COMPUTER-AIDED DESIGN & APPLICATIONS, 2018
VOL. 15, NO. 4, 476–487
https://doi.org/10.1080/16864360.2017.1419649

A comparative analysis of computer-aided design team performance with collaboration software

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ABSTRACT

For the past several years, the BYU CAD Lab has been developing collaborative computer-aided design (CAD) software. As this software is being developed, industry seeks to better understand the differences in performance between teams using multi-user CAD and single-user CAD to make informed decisions about implementing this new software into their engineering processes. In order to better understand the differences in performance between teams, an experimental study was conducted in which four multi-user teams and four single-user teams competed to create the best model of a hand drill. Key findings of this study were that multi-user CAD increases awareness of teammates' activities as well as communication between team members. Performance, with respect to the metrics of quality and time for completion, could be improved with increased familiarity with the multi-user CAD software. Future research directions are suggested and discussed.

KEYWORDS

Multi-user CAD; collaborative design; group dynamics

1. Introduction

Collaboration has always been essential in engineering. When a change in engineering tools occurs, there is typically a change in the way collaboration is implemented. One of the largest engineering changes came with the use of computer-aided design (CAD) software in the 70s [1]. With the advent of CAD, group design on the drafting table moved to individualized design in the CAD environment. For over 30 years, engineers in industry have been placed in a much more isolated environment. However, the recent move towards geographically dispersed design teams in globalized companies has prompted the search for ways to bring engineers back into a more collaborative environment [25], [2], [4]. In an effort to improve collaboration and communication, and thereby expedite the design process, multi-user computer-aided design software (MUCAD) was created [18]. Like any new tool, the situations in which it should and can be used are uncertain. To gain a better understanding of the impact that MUCAD may have on team performance, this research compares four MUCAD teams and four single-user CAD teams across a number of dimensions. This research will help industry make informed decisions on how to use MUCAD and in what situations it would be valuable.

1.1. Multi-user CAD

Multi-user Computer-Aided Design (MUCAD) enhances collaboration in design. MUCAD has primarily been researched at Brigham Young University (BYU), as well as at a few other universities and companies such as Onshape [17], [8], [6]. This software allows multiple people to manipulate 3D CAD models from different computers simultaneously, while updating and receiving each other's edits in real time.

With the development of MUCAD tools, such as NXConnect (developed at BYU), a variety of possibilities and challenges arise. Some of the foreseen possibilities are reductions in calendar time during the design process, enhanced design quality, and enhanced collaboration when users are not co-located [14]. Along with these perceived benefits, there are also challenges. These include understanding the impact of MUCAD on team dynamics, determining the best workflow for MUCAD teams, and determining whether MUCAD truly enhances the

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results obtained with traditional CAD software and scenarios [24], [12].

1.2. Related and past efforts

Because MUCAD is a fairly recent development there has been limited research done on the implications and limitations of this collaborative design software. However, virtual design teams, which are similar in many ways to MUCAD teams, have become increasingly more common [16]. Virtual teams are defined by Berry as relying on computer-mediated communication and often being geographically dispersed [3]. As a result, there has been extensive research done on the effectiveness of virtual teams over the traditional team. Additional research has been done in the last few years by Siebdrat et al. [20] and Katz and Te'eni [15] showing how virtual teams promise an increase in productivity.

The few studies involving MUCAD show that it has the potential to provide a number of benefits. MUCAD software and team dynamics have been compared to the online game Minecraft by French et al. [7], showing that MUCAD has the potential to provide the tools needed to facilitate large-scale collaboration of dispersed design teams. Stone et al. explored the impact of MUCAD software in co-located, three person teams that were given a 25-minute 3D modeling task [23]. This study showed that MUCAD improves team performance according to some measures, such as decreasing calendar time for modeling. However, this study was limited in its ability to accurately predict the effect of MUCAD in industry, partly due to the short time given to the teams to complete the task. Our research was designed to better replicate industry by having longer design times across multiple days. Table 1 shows where this research fits in with past research done in this field.

Exploratory tests involved two teams, one using MUCAD and the other using single-user CAD, working separately to design an escape pod. In this experiment, the team using MUCAD experienced fewer turn backs, had better interfaces, and created a more detailed model than the team using single-user CAD. Although these results seem to indicate that MUCAD software increases productivity and model quality, additional repetitions were needed to identify if the differences were primarily due to the difference in CAD software or some other factor. The foregoing research used a similar setup, but by involving four single-user teams and four multi-user teams, to gain more statistically significant results.

Table 1. An overview of where this current research fits in the field.

Team Type	Single-user Tools	Multi-user Tools
Co-Located	1) Common in industry	2) Past Research
Virtual	3) Increasingly common in industry	4) Current research

An important part of past studies involving MUCAD has been evaluating the CAD skill level of participants. The Purdue Spatial Visualization Test - Visualization of Rotations (PSVT:R), created by Guay in the 1970′s [10] has been used for this evaluation. This test examines one's ability to mentally rotate geometric figures and determine their orientation. Scores on the test have been shown to be highly positively correlated with success in learning and using CAD software [9], [11], [21]. Use of a new, revised version of the PSVT:R is administered by Dr. Yoon of Texas A&M, who has validated the test's psychometric properties [26]. Our study was designed to better understand how the PSVT:R test, self-ratings, and a modeling speed test would be correlated to the prediction of CAD skill.

