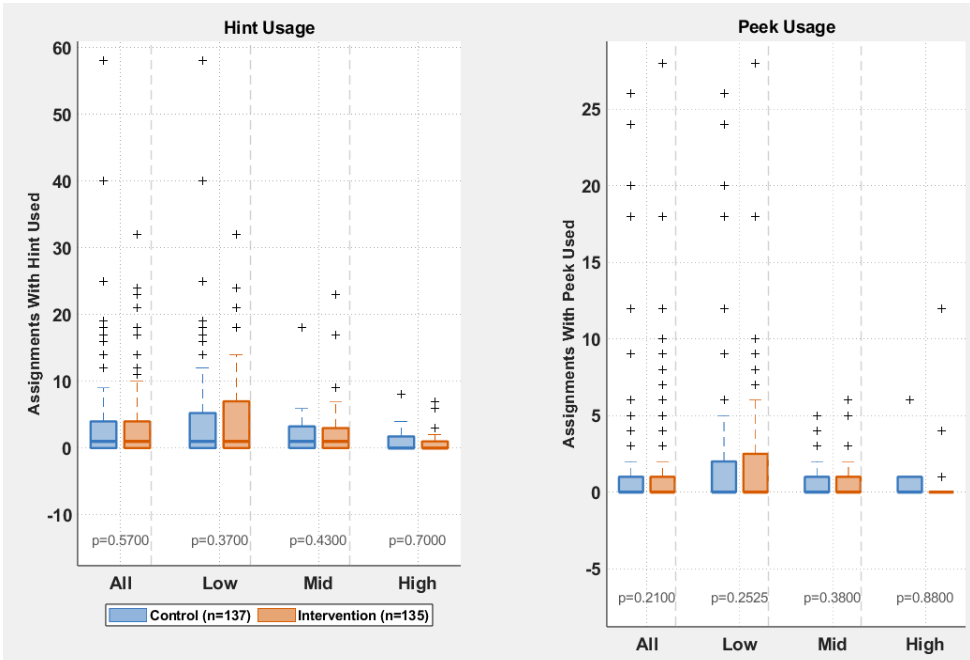
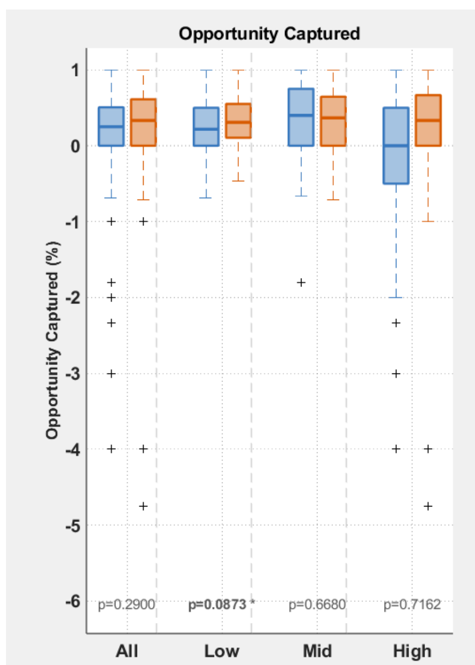


Figure 2. Comparison of Control and Intervention Groups: Opportunity Captured



High-performing students, however, exhibited negative Opportunity Captured, reflecting ceiling effects on the PSVT:R that limited the measurable improvement in their scores. Notably, although both groups showed negative Opportunity Captured, the intervention group's values were less negative, suggesting that the emails and associated assignments may have helped sustain persistence among high-performing students.

Persistence metrics acquired from the Spatial Vis software tell a similar story. Students in the intervention group earned a higher percentage of required stars and, on average, used fewer hints and peeks than students in the control group. Previous research with Spatial Vis has shown that persistence (repeated attempts without hints or peeks) is strongly correlated with PSVT:R gains, and that students who rely on hints and peeks are less likely to achieve substantial learning benefits [10][12][14]. The small reduction in hint and peek utilization suggests that the combined interventions nudged students towards more productive persistence behaviors, resulting in the improved PSVT:R scores observed.

All together, these results suggest that the combined intervention of a revised assignment set and performance-based emails was associated with small, positive shifts in persistence and PSVT: R gains, especially for initially low PSVT: R students. However, these results were not statistically significant.

