Are Two Heads Better Than One for Computer-Aided Design?

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With the availability of cloud-based software, ubiquitous internet, and advanced digital modeling capabilities, a new potential has emerged to design physical products with methods previously embraced by the software engineering community. One such example is pair programming, where two coders work together synchronously to develop one piece of code. Pair programming has been shown to lead to higher-quality code and user satisfaction. Cutting-edge collaborative computer-aided design (CAD) technology affords the possibility to apply synchronous collaborative access in mechanical design. We test the generalizability of findings from the pair programming literature to the same dyadic configuration of work in CAD, which we call pair CAD. We performed human subject experiments with 60 participants to test three working styles: individuals working by themselves, pairs sharing control of one model instance and input, and pairs able to edit the same model simultaneously from two inputs. We compare the working styles on speed and quality and propose mechanisms for our observations via interpretation of patterns of communication, satisfaction, and user cursor activity. We find that on a per-person basis, individuals were faster than pairs due to coordination and overhead inefficiencies. We find that pair work, when done with a single shared input, but not in a parallel mode, leads to higher-quality models. We conclude that it is not software capabilities alone that influence designer output; choices regarding work process have a major effect on design outcomes, and we can tailor our process to suit project requirements.
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1 Introduction

Technology is transforming the way we work and interact with others; mobile internet, digital tools, cloud computing and storage, and video conferencing have enabled new models of work in many industries, including the engineering and manufacturing sectors. People are connected as never before and diverse, and geographically distributed teams are can unlock innovation and are becoming more common [1,2]. The nature of engineering design work is changing rapidly: large and diverse teams with access to digital fabrication tools (such as three-dimensional (3D) printers, laser cutters, and CNC mills) are seeing changes to the techniques of modeling, prototyping, and decision making in design.

Computer-aided design (CAD) software is an important tool in the engineering designer's toolbox. CAD has been traditionally used for drawing representations but today, 3D models serve a larger purpose as digital prototypes [3,4]. 3D modeling techniques used today were established early on in CAD research. For example, parametric modeling was introduced in Ivan Sutherland's thesis in 1963 [5]. However, we did not see commercial CAD software using solids and parametric modeling techniques until the late 1980s. The subsequent decade saw the onset of commercial internet services which led to a wave of interest in developing CAD collaboration tools. Product data management (PDM) methods only became commercially available in the 1990s and remain the standard in CAD collaboration, even today. We are now at another such cusp in technology transformation for CAD collaboration.

With the advent of cloud computing, it is now possible to collaborate seamlessly on an increasing number of tasks, including CAD. Engineers can view and modify CAD geometry synchronously, analogous to text editing in Google Docs. This is a big step forward from the individual-focused check-in/check-out process of PDM tools. In the near future, real-time collaboration has the potential of becoming the new standard. As design researchers, it is important that we understand the implications of this shift in CAD collaboration capability.

Mechanical engineering research predates the discipline of software engineering, and knowledge of design teamwork is an ongoing area of inquiry in our field [6–13]. However, in the case of real-time collaboration, software engineers have embraced the working style much earlier than mechanical engineers, and thus we look to practices in this field for inspiration. We argue that mechanical design projects follow a progression similar to software development, starting from an ambiguous ideation phase and eventually leading to a structured detailed design product [14], and thus methods may be valuable in both contexts.

In this paper, we investigate new CAD working styles that mimic pair programming, the popular mode of working collaboratively in software development. Pair programming is a software development technique in which two developers work together on one piece of code. We aim to test established relationships from pair programming in the context of collaborative CAD work.

2 Background

2.1 Computer-Aided Design Collaboration. Real-time computing platforms in CAD have been discussed since the late 20th century [15]. Research in collaborative CAD has predominantly focused on developing tools and architecture to support real-time collaboration [16]. Such synchronous CAD tools have been successfully deployed in research labs [17–19]. Previous research has looked at communication patterns and team dynamics in collaborative CAD teams to enable more efficient collaboration techniques [20,21]. More recently, virtual reality/augmented reality techniques are being considered to improve collaborative CAD [22,23]. However, in the industry, traditional collaboration is still prevalent.

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Teams using a top-down modeling strategy with PDM tools are still the norm [6].

The adoption of cloud-based CAD tools is in its early stages but growing [24,25]. Consequently, design research insights on commercial grade cloud-based CAD are limited but important to set the scope of our work [26]. Eves et al. developed multi-user CAD (MUCAD) as an add-on to Siemens NX [27]. As a result, MUCAD brings real-time functionality to a traditional CAD software. In their experiments, the authors found that MUCAD teams showed a higher level of awareness of the CAD model and showed more efficient communication. It was observed that teams with a high mismatch in skill levels expressed higher dissatisfaction. Eves et al.'s work used speed, quality, communication, skill mismatch, satisfaction, and awareness level as metrics of comparison. Our metrics are influenced by Eves et al.'s work. For example, in an earlier version of this work, Phadnis et al. compared the effect of skill mismatch and communication on speed of CAD work [28]. In prior work, Zhou et al. compared the user satisfaction of using synchronous CAD versus individual CAD, using automated emotion detection techniques [29]. The power of the results from much of the experimental work to investigate collaborative CAD has been limited by the sample size.