2. Methods

This study was setup to simulate virtual teams found in industry. Industrial virtual teams often have limited contact with each other due to large distances, multiple projects, or time zone differences. The study strove to simulate some of these conditions by requiring team members to collaborate together on a three day project physically distributed from one another, communicating only through audio or text. Team members in general were not familiar with members of their team, contributing to the sense of team members being from separate locations, time zones and even cultures. Figure 1 is an example of the schedule participants would have experienced over the simulated industrial project's period of performance. Although the schedule permitted multiple teams competing during the same week, they were never working at the same time (i.e. morning or afternoon teams).

On the first of three days all participants were given identical team training on single-user NX 8 CAD software, used in the study via a recorded video training. The 11 minute video addressed several basic functions of the NX 8 software. If the team being trained was designated as "multi-user" they would receive additional training specific to NXConnect (the MUCAD software they would be using). This MUCAD video was 9 minutes long and gave two brief examples of how teams may use NXConnect and troubleshoot problems likely to occur while modeling. Teams designated as "single-user" were given information on how to access the email server for transferring files. At the end of the training, all teams were given an identical 15 minute project briefing. During this briefing each team was asked to design a drill in the CAD

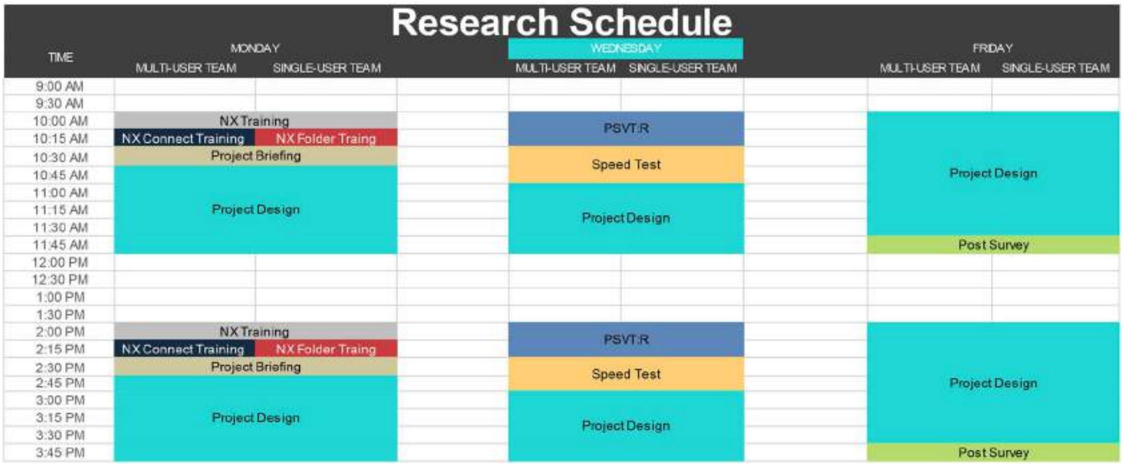

Figure 1. Typical study setup for a given week.

software they were assigned (NXConnect for multi-user and NX 8 for single-user). Each team member was given a hard copy of instructions for mirroring halves of the drill handle, as well as pictures of different drills, with one drill showing an exploded view and listing all of its parts. Each team member was also given a rubric, which they were to use as a guide in their design.

After the training, proctors guided participants to assigned seats where they were tasked to design a drill with their team beyond physical sight and hearing of each other. Each team member was placed in a different portion of the lab where other projects in the lab continued on as normal. Proctors were instructed to record observations, address software challenges, and refrain from giving design help. The one exception was that proctors could assist in mirroring the handle of the drill by using a detailed set of instructions (which were given to participants during the training). After an hour and ten minutes of modeling, participants were asked to stop modeling. Proctors then saved all progress and reset the computers for the next team.

On the second day the team was given the first hour to complete two tests individually. Each participant was asked to take thirty minutes or less to complete a PSVT-R test, and thirty minutes or less to complete a speed modeling test. In between these tests, team members were asked to wait for their teammates to finish before moving on. Both tests were also completed at participants' assigned seats away from teammates and were to be done on their own. After the entire team had completed the two tests they were given thirty minutes to continue modeling the drill. At the end of the thirty minutes proctors again asked participants to stop modeling, saving the progress as participants left.

On the last of the three days, team members were given one hour and fifty minutes to model with a five minute break half way through. Proctors had participants return to assigned seats taking careful notes as the team modeled. After an hour and fifty-five minutes proctors asked participants to stop modeling. Each team member was asked to follow a link to fill out a final survey about their experience and to a form that allowed the lab to reimburse them for their time.

The following subsections discuss further details of how the study was carried out and techniques applied to mitigate bias from the study.

2.1. Judging

The screen shots from the final models were put into a standard three page format for each team and given to a panel of judges. Each team's model was represented by a sheet with each component modeled, the most current assembly of the model, and the two sides of the drill handle. An example of the components sheet given to the judges is shown in Figure 2. Judges were not given information regarding who was on which team, or if a team was multi-user or single-user. The judges rated each model based on the same rubric given to competing teams on the first day. Judge ratings were averaged and used to compare different teams.