Overall Class Performance

In addition to comparing the opportunity captured in PSVT:R scores, student performance in other aspects of the course, such as grades on their team design-build project, their individual software assignments, and their overall grades, was evaluated. Table 4 compares the average grades between the intervention and control groups for these specific grading categories.

Table 4. Comparison of Term Project, Software Project, and Overall Grades between Intervention and Control Groups

	Average Design-Build Project Grades		Average Software Assignment Grades		Average Overall Grades	
	Control	Intervention	Control	Intervention	Control	Intervention
All Students	30.57%	30.81%	18.36%	18.77%	88.27%	89.88%
Low PSVT:R	30.60%	30.24%	17.68%	17.82%	87.83%	87.43%
Mid PSVT:R	30.11%	31.34%	19.23%	20.56%	90.01%	93.47%
High PSVT:R	31.15%	31.44%	18.75%	18.52%	89.11%	90.75%

Findings comparing overall class performance between the intervention and control groups were mixed. On average, students in the intervention group performed slightly better, though not statistically significantly, with overall grades of 88.27% and 89.88% for the control and intervention groups, respectively. When delving into the subgroups, the results show that students in the low PSVT:R group perform slightly worse overall, with control and intervention scoring 87.83% and 87.43%, respectively. The Mid group performed better overall, with average grades of 90.01% and 93.47% in the control and intervention groups, respectively. Finally, in the high PSVT:R group, the intervention performed slightly better than the control, with scores of 89.11% and 90.75%, respectively.

None of these analyses showed statistically significant t-test results, with the lowest p-value being 0.112 for the difference in overall grades in the Mid group between the intervention and control. The lack of statistical significance suggests that while the emails may have had a slight positive effect on the students, the magnitude of that effect was not large enough to distinguish between the control and intervention groups. The findings from this analysis highlight that students with low PSVT:R struggle more in the course than students in the Mid or High PSVT:R groups. Additionally, the slightly higher overall grades in the intervention group suggest that the emails and scaffolding may have had a slight positive effect on the class's overall performance, but the results are inconclusive.

Personalized Student Emails

The email intervention was designed to complement the revised assignment set by drawing students' attention to their Spatial Vis behaviors through semi-personalized emails/feedback. Praise emails reinforced effective behaviors (completing required assignments without hints or peeks), reminder emails targeted incomplete assignments, and “use fewer hints and peeks” emails addressed overreliance on support and encouraged students to make use of office hours or other resources.

Table 5 summarizes the student emails received and sent. Among the 135 students who received emails, 99 completed the end-of-quarter survey, which asked about their recollection of specific types of emails and how these emails impacted their motivation. Email logs indicated that praise-type emails were the most common, sent to 125 out of 135 students receiving an email (92%). In contrast, reminder emails regarding incomplete assignments were sent to 32 students (23%), office hour invitations to 7 (5%), and “use fewer hints and peeks” emails to 33 students (24%). Some students may have received emails in multiple categories. Students' recollection of receiving specific emails in the end of quarter survey closely followed the pattern of emails sent, with 88 of the 99 survey respondents (89%) remembering receiving praise emails, compared to 16 (16%) remembering receiving completion reminders, 12 (12%) recalling office hours invitations, and 12 (12%) recalling emails encouraging the reduction of hint or peek utilization.

Table 5. Intervention Group Student Emails Received and Sent (higher than 100% total due to multiple emails)

Category	Student Recollection of Emails Received	Actual Emails Sent
Praising your efforts	88 students (89%)	125 students (92%)
Encouraging you to complete your assignments	16 students (16%)	32 students (23%)
Encouraging you to come to office hours	12 students (12%)	7 students (5%)
Use fewer Hints and Peeks	12 students (12%)	33 students (24%)

Table 6 summarizes students’ responses from the intervention group in the end-of-term survey regarding the impact of these emails on their motivation. Students generally viewed these emails as motivational rather than discouraging. Among the 99 students who recalled receiving emails (out of the 135 students who received emails), none reported that the emails discouraged their motivation to any degree, and 24% indicated that their motivation remained unchanged. In contrast, 40% of students reported that emails moderately increased their motivation, and 35% reported that they greatly increased their motivation, indicating that 75.8% of the intervention group perceived at least some motivational benefit from the performance-based emails. This pattern aligns with broader findings on positive support and feedback in STEM courses, which can enhance students' motivation, sense of support, and willingness to persist through challenges

[15]. It is also consistent with prior research suggesting that timely, personalized messages can increase engagement and support the completion of course activities [16].