Stone et al. studied the sensitivity of team sizes in cloud-based CAD collaboration [30]. Teams of one to four people were tasked with completing CAD models of varying complexity. Single users were faster at modeling simpler models and larger teams produced better quality models. The outcome of this work led to a prediction function that calculated CAD model completion times. In another study, Stone et al. tracked communication patterns in an effort to study team dynamics within MUCAD teams [31]. They found that better-performing teams communicated less than lower-performing MUCAD teams. In earlier MUCAD work, researchers have focused on the composition of the cloud-based CAD architecture and conflict avoidance strategies [32–34]. During these studies, MUCAD was still in development and this limited the results of research using this tool.

With the release of commercial cloud-based CAD software, we can now reliably study the effects of real-time collaboration. One of the major differentiating factors of synchronous CAD tools is their ability to allow manipulation of CAD geometry collaboratively, at the part level. Such collaboration has not been studied before and we strive to discover new insights in this regard.

2.2 Pair Programming. Our study takes inspiration from the software development field. Extreme programming (XP) techniques were popularized after the release of the Agile manifesto in 2001 [35]. Pair programming, a subset of XP techniques, is common in software engineering teams. The benefits of pair (dyadic) programming have since been studied in both research and industry settings [36–38]. The results are mixed on speed gains from pair programming; but quality and engagement of software developers have been unanimously shown to increase [39,40]. The discrepancy in speed results arises because of how pair work is accounted for in these studies. Pairs, together as a unit, have shown to produce more coding output than individuals. However, on a per-person basis, pair participants are actually slower than individuals. Quality on the other hand is defined by the number of errors per line of code. Both speed and quality definitions, pertaining to our work, will be discussed in more detail in Sec. 3.5.

An understanding of pair programming in research settings helps teams in the industry to accurately deploy these techniques. For example, one of the benefits of pair programming discovered through research is its ability to provide an enhanced knowledge-sharing experience [41]. Given that pair programming has shown success in software engineering, in our work, we investigate the effect of pair work in CAD.

2.2.1 Remote Pair Programming. Traditionally, pair programming sessions strictly adhered to a driver-navigator style collaboration [42]. In such a pair, only one participant codes at a time, freeing up the second person to review. Pair programmers share control and switch roles as necessary. Typically, these sessions are held in physical proximity and often by sharing the same terminal.

In a virtual setting, pair collaboration is implemented using screen sharing tools [43]. This style of collaboration was introduced in 1987 as What-You-See-Is-What-I-See (WYSIWIS) and developed as a groupware project called Colab at Xerox [44]. WYSIWIS based tools are still in use today and preferred for their simplicity and increased awareness [45–47]. The premise being more eyes on the written code makes it higher quality and error-free [48].

Newer code compilers allow multiple programmers to edit at the same time [49,50]. This style of work, also known as distributed pair programming, can be unstructured and breaks away from the strict driver-navigator role-play [51]. The added editing freedom allows for parallelization of work and is touted to be faster, however, possibly at the cost of reduced quality [37,52]. Typically, parallel coding setups require advanced tools capable of integrating multiple code streams without conflicts [53]. Similar to cloud-based CAD research, the pair programming literature has used speed and quality metrics to compare coder's outcomes [37].

In this study, we emulate both traditional pair programming and remote pair programming in the context of collaborative CAD.

2.3 Research Framework. We report the results of a series of experiments aimed to test the generalizability of the findings from the pair programming literature to a pair of CAD users, which we refer as pair CAD. We collected data from human subject experiments, where our participants worked with a consistent CAD software package but in three different working styles, represented in Fig. 1. Individual CAD work shown in Fig. 1(*a*) simply means a single designer working by themselves. The first pair CAD style (Fig. 1(*b*)) has both designers working on an instance of the common CAD database which allows for parallel work, like Google Docs [54]. This style is referred to as Parallel CAD. In Parallel CAD, each designer can edit the CAD file with their partners, simultaneously. We anticipate that this mode will allow for more editing freedom but reduced awareness, as there is no obvious incentive to overlook each other's work. The second style in Fig. 1(*c*), called Shared CAD, is akin to screen sharing or WYSIWIS methods [44]. Both designers share the CAD user interface (UI) but from separate terminals. This allows only one designer to actively manipulate the CAD geometry at a time, and results in the partner's directed attention to the same view and activity.