2.2. Software

This study used NX 8 CAD software produced by Siemens, a company previously known as Unigraphics. We used this commercial grade software with an educational license from Siemens. This study also used NXConnect, considered research software that has been recently developed at the BYU Site in the NSF Center for e-Design. At the time of this study, the current version of NXConnect had some deactivated features.

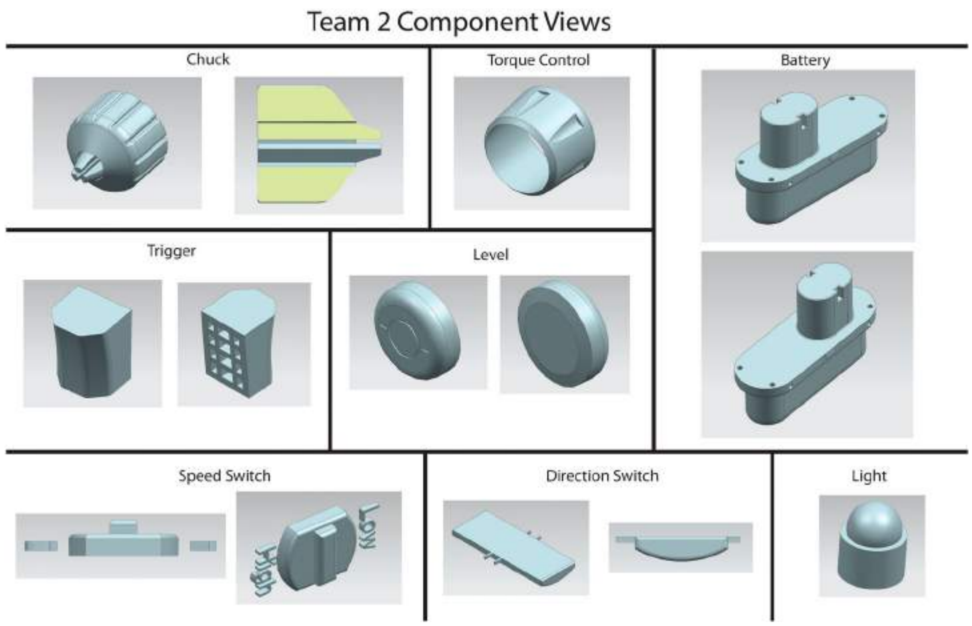

Figure 2. Example of material presented to judges from a single team.

To help keep performance comparable between NXConnect and single-user NX 8, a handicap was placed on single-user NX 8. This handicap simply deactivated and grayed out all of the buttons that were not supported by NXConnect. Deactivated buttons in NXConnect were also grayed out. Despite software glitches that occurred, the limitation generally prevented any participant from using a feature not available to any other participant.

Multi-user and single-user teams both were allowed to use Skype. Only the single-user teams were allowed to use Gmail, encouraging multi-user teams to use NXConnect to share files.

2.3. Data collection

We recorded comprehensive data through video and audio of facial expressions, modeling styles, and team chats. Because of the nature of this type of data we obtained IRB approval (Institutional Review Board) and had participants sign an approved consent form at the beginning of the study. This form gave a brief review of the study layout, the purpose of the study, how personal data would be kept confidential, and IRB contact information. Personally identifying data collected came in the form of video, audio, and survey data.

2.3.1. Video

Video was recorded of each team member from a Webcam mounted to the screen of each computer used during the study. Screen capture software also recorded the screens of each computer. Video was recorded while participants were modeling. During the recording, proctors would indicate the start and stop times of the video either by a verbal signal or by blanking the screen. This video data allowed us to study modeling methods, potential software issues, nonverbal forms of communication, team dynamics, and participant involvement.

2.3.2. Audio data

Audio data was primarily recorded via a microphone in each participant's headset. The headset mics filtered out most background noise making it easier to distinguish which team member was speaking. Secondary audio data came from each computer's webcam. This data was used when the headset mic was muted, unused, or not recorded. The secondary audio did not filter as well as the headset mic and so picked up a lot of background noise. Audio data was used in studying team communication. By listening to the team as a whole we could approximate planning session lengths and identify team strategies.

2.3.3. Survey data

Two surveys assisted in better comparing teams' performance. The first survey was focused on finding the skill level and availability of potential participants. The survey asked questions such as:

- "How familiar are you with NX?"
- "Have you taken ME EN 471 or an equivalent advanced CAD course?"
- "Can you dedicate 6 hours (in three two-hour blocks) to participate in this study?"

This survey was used to filter candidates and organize them into feasible teams. A discussion of the effectiveness of using this survey for creating teams of comparable skill level occurs in later sections of this paper. The second survey was filled out by participants who completed the study. This survey asked questions about team member experience with the study, their familiarity with other teammates, and how they felt their team performed. Some examples of these questions include:

- "What about the collaboration process was frustrating, if anything?"
- "How well did you know Team Member A before the competition?"
- "In thinking about your team as a whole, how would you rate your team in the following categories? [NX modeling skill]"

Data from this survey was used in evaluating several research questions. Overall, it gave us insight into the minds of teammates above and beyond what we could glean from the video and audio data.