Table 6. Intervention Group Student Response to Email Impacts Relating to Spatial Vis

Discouraged motivation greatly	0%
Discouraged motivation moderately	0%
Motivation remained unchanged	24.2%
Increased motivation moderately	40.4%
Increased motivation greatly	35.4%

A concern with this analysis is that few emails requesting that students attend office hours or use fewer hints or peeks were sent, and further analysis of those emails may be needed. Additionally, the emails relied on weekly aggregate data on hint and peek utilization, which may have been insufficient to capture any nuance or patterns of struggle on specific assignments. Future research could use additional indicators of struggle on assignments, such as the number of attempts or analysis of specific sketches, to allow for earlier, targeted support for students who are showing signs of struggling.

Results Related to the Difficulty Metric

Using the values calculated by the difficulty metric previously described in Equation 3, the intervention and control groups were compared on each assignment and across assignment sets. The results show differences in difficulty between the two groups across a variety of assignments. These data are represented graphically in Figure 3, which displays the difficulty value differences for every assignment that was common to both control and intervention groups.

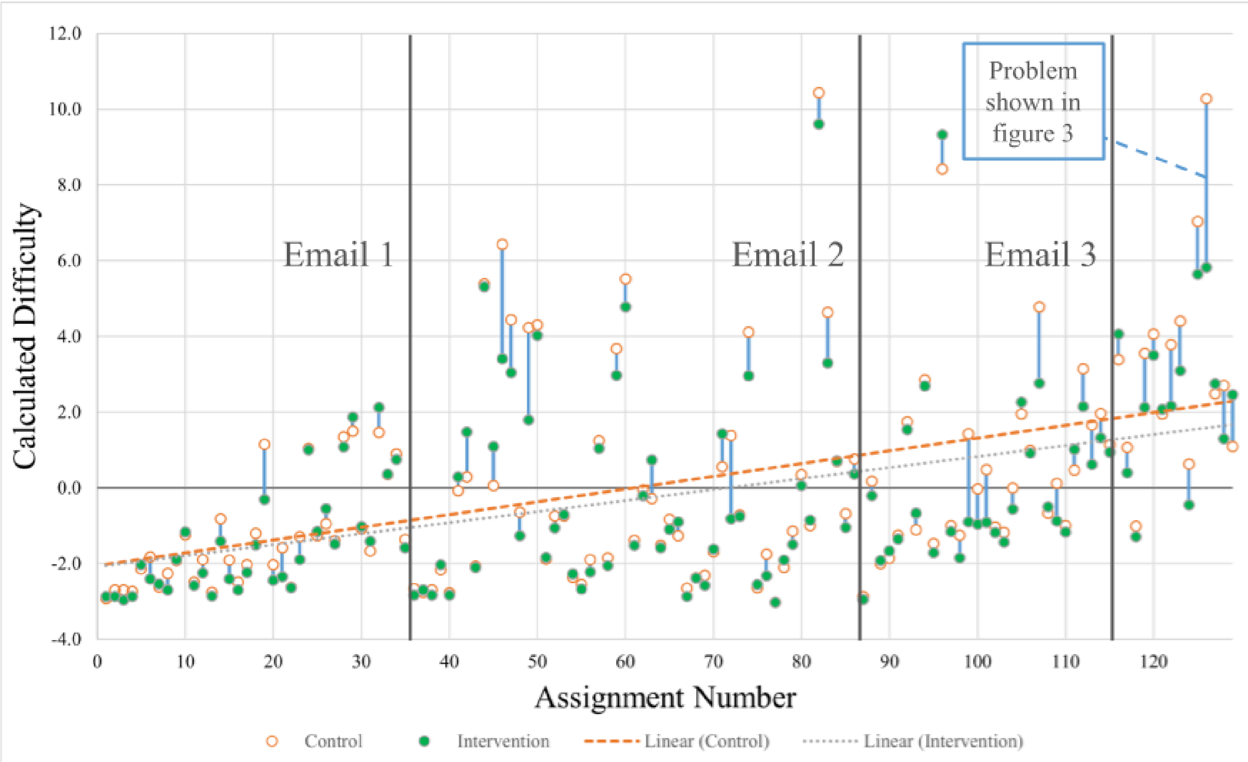


Figure 3. Calculated Difficulty Over the Assignment Set for Intervention and Control Groups