Figure 2 shows a summary of our research questions. We test the effects of Parallel CAD and Shared CAD control in comparison to Individual CAD control. We anticipate seeing differences in outcome due to the tradeoff between awareness and editing freedom during CAD collaboration. Like mentioned previously, to maintain consistency with prior literature, we use speed, quality, communication, user activity, and satisfaction as metrics of comparison.

This study's primary research questions are:

– RQ1: On a per person basis, is Individual CAD faster than Parallel CAD and Shared CAD?
– RQ2: Does Shared CAD lead to higher quality compared to Parallel CAD and Individual CAD?

This study's supporting research questions are:

– S1: Do Shared CAD participants communicate more than Parallel CAD?
– S2: Do Parallel CAD participants show more equal user activity than Shared CAD?
– S3: Are Parallel CAD and Shared CAD participants more satisfied than Individual CAD?

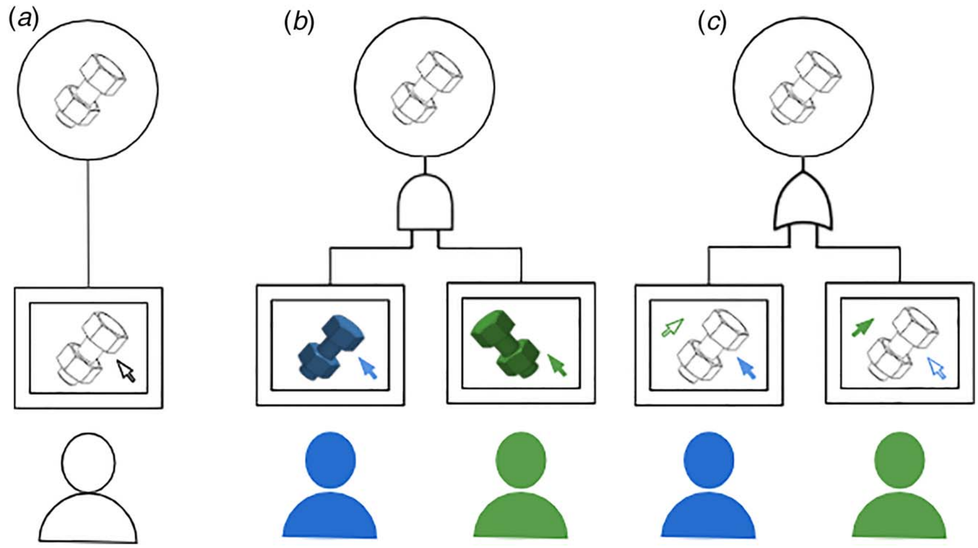

Fig. 1 Representation of various CAD working styles: (*a*) Individual CAD user accessing model via a single workstation, (*b*) Parallel CAD users sharing a common CAD database through independent workstations and controls, and (c) Shared CAD users sharing access to a single database, but with one-at-a-time shared mouse/keyboard control from independent workstations

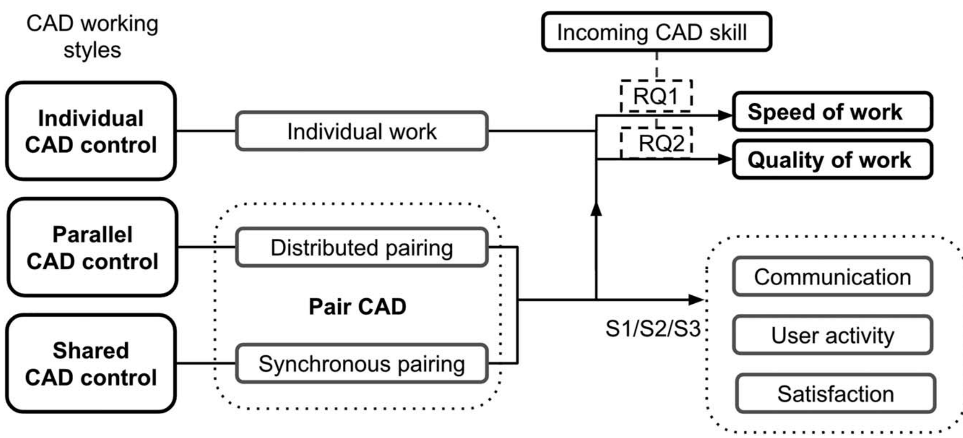

Fig. 2 Research model showing mapping of research questions to various CAD working styles, and experimental variables

3 Methods

3.1 Overview. The experiment was conducted at the University of Toronto (UofT) with approval from the Research Ethics Board (REB). Our lab setup was designed to be flexible to accommodate both training and experiment conditions. This necessitated an easily configurable hardware setup and coordination amongst multiple research staff. A standard operating procedure (SOP) was followed by research coordinators to maintain consistency in every run of the experiment.