2.4. Participants

Participants were solicited via posters, fliers, and announcements in various engineering classes. Incentives in the form of prizes and compensation were also advertised. Most applicants had stated they had taken an introductory course in CAD and have had additional experience with CAD modeling. The proctors found that most of the participants were engineering students. All accepted participants were compensated the same if they were in attendance for their entire project. To incentivize high performance, teams received additional rewards if they performed better than the others. However, some participants may have been motivated to come for the monetary compensation for participation only, and may have not been interested in the physical prize. This lack of interest in a prize could result in a decreased motivation to perform well, which would introduce a confounding factor although an assumption is made that this impacted all teams equally.

Those who wanted to participate in our study completed an online survey that included an availability calendar. The schedules submitted were compiled and filtered through a MATLAB script that returned a list of potential four person teams, combinations that could participate as a complete team, two hours a day for three days. After applicant schedules were filtered, four person teams were then manually selected. This was done using estimated team skill levels from survey responses to create a list of teams with relatively similar skill levels. Teams were further organized so that no one person participated more than once. In most cases, we successfully avoided putting participants with significant past NXConnect experience on multi-user teams as it would give such teams an unfair advantage when competing against other multi-user teams. As discussed later, the methods for organizing teams could be improved in future studies.

3. Results and discussion

3.1. Team performance

A major motivation for this study was to better understand how performance varies between teams using multi-user CAD and single-user CAD, as measured by model quality and productivity. General team performance is expected to be higher when using multi-user instead of single-user CAD. The average score of each team is shown in Table 2. The completed CAD models for each team can be seen in Figure 3, shown in order of decreasing score and separated into multi-user (on the bottom) and single-user teams (on the top). To evaluate performance as measured by the judges' scores, a multiple regression using model effects of average team speed test score, minutes lost due to bugs, and team type (i.e. single-user vs multi-user). By doing this, we hoped to compensate for skill level differences between teams and bugs caused by the beta software NXConnect. The results for the team level comparisons did not give statistically significant results, and thus the performance improvement when using MUCAD is inconclusive. At least two factors limited this significance. The relatively small sample size (eight teams) impacted the results but another factor that may have caused problems was the teams being unbalanced in skill level. Some teams had a much higher skill level as determined by speed test scores, making it difficult to directly compare the model quality between teams. More details about findings regarding skill level are discussed later in the Skill Level Prediction section.

Although significant results for performance based on judges' scores were not found, other observations and statistical analyses were made that can be used as

Table 2. Average Judges' Scores.

MU/SU	Average Score	Team ID
SU	95.3	3
SU	78.3	2
SU	74.7	6
SU	65	8
MU	87.3	5
MU	78.3	1
MU	70	4
MU	66.3	7

Figure 3. Assembly views of all teams completed models.

metrics to compare performance between multi-user and single-user teams. These provide insight into some of the benefits that can be gained through using MUCAD software. The remainder of this paper will discuss these observations and analyses, which include user experience, awareness, communication, skill level prediction, and UI Analytics.

3.2. User experience

Each team was expected to have a different experience based on whether the team was assigned multi-user or single-user software. Because MUCAD software allows for an increase in collaboration, we expected MUCAD teams to become more familiar with their teammates than single-user teams. In order to collect this data, each participant was asked to rank their familiarity with each of their teammates on a scale of familiarity from 0 to 4 (where 0 corresponded to none or very low familiarity and 4 corresponded to very high familiarity). This question was asked in reference to the participant's familiarity before the experiment and after the experiment. By taking the difference between each participant's responses, we were able to analyze the data using a two-sample t-test. Statistically significant evidence was found that through the experience multi-user teams were 0.33 more familiar with their teammates than single-user teams. (MU-SU = 0.33 on a scale from 0 to 4; p-value of 0.0008).

Due to the opportunity for enhanced collaboration, the hypothesis was made that multi-user teams would be more satisfied with their team than single-user teams. In order to measure the user experience, a post-survey question was asked that stated, "Overall, how satisfied were you with your team?" Participants could then rate their satisfaction on a scale from 0 to 4. However, a two-sample t-test analysis found no statistically significant evidence that multi-user teams were more satisfied than single-user teams (MU-SU = -0.067 on a scale from 0 to 4; p-value of 0.60). A larger sample size of teams would be required to extract significance and reject the associated null hypothesis.

In addition to team satisfaction, team frustration data was also collected. In order to measure the user experience, a post-survey question was asked that stated, "How frustrated were you with the collaboration process?" Participants could then rate their frustration on a scale from 0 to 4. Analyses found no statistically significant evidence suggesting multi-user teams were less frustrated with the collaboration process than single-user teams (MU-SU = 0.53 on a scale from 0 to 4; p-value of 0.097).

A second post-survey question was then asked, "What about the collaboration process was frustrating?" This question was designed to better target the source of frustration for virtual MUCAD teams. The responses were then placed into six main categories. Table 3 shows the percent of the total frustration caused by each category and shows that multi-user and single-user teams experienced frustration for very different reasons.