The release schedule for the three weekly emails and the linear trendlines for the two groups is also overlaid on Figure 3. The email timing positions are approximated based on which problems were assigned when the emails were sent. The linear trendlines for the control and intervention groups had slopes of 0.0336 and 0.0291, respectively, indicating a greater difference in calculated difficulty between the two groups as the assignment set progressed. This shows that the control group had greater difficulty completing the problems than the intervention group, i.e., more attempts and/or hints were needed for the assignments that both groups shared. Figure 3 also includes a callout for the assignment with the largest difference between the control and intervention groups, which is further described in Figure 5.

Table 7 summarizes the average differences in calculated difficulty between the intervention and control groups based on the lesson type. A positive value indicates that the control group experienced a higher calculated difficulty on those assignments. The table shows that for all lessons except for Iso cubes, the control group experienced greater difficulty with their assignments. Additionally, the difference in calculated difficulty between the two groups increases near the end of the assignment set, specifically in the last two common lessons, Rotations about 1 Axis and Rotations about 2 Axes, which were the lessons that the scaffolding questions targeted.

Table 7. Average Difference in Calculated Difficulty between Intervention/Control per Lesson

Lesson	Intervention	Control Difficulty - Intervention Difficulty
Introduction	No Intervention	0.16
2D Rotations	No Intervention	0.33
Iso Cubes	No Intervention	-0.40
Ortho Cubes	Email 1 Is Released	0.31
2D to 3D	No Intervention	0.11
Slopes and Curves	Scaffolding Problems	0.33
Flat Patterns	Email 2 Is Released	0.26
Rotations about 1 Axis	Scaffolding Problems	0.50
Rotations about 2 Axes	Scaffolding Problems and Email 3 is Released	0.84

Results Related to Variations in Assignment Sets

As described previously, the assignment set for the intervention group included additional assignments for Rotations about 1 Axis or Rotations about 2 axes, as they had strong correlations with Opportunity Captured, based on analysis from a prior implementation of this course. These assignments are referred to as scaffolding assignments, with some examples shown in Figure 4. The instructions for these assignments require the student to rotate the object first according to the blue rotations, then the red rotation.

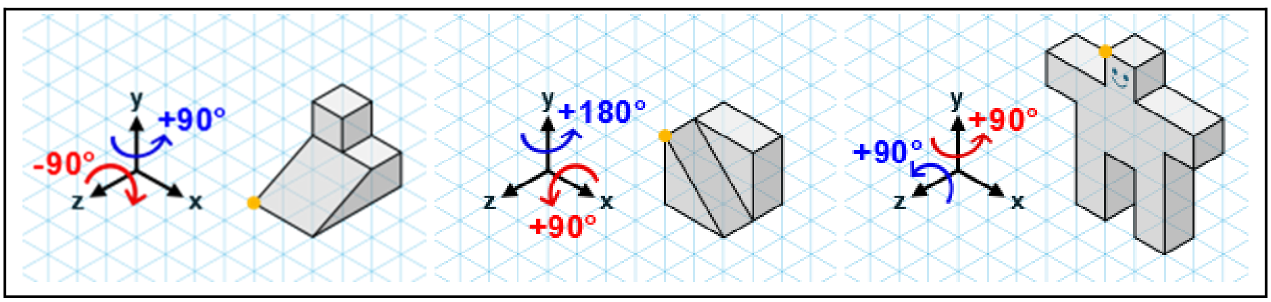


Figure 4. Example Scaffolding Problems that were only assigned to the Intervention Group

Assignments required of both the control and intervention groups enabled a granular comparison of performance between the two conditions. When the intervention group reported a lower difficulty rating for a given assignment, this suggested that they found that task easier, consistent with greater learning in that specific area. Such gains could arise directly from the scaffolding assignments or indirectly from the email intervention. Figure 5 illustrates the assignment with the largest apparent learning gain: the control group reported a difficulty rating of 10.3, whereas the intervention group's rating was substantially lower at 5.83. The large difference in the two groups' experienced difficulties suggests that the scaffolding likely had a positive effect on students' Spatial Visualization performance, in addition to any effects from the emails.