3.2 Experiment Phases. All participants in the experiment went through the phases outlined in Fig. 3, namely, Training, Baseline, Practice, and Experiment. Participants completed both pre-study and post-study surveys. In the Training phase, we demonstrated study-specific CAD software capabilities. The research coordinators first demoed the use of a software feature, followed by hands-on exercises wherein participants worked independently. We customized our CAD software toolbar to show a subset of the full feature set which was specific to our experiment needs.

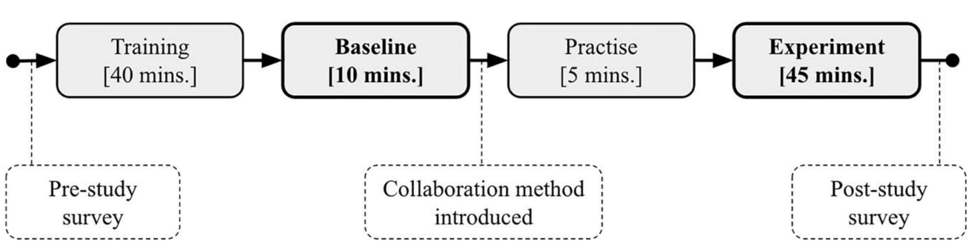

Fig. 3 Progression of participants through phases of the experiment. Time for each phase is shown in square brackets.

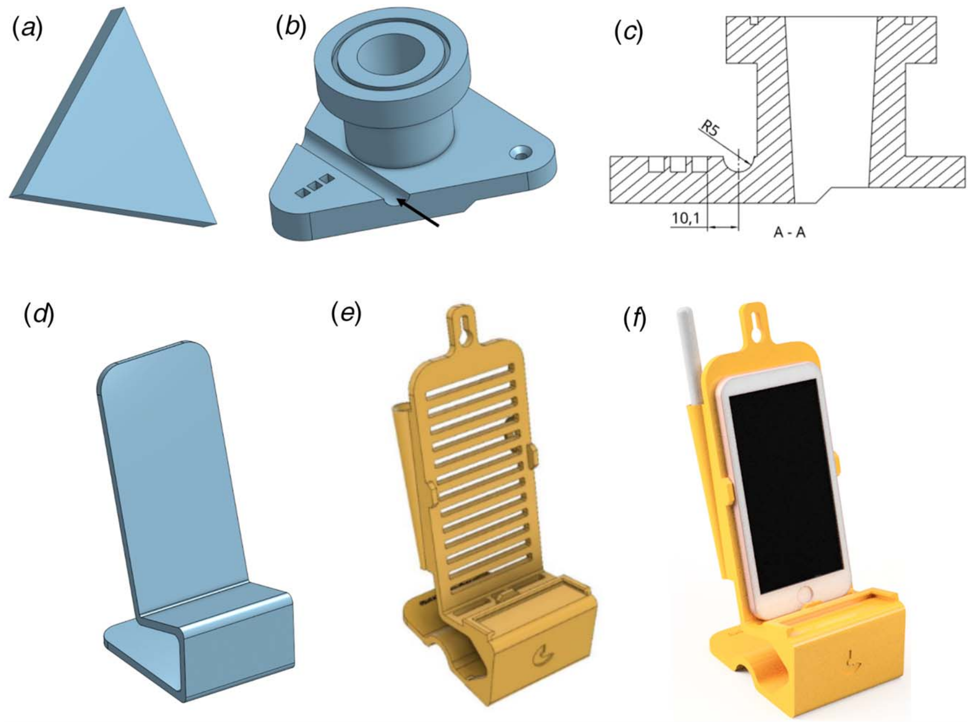

Fig. 4 (*a*) Initial CAD file provided in Baseline phase, (*b*) final CAD file in Baseline phase, (c) instructions (in mm) in Baseline phase, (*d*) initial CAD file provided in Experiment phase, (*e*) final Experiment phase CAD file renderings, and (*f*) use case of Experiment phase design artifact

Unlike in other cloud-based CAD experiments, we decided against using a CAD visualization test to qualify participant CAD skill [31,55]. Instead, performance in the Baseline phase was used as an indicator for the participant's incoming CAD skill. We used a minimum performance threshold as the prerequisite to continue in our experiment. Participants who could not finish a single Baseline task were asked to abort the experiment, and their data were discarded.

Next, participants were introduced to their prescribed working style. In the Practice phase, participants continued to work on Baseline tasks, but used the collaboration method. Participants were encouraged to ask questions and research staff checked in during and at the end of the Practice phase.

Finally, in the Experiment phase, participants used the prescribed working style to work through a new set of design tasks. The Experiment phase drew upon participants' experience from all previous phases and their ability to use the provided collaboration method.