Interestingly, single-user team members had four times more communication-based frustration than

Table 3. Percent of total frustration caused by different categories.

	Percent of Total Frustration		
Category	Multi-user	Single-user	Combined
Communication	11	44	55
Software Bugs	19	4	23
Inexperience	4	7	11
Team Members	7	0	7
Software Limitations	0	4	4

multi-user team members. Single-user team members expressed that frustration was due specifically to communication dealing with component interfaces and the communication of dimensions. Multi-user team members expressed specific frustration with being unable to have an initial non-virtual planning session. This response is consistent with the literature on virtual teams, which recommends that virtual teams have a face-to-face kick-off meeting [13]. Of the 11% frustration due to communication in the multi-user teams, there were no complaints about communication within the virtual environment (i.e. it was regarding other communication media).

During the course of the study, the multi-user teams experienced a number of software bugs. 19% of the total frustration was due to the experimental beta software. In particular, participants reported specific frustration due to "random" work deletion and previous modeling state reversion. Some frustration was expected in this particular area. Although the beta software has many advantages, the current state of the software is limited as described previously. These limitations include deletion, state reversions, and system freezing. As MUCAD is further developed, these limitations may be resolved.

Frustration with team members, expressed by multi-user team members, contributed to 7% of the total frustration. An explanation for this could be that although both multi-user and single-user software required team cooperation, the multi-user environment required a more close-knit collaboration. With a required increase in the level of collaboration, frustration with team members likely arose due to increased expectations. The multi-user teams were continuously aware of the state of every component, and when those did not meet their own expectations, individuals expressed frustration.

On the other hand, single-user team members expressed frustration due to NX software limitations. As expected, team members felt that they were unaware of other teammates' progress due to the nature of the single-user environment. There were no complaints on software limitations from the multi-user team members.

An analysis of satisfaction with the collaboration processes between multi-user teams and single-user teams was also performed. Each team member was asked "How much did you enjoy the collaboration process?" The data suggests that multi-user teams were generally more satisfied with the way in which they were able to communicate throughout the study over those users who used single-user CAD (MU-SU = 0.8895 on a scale from 0 to 4).

3.3. Awareness

Physical separation of teammates during this study meant that all communication about each teammate's work was digital. Participants were not allowed to collaborate in person at any point. It was hypothesized that MUCAD, with its capability of allowing all users to see and work on a part simultaneously, would increase awareness of teammates' activities.

A two-sample t-test was done comparing the responses of multi-user and single-user participants to the question "Overall, how aware were you of your teammates' activities throughout the project?" This test showed that on a 0 to 4 scale, MUCAD teammates rated their awareness of their teammates' activities 1.13 points higher than single-user teammates with a p-value of 0.0008. This result is summarized in Figure 4. This increased awareness proved to be beneficial because it reduced extra work needed to fix problems with part interfaces and allowed all users to better understand the current state of the model. Although this increased awareness did not directly correlate with the performance differences (which was not significant described previously), there are some interesting case studies that show ways which MUCAD, when used properly, could enhance the collaboration process.

3.3.1. Interface awareness

On single-user teams, teammates modeled individual parts and then sent them to one teammate who assembled the parts. Sometimes when the parts were assembled it was found that parts did not interface correctly and had

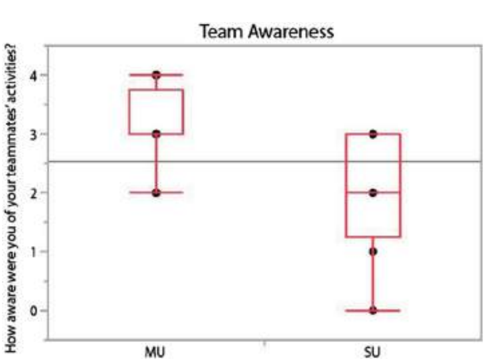

Figure 4. Plot showing quantiles for multi-user and single-user team awareness.

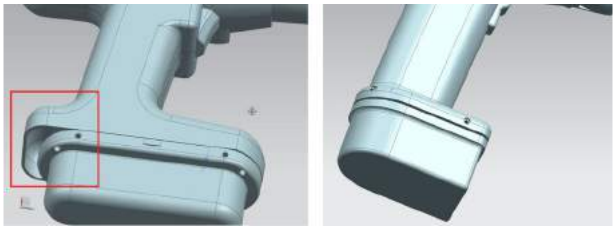

Figure 5. Battery-handle interfaces for two teams, Team 2 (single-user – left) and Team 5 (multi-user – right).

to be modified, wasting design time. Two case studies, one from a multi-user team and one from a single-user team, help illustrate the benefits of increased interface awareness. In both cases, the handle and the battery were modeled by different team members. The battery needs to be able to fit into the base of the handle, and poor design of the two parts could result in interference or a poor fit.

In Team 2 (single-user), difficulties occurred with the battery/handle interface. One teammate was modeling the handle, while another teammate was modeling the battery. When the two parts were put together in the assembly, the battery did not properly match up with the base of the drill handle, leaving the gap marked by the box in Figure 5. Although an attempt was made to modify the battery, the team was unable to complete this in time.