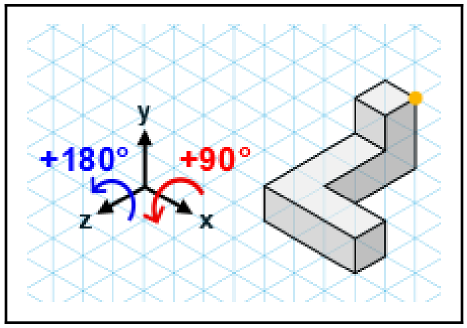


Figure 5. Problem with the Highest Difference in Difficulty between Control and Intervention.

Conclusion

The use of digital learning software creates rich opportunities for fine-grained clickstream data collection that can support highly customized feedback to students. This is particularly powerful for tasks such as sketching, where multiple attempts allow persistence and other learning behaviors to be quantified rather than inferred indirectly.

In this study, a persistence metric, based on clickstream data on hint and peek utilization, was used to trigger up to 3 personalized emails to students in the intervention group throughout the course. These emails included praise for students with high persistence and encouragement for students with lower persistence. Results of the end-of-course survey responses showed that students generally recalled receiving the emails, especially the praise messages, and 76% of students in the intervention group reported that the emails increased their motivation moderately or greatly. This suggests that even a small number of targeted, semi-personalized emails can improve student motivation. Additionally, students in the intervention group showed slightly higher opportunity captured across all subgroups. The increased motivation and increased opportunity captured observed in the intervention group may reflect the impact of the emails.

Clickstream data also enabled tracking performance on specific assignments and identifying where additional scaffolding might be beneficial. Based on data from the previous course, the intervention group received more scaffolded assignments on rotations about one and two axes, and, as a result, intervention students showed lower difficulty on more advanced rotation problems (i.e., they required fewer attempts on average, and used fewer hints and peeks). These rotation assignments align closely with the PSVT:R, and the intervention group also demonstrated higher gains on the post-PSVT:R test. The findings suggest that targeted scaffolding can be beneficial in selected topics, but instructors must still decide how to balance emphasis across different areas of the curriculum.

A major limitation of the presented study was that the revised assignment set and the email intervention were implemented simultaneously for the intervention group, making it difficult to separate their individual contributions to engagement and PSVT:R gains. The small positive increase in Opportunity Captured and in hint/peek usage likely reflects the combined influence of both components, but without separate intervention conditions, it is not possible to determine which element drove the observed effects. In addition, the intervention was confined to the first five weeks of the course; the primary outcome measure (PSVT:R) is susceptible to ceiling effects among high-pretest students and limited overall statistical power due to small subgroup sample sizes and low effect sizes. Together, these factors help explain why several trends may have favored the intervention. However, the results were not statistically significant and suggest the need for longer studies that test the emails and assignment scaffolding separately.

Despite these limitations and results, the findings offer several implications for instructors using the Spatial Vis software. First, they prove the feasibility of using data from prior cohorts to refine assignment sets, highlighting problems strongly associated with Opportunity Captured. Second, students' positive perceptions of the performance-based emails suggest that semi-personalized messages can productively complement the spatial visualization software and in-class instruction. Future work should examine the assignment and email interventions separately, but even in their current form, the results show that instructors can leverage hints, peeks, and other Spatial Vis metrics to deliver targeted support to students who may be struggling.

Disclosure

Nathan Delson and Lelli Van Den Einde have an equity interest in eGrove Education, Inc, a company that may potentially benefit from the research results. The terms of this arrangement have been reviewed and approved by the University of California, San Diego in accordance with its conflict of interest policies.

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Appendix

Reflection Questions Relating to Email Intervention

14. Did you receive any emails directly from Professor VDE (not a canvas announcement) regarding your Spatial Vis homework performance? * Dropdown

Mark only one oval.

- ( ) Yes
- ( ) No *Skip to question 18*
- ( ) I don't remember *Skip to question 18*

Spatial Vis Continued

15. Describe the contents of the email(s) you received about Spatial Vis ? * Check all that apply.

Check all that apply.