3.3 Design Task. Design tasks were presented sequentially and after submitting, participants were not allowed to go back to a previous task. This ensured everyone progressed through the experiment in the same sequence. Each phase was populated with adequate design tasks such that no participant could finish the experiment before the stipulated phase times. All design tasks were created to be independent of each other. This was particularly important to pair CAD participants as it allowed for simultaneous work without disruption. Note that Training phase design tasks are not presented in this section, but an example is shown in Appendix A (Fig. 10).

We modeled Baseline phase design tasks on the Certified SOLIDWORKS Professional (CSWP) exam [56]. As shown in Fig. 4(*a*), participants started with a simple 3D model. Then, they were asked to progressively add complexity which would eventually lead to a final CAD file shown in Fig. 4(*b*). The transition steps were presented through a series of prescriptive drafting-focused design tasks. In total, the Baseline phase consisted of nine design tasks. An example drawing is shown in Fig. 4(*c*). A complete page pertaining to Fig. 4(*c*) is shown in Appendix A (Fig. 11). As a reminder, in the Practice phase, participants continued working on the Baseline phase CAD files.

The CAD model at the beginning of the Experiment phase depicted an initial version of a cell phone holder, as shown in Fig. 4(*d*). Then, the use case was explained using Fig. 4(*f*). Participants were asked to add features to the initial design based on a series of design task pages that showed a sequence of such user requirements. These requirements were still mostly detailed design and drafting focused, but with more complexity and open endedness. In total, the Experiment phase consisted of 14 design tasks. See an example of the Experiment design task in Appendix A (Fig. 12). Successful completion of all design tasks in the Experiment phase would result in a final design shown in Fig. 4(*e*).

3.4 Equipment (Hardware and Software). Our lab space emulated a typical design office environment; devoid of body mounted sensors and excessive video recording equipment. This provided a more natural setting for our participants. Figure 5 shows our setup and highlights the hardware listed here:

(1) Headphone with mic: Over-the-ear headset with external mic, remote control of volume and mute function.
(2) Web camera: Display mounted camera with 1080p × 60fps recording capability and a stable frame rate.
(3) Display: Ultra-wide 34″ (2560 × 1080) display that mimicked dual monitors. This allowed showing the design task instruction and CAD environment, side-by-side.
(4) Keyboard and mouse: Standard keyboard and three button mouse with scroll wheel.
(5) Furniture: Chairs had height and tilt adjustment. Portable room dividers were used to reconfigure the lab space during the Training and Experiment phases, see Fig. 5(*b*). The partitions also acted as noise barrier.
(6) Computers: All workstations had the necessary spec capable of processing cloud-based CAD software, audio/video

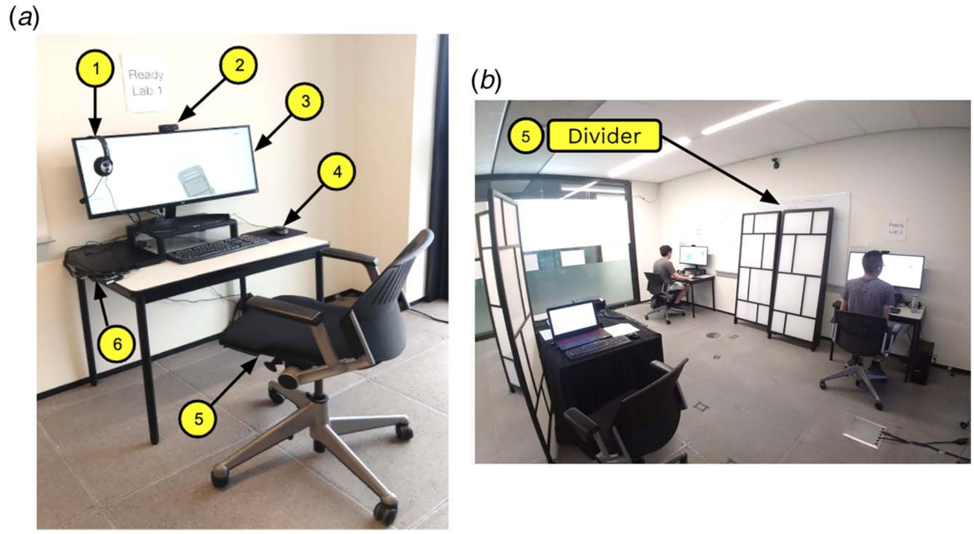

Fig. 5 (*a*) One of four participant workstations used in experiment and (*b*) movable divider screens used to reconfigure lab space for various phases

recording software, collaboration tools, and UI analytics, all at the same time. In addition to a multi-core CPU, computers were equipped with a high-performance graphics card to assist with the additional video rendering requirements of the CAD software.

The use of the noninvasive hardware approach meant that we relied heavily on software solutions to generate data. Below is a list of software tools used in the experiment.