In Team 5 (multi-user), two different teammates also worked on the handle and the battery. However, each person was able to see the other teammate's part as they were working to assure that the interface dimensions matched. At one point these two teammates had a conversation in which they were both able to look at the current drill model and discuss how they would coordinate their efforts to make the parts successfully interface.

3.3.2. Current state awareness

Differences in how aware teammates were of the current state of the model were also observed. This included awareness of what was being worked on by each person and what still needed to be done. Without this awareness, teammates at times did not know what needed to be worked on next or how their part related to the rest of the assembly. Team 1 (multi-user) and Team 2 (single-user) both had team conversations through Skype about the state the model and what still needed to be done. However, the multi-user team seemed to do this more easily because everyone on the team had access to the full assembly at all times. Multiple team members made suggestions on what still needed to be done.

Team members on single-user teams managed this state awareness by using screen-sharing or emailing parts, and one team member generally led out when having team conversations about remaining tasks. An interesting observation is that the highest performing team, Team 3, which was single-user, emailed parts to each other frequently, which created an effect similar to multi-user in that they were frequently updated on the current status of the model and could see how their parts needed to fit in. This demonstrates that it may be possible to achieve a needed level of awareness in a single-user CAD team with additional overhead activities. In other words, a significant amount of extra work is required to share parts back and forth. This indicates that having access to the actual CAD data facilitates awareness more than screen sharing or other methods of transferring this information between team members.

3.4. Communication

When analyzing the data recorded from participants communicating in teams, we focused mainly on high-level patterns in the data. We hypothesized that multi-user teams would in general communicate more than single-user teams and specifically would have longer planning sessions than single-user teams.

The left and right plots in Figure 6 show the average communication per minute of all the multi-user teams and all the single-user teams respectively. While the study was broken into three different days, audio data recorded during team modeling is presented here as one continuous stream. The data supports our supposition that multi-user teams would communicate more than the single-user teams. For this study, the average percentage of time the multi-user teams were actively communicating through audio was 8.36% which was about 60% more than the single-user team average which was 5.22%.

From previous research, communication has been found to impact productivity. Clampitt and Girard found that several forms of communication had an impact on productivity [5]. While all the types studied had a significant impact on productivity, they found that "the Personal Feedback factor was perceived as having the most significant impact on employee productivity" and that "Co-worker Communication, Media Quality, and Corporate Information" had less of an impact. Essentially, more communication does not directly correlate with increases in productivity, but it can have a significant impact. Clampitt and Girard found that communication was correlated with job satisfaction which they suggested could be correlated with productivity, since job satisfaction can have an accumulative effect [5]. Although in this current study the connection was indeterminate.

The average initial planning session times for multi-user teams versus single-user teams had no significant difference, being within 30 seconds of one another. Timing of the team planning sessions was somewhat

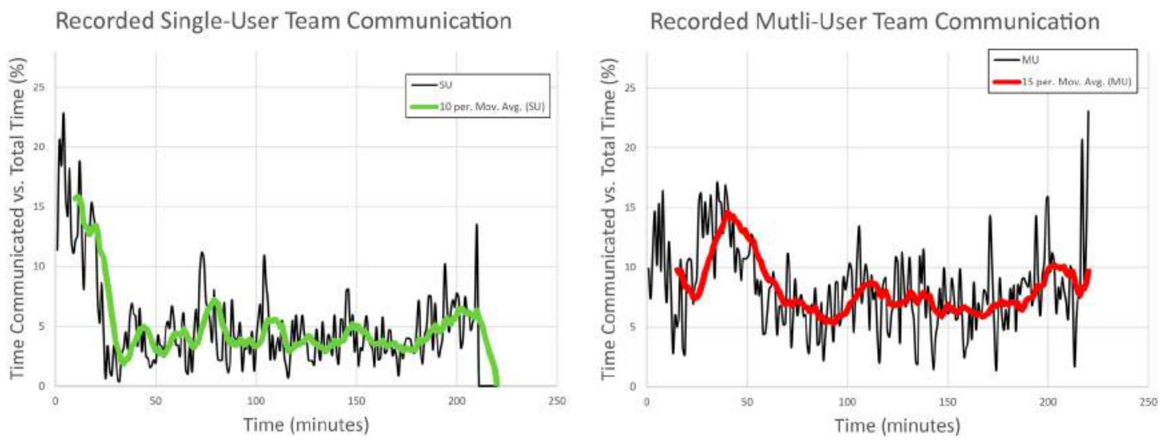

Figure 6. Audio communication trends.

Table 4. Initial planning time.

MU/SU	Planning Time	Score	Team ID
SU	11	95.33	3
SU	12	74.67	6
SU	14	65	8
SU	20	78.33	2
MU	11	87.33	5
MU	14	70	4
MU	15	78.33	1
MU	16	66.33	7

Table 5. Skill measurement comparison.