- [ ] Praising your efforts
- [ ] Encouraging you to come to office hours
- [ ] Encouraging you to complete your assignments
- [ ] Use fewer Hints and Peeks

16. Did the email impact your motivation relating to Spatial Vis? * Dropdown

Mark only one oval.

- ( ) Discouraged motivation greatly
- ( ) Discouraged motivation moderately
- ( ) Motivation remained unchanged
- ( ) Increased motivation moderately
- ( ) Increased motivation greatly

17. Describe how you reacted to receiving these emails. *

____

Email Examples

Email 1: Praise Email

Subject: [Student First Name], great work on the extra Spatial Vis assignments!

Hi [Student First Name],

I hope the start of the quarter is going well. I reviewed your submissions for [Lesson(s) #] and I'm really impressed by your dedication. You've completed [# of optional lessons] optional assignments beyond the required set, which is truly going above and beyond.

Your extra effort doesn't go unnoticed, and it's this kind of initiative that often leads to significant improvements in spatial visualization skills. By challenging yourself with additional practice, you're reinforcing concepts and developing a deeper understanding of the material.

Keep up the fantastic work! If you have any questions or need further clarification on any concepts, please don't hesitate to reach out during office hours or via email.

Best,
[Professor Name]

Email 2: Go to Office Hours

Subject: [Student First Name]- Office hours invitation

Hello [Student Name],

I hope your week is going well. While reviewing your progress in [Lesson(s) #], I noticed you've been using the hint and peek feature more frequently than usual. This could indicate some areas where we can work together to enhance your understanding and confidence.

Encountering challenges is a normal part of the learning process, especially in engineering. To ensure you're getting the most out of this class, I'd like to invite you to office hours for some one-on-one support and provide you with additional practice to reinforce key spatial visualization and sketching concepts.

My office hours are in [location] on [Date/Time]. Additionally, our TAs are available in [location] on [Dates/Times] every week. Please feel free to drop by at any of these times. We're here to support your growth and success in this class!

If these times don't work for you, let me know, and we can arrange an alternative meeting.

Looking forward to working with you!
Best,
[Professor Name]

Email 3: Incomplete Assignments

Subject: {{ FirstName }}, Friendly Reminder to complete your Spatial Vis lessons

Hello {{ FirstName }},
I hope you're having a good week! I noticed that you haven't yet completed some assignments for Lessons #, and I wanted to check in to see how things are going.

Staying caught up with these assignments is important for building your understanding and keeping pace with the course. If you're finding any of the material challenging or need extra support, please know that I'm here to help.

Here are some strategies to help you complete your assignments more effectively:

- Try to solve each problem independently for at least 5–10 minutes before using a hint.
- If you're stuck, take a short break and return to the problem with fresh eyes.
- Try some of the optional assignments to build your skills.
- If you're stuck, reach out to me. Sometimes a quick question can save you a lot of time.

Remember, it's normal to face challenges, and working through them is a key part of learning. Your effort and persistence truly make a difference!

If you have any questions, just let me know. I'm here to support your success. Keep up the great work. I look forward to seeing your progress!

Best,
[Professor Name]

Email 4: Try a few more times before utilizing the hints

Subject: [Student First Name], here's a tip that will help maximize your learning in Spatial Vis
Hello [Student Name],

I hope your week is going well. While reviewing your progress in [Lesson #], I noticed you've been using hints quite frequently after only one or two attempts at a sketch. I wanted to reach out because this approach might be limiting your potential for deeper understanding and skill development.

It's natural to seek quick solutions when faced with challenges, but in spatial visualization, the process of working through problems independently is where the most significant learning occurs. By relying less on hints and persisting with your own efforts, you're likely to see greater improvements in your spatial reasoning skills.

Here are a few suggestions to enhance your learning:

- Try to solve each problem independently for at least 5-10 minutes before using a hint.
- If you're stuck, take a short break and return to the problem with fresh eyes.
- Try some of the optional assignments to build your skills.

Remember, encountering challenges is a normal and valuable part of the engineering learning process. Your persistence in working through these challenges will significantly boost your understanding and confidence.

Keep up the effort - your persistence will definitely pay off!

Best,
[Professor Name]