- Cursor tracking: A PYTHON script logged participants' cursor locations, mouse clicks, keyboard strokes, and scroll activity.
- Video recording: We processed two video and audio streams using open broadcaster software (OBS). This allowed us to intermix audio/video tracks in real-time.
- Automation script: Given the complexity of the software suite, it was important to keep all data tracks synchronized in time. A version of the cursor tracking script was adapted to automate initializing of OBS and cursor tracking.
- CAD tool: We used Onshape as our CAD platform for all three working styles. It is fully cloud-based and provided real-time collaboration. All workstations used Windows 10 as the operating system and Google Chrome as the web browser.
- Communication: For pair participants, audio communication was connected through Google Hangouts. To minimize interference from multiple pair runs, we induced white noise in the background.

3.5 Operationalization Matrix. An operationalization matrix, shown in Table 1, was created in the planning stages of our work and helped us in designing the experiment method [58,59]. Table 1 ties research questions from Fig. 2 to datasets from the experiment.

3.6 Participants. Majority of the recruited participants were students. Experiments with student subjects have precedence in design research and pair programming literature [60–62]. We recruited from a range of universities in the Greater Toronto Area. Our experiments spanned over three semesters: Summer 2019, Fall 2019, and Winter 2020. Participants were paid for their time at the rate of $15 Canadian Dollars per hour. We received 201 signups expressing interest in participation. Sixty-six people were invited to the experiment, out of which 60 participant's data were accepted.

The average age of participants was 24.7 years, with 33.4 months of 3D CAD experience. 21.7% of participants self-identified as female. Participants were randomly assigned to their working styles ensuring that participants knowing each other were not in the same pair. This helped in maintaining consistency and did not offer unfair advantage to pairs with preexisting work relationships.

4 Results

4.1 Primary Research Questions. As a pair, Parallel CAD participants completed the most tasks (6.3 tasks on average) followed by Shared CAD (4.9 tasks on average) and Individual CAD (4.2 tasks on average). In other words, cumulatively, pairs accomplished more tasks than individuals. This result is also

Table 1 Operationalization matrix showing mapping of research questions to experimental data

Construct	Variables	Type of data (qty.)	Data source
Speed of work (RQ1)	Number of CAD tasks completed	Quantitative data ($n = 37$)	Time log sheets and user activity data from Qualtrics survey
Quality of work (RQ2)	Average quality of tasks completed	Quantitative data ($n = 37$)	Rating CAD files using standardized grading rubric [57]
Communication (S1)	Amount (%) of study time spent communicating	Quantitative data ($n = 23$)	Audio trace from web camera recording using open broadcaster software
User activity (S2)	Amount (%) of study time when the cursor was active	Quantitative data ($n = 60$)	Custom PYTHON script tracking cursor location, clicks, scroll, and keystrokes
Satisfaction (S3)	Self-reported satisfaction scores	Quantitative data ($n = 60$)	Average of Likert scale responses to post-study survey question

Table 2 Schematic showing calculation of speed in Experiment phase for Individual CAD participants

Code name	Design Task 1	Design Task 2	Design Task 3	Design Task 4	Design Task 5	Design Task 6	Design Task 7
Ind 1	739.8	394.8	612.1	330.3	462.8	NA	NA
Ind 2	1466.7	372.9	434.5	222.3	203.6	NA	NA
Ind 3	849.4	465.2	743.0	283.6	NA	NA	NA
Ind 4	407.7	250.8	403.7	567.7	483.3	366.3	218.7
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Ind 15	1125.6	485.9	1088.5	NA	NA	NA	NA
Average time	1016.7	507.0	596.9	445.1	341.0	440.3	218.7
Modifier ratios	4.7	2.3	2.7	2.0	1.6	2.0	1
Speed	4.7	7.0	9.7	11.7	13.3	15.3	16.3

visually illustrated in Appendix B (Fig. 13), which shows the final CAD files for all participants.

However, on a per-person basis, Individual CAD participants completed more tasks, followed by Parallel CAD and Shared CAD. This result is the first evidence in support of research question RQ1 and will be elaborated on in Sec. 4.1.1. The difference in the number of tasks completed per person by the three working styles was found to be statistically significant at the 5% level in a one-way analysis of variance (ANOVA).

4.1.1 Speed and Quality Metrics. Each task in the Experiment phase had a different mean and variance for a given working style. This can be seen in plots of task completion times in Appendix C (Fig. 14). To nullify the random effects from varying complexity of design tasks, we normalized speed metrics on a per-working-style basis. Table 2 shows a partial view of the approach used to calculate new normalized speed metrics. For illustration, we show calculations for Individual CAD participants only. A similar table was set up for all working styles in the Baseline and Experiment phase. Note that any final and incomplete tasks were excluded from our calculations. Our approach of calculating the speed score is summarized by Eq. (1), and the same is explained next.

The normalization process started with finding the average time taken for each task. Then, the minimum value from all average completion times was used as a reference. In Table 2, design task 7 is used as a reference and marked "1" in the modifier ratio row. Modifier ratios for the remaining tasks were calculated by dividing each average task completion time by the reference value. Lastly, the speed row shows a cumulative sum of values in the modifier ratios row.