Team ID	Average Self-rating (0–4)	Average PSVT:R (0–30)	Average Speed Test (minutes)	Judges' Score
1	2.75	28	28.1	78.3
2	2	25.3	24.3	78.3
3	2.75	26.5	24.1	95.3
4	2.25	27	36.1	70
5	2.75	26.8	33.4	87.3
6	3.25	28.3	21.2	74.7
7	2.75	24.8	27.3	66.3
8	1.75	27.5	38.8	65

subjective and so are expected to be accurate within 2–3 min. The data collected is presented in Table 4. While there does not seem to be any correlation between the team type and initial planning length, longer planning time does seem to be correlated to poorer overall score, perhaps due to the total length of the project, though this correlation is not statistically significant.

3.5. *Skill level prediction*

An important part of this study was accurately accounting for the differing NX skill levels of the study participants. All study participants had some previous CAD experience, but some were very proficient with NX while others struggled with basic features. In order to understand the effectiveness of different methods for predicting skill level, we performed analyses comparing PSVT:R score, speed test score, and self-rating. These comparisons showed that PSVT:R is not as effective as the speed test at predicting skill with a specific CAD package, and also showed that people are not good at predicting their own skill level.

As mentioned in section 2.4, we attempted to create teams with similar overall skill levels. The metric for determining skill level was a pre-survey question asking "How familiar are you with NX?" which was answered on a scale from 0 to 4. Although the teams created were well balanced according to these self-ratings, it was seen during the study that certain teams were much more proficient with NX than others. We expected that self-perception of individual CAD proficiency would generally match evaluated individual proficiency. However, a statistical analysis showed that there is no correlation between these two metrics. From this analysis we conclude that a person's self-perception of CAD skill is not always accurate and should not be used as a primary means for determining skill. A similar phenomenon has been observed in other areas, for example, in the realm of second language self-assessment. Studies show that individuals are inaccurate when evaluating their own second language skills, unless they have had recent experience practicing the language skills that are being assessed [19]. Similarly, better self-assessments of CAD skill level would be expected if the assessment is done after participants have completed a CAD modeling task.

As mentioned in the Methods section, the PSVT:R and a speed test were administered to study participants to evaluate their CAD modeling skill. We expected that single-user CAD skill would be positively correlated with PSVT:R score, but a regression between these two scores showed no correlation. The lowest PSVT:R score of any of the participants was 22 out of 30 with an average score of 26.75, meaning that two thirds of the resolution of the scale was not utilized, making it more difficult to

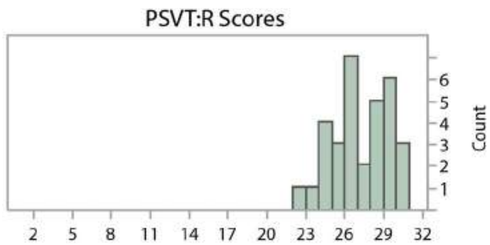

Figure 7. Histogram of all PSVT:R scores.

distinguish skill differences. A histogram showing the distribution of PSVT:R scores can be seen in Figure 7. This data comes from a population of individuals who already had a certain level of CAD experience, indicating that the PSVT:R may not be the best test for evaluating CAD skill in a population where all individuals are familiar with CAD software. The PSVT:R has typically been used to predict students' ability to learn 3D modeling software in an introductory engineering graphics course [22]. Because nearly all of the study participants had successfully completed an introductory engineering graphics course, they were expected to perform, and did perform, quite well on this test.

In order to further investigate the accuracy of the speed modeling test for predicting CAD skill, we performed a regression of individual speed test scores and individual skill as evaluated by a person's teammates in the post-survey. In doing this, we assumed that after working together as a team for the 3.5 hours of modeling time, teammates would have gained a good sense of each teammate's relative skill level. This regression did yield a statistically significant correlation, indicating that the speed test is a good indicator of individual CAD skill.

3.6. User interface analytics

In order to better understand the modeling styles of multi-user CAD versus single-user CAD, user interface analytics were collected. These analytics contain a variety of useful data including the time stamp for all buttons pressed, the name of each button pressed, and the part file in which the user modeled. Analyses can be performed on team modeling style by comparing and contrasting this team data.

The winning team, Team 3, received a score of 96.33 from the judges while Team 8 scored the lowest with a score of 65. Both teams used single-user software. Figure 8 shows the user-interface analytics for both Team 3 and Team 8 for all three days of the study. On day one, Team 3 started eight of the nine components whereas Team 8 only started two of the nine components.

3.6.1. Differences in modeling styles

Distinct modeling styles are seen between the two top teams, Team 3 and Team 5. The winning team, Team 3, received a score of 96.33 from the judges while Team 5 came in second with a score of 87.33. Figure 8 shows the user-interface analytics for both Team 3 and Team 5 for all three days. On day one, Team 3 started eight of the nine components whereas Team 5 started all nine components. Members on Team 3 worked nearly exclusively on individual parts for the length of the study, only working on the same component occasionally. Members