Each participant's speed was determined by the value in the speed row, corresponding to the number of completed design tasks. For example, ICC 3 completed four design tasks in the Experiment phase, so their experiment speed was 11.7.

As pair CAD participants worked with another person, their speed score was halved

$$(\text{Speed})_{w,n} = \sum_{i=1}^{n} \frac{(\text{Average time})_i}{\min(\text{Average time})_n} \quad (1)$$

Quality ratings were calculated for each task as a percentage value based on the four categories: completeness, conciseness, consistency, and validity. These categories were adapted from prior work on CAD modeling quality by Company et al. [63]. A detailed description of the quality metric can be found in Arshad et al.'s publication [57]. Partial view of the grading rubric is shown in Appendix D (Tables 6 and 7). Quality scores were calculated as the average of ratings by two coders who used a grading rubric with an inter-rater reliability (IRR) of 96%; representing "almost perfect agreement" [64].

The normalized speed and quality metrics for all working styles are shown in Fig. 6. Treating Individual CAD as a reference, we see that Parallel CAD participants were slower and produced lower quality work. Shared CAD participants were slowest but produced the highest quality work. Two separate one-way ANOVA models tested the differences in speed and quality, and both model results were found to be statistically significant, thus serving as evidence in support of the research questions RQ1 and RQ2.

4.1.2 Assessing Influence of Pre-Existing Computer-Aided Design Skill. In this section, we test the dependency of speed and quality on participants' Baseline phase performance. In other words, we assess the effect of participant's preexisting CAD skill on their Experiment phase performance. For simplicity, we will refer to speed and quality scores from the Experiment phase as speed and quality. And metrics from the Baseline phase will be referred to as Baseline speed and Baseline quality.

We used stepwise linear regression models to investigate the dependence between Baseline metrics versus Experiment metrics.

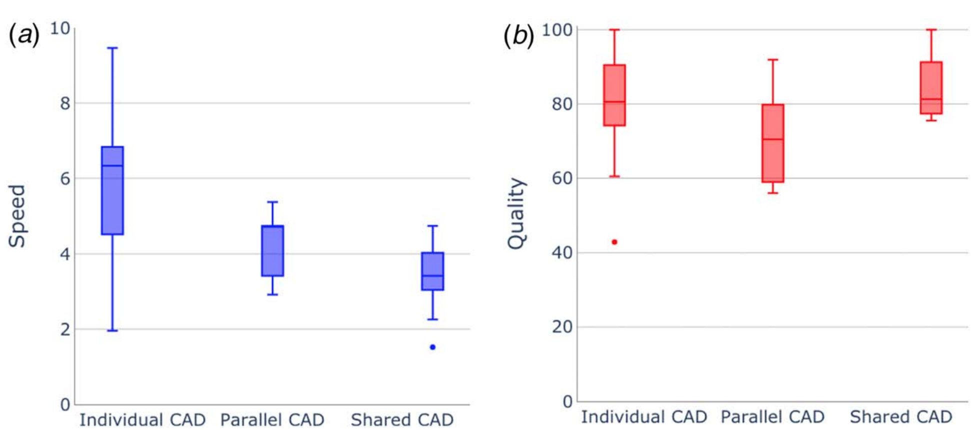

Fig. 6 (*a*) Speed and (*b*) quality metrics for all participants in Experiment phase, per-working style

Table 3 Results from stepwise regression models wherein speed and quality were treated as dependent variables

	Speed estimate (Delta)	Quality estimate (Delta)
Individual CAD speed	6.0 (0.0)	69.2 (0.0)
Parallel CAD speed	**2.4 (−3.6*)**	78.6 (9.5)
Shared CAD speed	**1.4 (−4.6*)**	**98.7 (29.6*)**
Baseline speed: Individual CAD speed	3.6 (−2.4)	N/A
Baseline speed: Parallel CAD speed	5.4 (−0.5)	N/A
Baseline speed: Shared CAD speed	5.4 (−0.5)	N/A
Baseline quality	N/A	N/A
Individual CAD speed: Individual CAD quality	5.5 (−0.5)	86.8 (17.7)
Parallel CAD speed: Parallel CAD quality	**2.8 (−3.2*)**	58.6 (−10.6)
Shared CAD speed: Shared CAD quality	3.9 (−2.1)	77.2 (8.1)
R^2	0.74	0.53

Note: All delta values higher than two standard deviations (2*1.5 for speed and 2*12.8 for quality) are highlighted in bold and marked with an asterisk.

We assembled two models wherein the independent variables were Baseline speed, Baseline quality, and the three working styles. In each model, the dependent variables speed and quality were treated individually. All values used in the regression analysis were normalized using z-score equivalent values. This allowed us to benchmark all variables at the same level and made comparing them easier. The full set of input values to our regression models are shown in Appendix E (Tables 8–10).