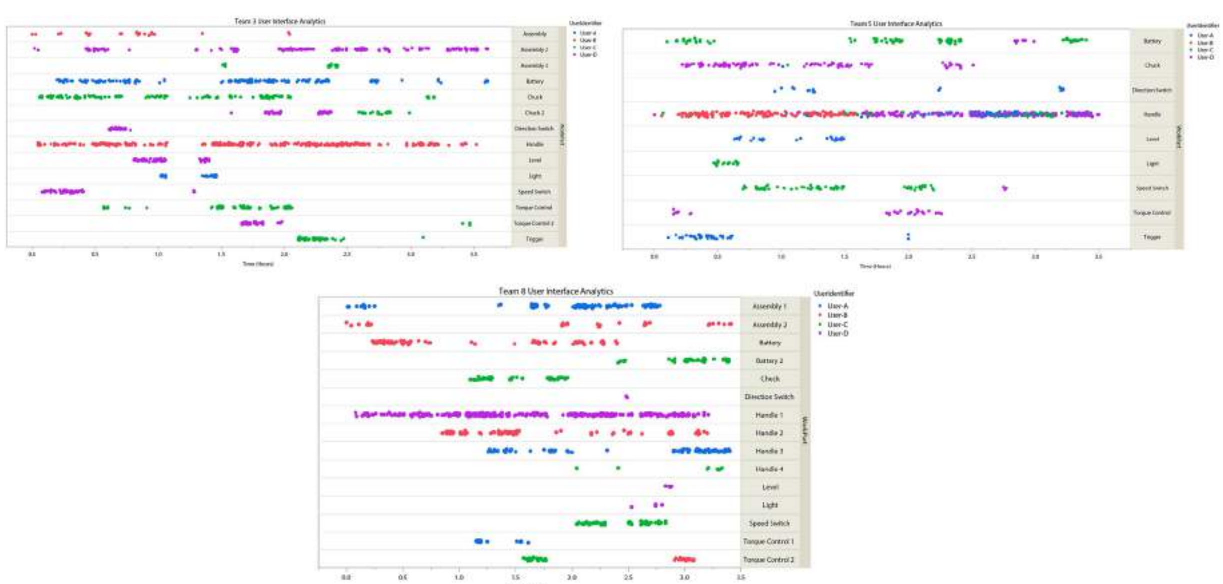

Figure 8. User interface analytics data for Team 3 (top left), Team 5 (top right), and Team 8 (bottom).

on Team 5 worked simultaneously on components near the end of the study, but initially "specialized" in a certain part or parts. There was no simultaneous work from multiple team members on any component on day 1. This trend carried into day 2, where there was only slight collaboration on the largest part, the handle. However, even this collaboration was not performed simultaneously. On day 3 there was extensive simultaneous work on components. All three users modeled simultaneously during various instances during the last day of the study. The most simultaneous component assistance occurred in the handle. It should be noted that the handle was also used as the assembly file for the drill.

From these observations it is seen that Team 5 largely used MUCAD as if it were a single-user software on the first and second day. The power of MUCAD comes in part from the ability to work simultaneously on the same component. By not exploiting this strength of the MUCAD software, Team 5 placed itself at a disadvantage. It is possible that Team 5 could have performed better than Team 3 had they better known how to take advantage of the strengths of MUCAD.

4. Conclusion

Understanding the differences in performance between teams using multi-user and single-user CAD is essential for those in industry making decisions about implementing MUCAD software. This study has made a preliminary investigation of those differences in a multiple-day, new design scenario. It has been found that MUCAD increases awareness of teammates' activities and increases communication between team members. Different sources of frustration for single-user and multi-user teams have been identified, as well as differing patterns of modeling style. These findings demonstrate that MUCAD software has significant potential to improve team collaboration and performance, and we believe that future studies will further demonstrate this.

4.1. Lessons learned and future work

Although the study was overall successful, there were some lessons learned that can improve future studies. As discussed, some of the greatest difficulties came from not having balanced NX skill across all teams. This meant that some teams performed significantly better than others due to individual skill levels and made it difficult to directly compare the teams. As discussed earlier, we found that a speed test is a more effective way to evaluate an individual's skill with a specific CAD system. A suggestion for future studies is to test for CAD skill using a speed test before forming teams.

Another key observation regarding skills is that having participants who have successfully climbed the learning curve for the software that they will be using will allow them to take advantage of the full benefits of the software. In the case of both NX and NXConnect, many users struggled to find the software features needed to create their models. It was difficult to compare effectiveness when neither group was able to use the capabilities of the software in the most productive way.

Since the MUCAD software is still under development, bugs sometimes caused significant problems for multi-user teams. It would be good to develop a more accurate way to account for time lost due to bugs so that this can be factored into performance. In this study, minutes lost due to bugs was based on each participant's own estimation at the end of the study.

Future studies may explore different factors that could have an impact on the effectiveness of MUCAD teams, including team composition and leadership. We have shown that multi-user teams communicate more than single user-teams, but future research could further explore whether this is causal or simply correlated with improved performance. Other studies could explore the benefits of MUCAD in design scenarios other than the new design scenario tested in this study. These could include early design/concept generation, engineering change orders, and design review scenarios. We have shown that there are different modeling styles for single-user vs multi-user CAD and for high-performing vs low performing teams. Further research could better define these modeling styles, including whether it is more beneficial for multi-user team members to collaborate at the part or assembly level.

Acknowledgements

We would like to acknowledge and thank the following individuals for their help and contributions to this paper: Dr. Ed Red of Brigham Young University and David French.

This research was supported through funding from the National Science Foundation Center for e-Design – Brigham Young University Site.

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