In stepwise regression, multiple regression models are validated iteratively by removing the weakest correlation term each time. The final outcome is a list of factors that best explains the relationship between the response variable and predictor variable. Table 3 shows the results of both regression models pertaining speed and quality. All values are estimates of the response variable, listed as the column heading, to a change in the predictor variable, listed as the row heading. For example, the models suggest that an Individual CAD participant performs at a speed of 6.0 and with a quality rating of 69.2, on average. The values mentioned in parenthesis are calculated as a deviation from the reference value, in this case, Individual CAD performance. A higher positive value in parenthesis means better performance compared with the reference, and vice versa. Further, all delta values higher than two standard deviations (2*1.5 for speed and 2*12.8 for quality) are highlighted in bold and marked with an asterisk.

In the speed estimate column, we see that all working styles had a significant effect on speed in comparison to the effect of Baseline speed. However, the interaction between Parallel CAD and quality is also significant.

In the quality estimate column, Baseline speed and Baseline quality were both removed. Working in Shared CAD had a dominant positive effect on quality, but the difference between quality of Individual CAD and Parallel CAD was not significant.

Lastly, Baseline quality was found to be insignificant and removed from both speed and quality estimates. The interaction between speed and quality is noticeable in both models and is investigated in Sec. 4.1.3.

Figure 7 shows the magnitude of main effect sizes for each regression model, along with the confidence intervals. Each main effect assumes that other attributes are held at a constant average value. The below plots reinforce the regression model result that the change in working style had the biggest effect on speed. However, the wide range confidence interval of the speed/quality interaction in Fig. 7(*b*) warrants further investigation.

4.1.3 Testing Interaction Between Speed and Quality. In both of the previous regression models, we saw indications of a high correlation between speed and quality. Figure 8(*a*) shows the clustering of the speed versus quality data for all working styles. Individual CAD and Shared CAD participants data follow a positive slope and Parallel CAD data track a negative slope.

Figure 8(*b*) is an interaction effects plot where the effect on quality is depicted on the *x*-axis and variables of interest are listed on the *y*-axis. All line plots were created by holding the respective variables (shown on *y*-axis marker) at a fixed value. The corresponding line plots were created by varying the *x*-axis variable over a range. This second (*x*-axis) variable was working style (Individual CAD to Shared CAD) in the top half and speed (1.5–8.5) in the lower half.

In the top half, we see that over different constant speed values, changing working style has a consistent effect on quality. In the bottom half, we see that a change in speed affects each working style differently. As speed increases, quality increases in Shared CAD and Individual CAD. But as speed increases, quality decreases for Parallel CAD. This result is in agreement with Fig. 8(*a*).

Findings so far had us suspect that a third covariate, experience as measured by Baseline speed, might have affected the speed versus quality interaction outcome in Fig. 8. However, a further interaction analysis of Baseline speed and quality did not support this hypothesis, and further work is required.

4.2 Supporting Research Questions. Results for the supporting research questions outlined in Sec. 3.2 are summarized in Table 4. Shared CAD participants communicated almost twice as much as Parallel CAD participants. This difference was found to be statistically significant, when tested with an independent two-sample *t*-test ($p < 0.01$). The difference in user activity, indicated by cursor data, was validated using a one-way ANOVA model and was also found to be significant ($p < 0.01$). However, as the ANOVA analysis included three samples, it could mean that only

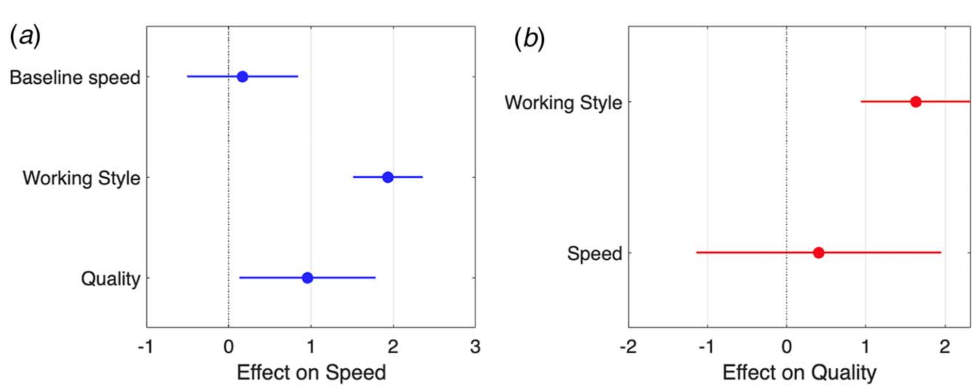

Fig. 7 Main effects of (*a*) speed and (*b*) quality from the stepwise regression

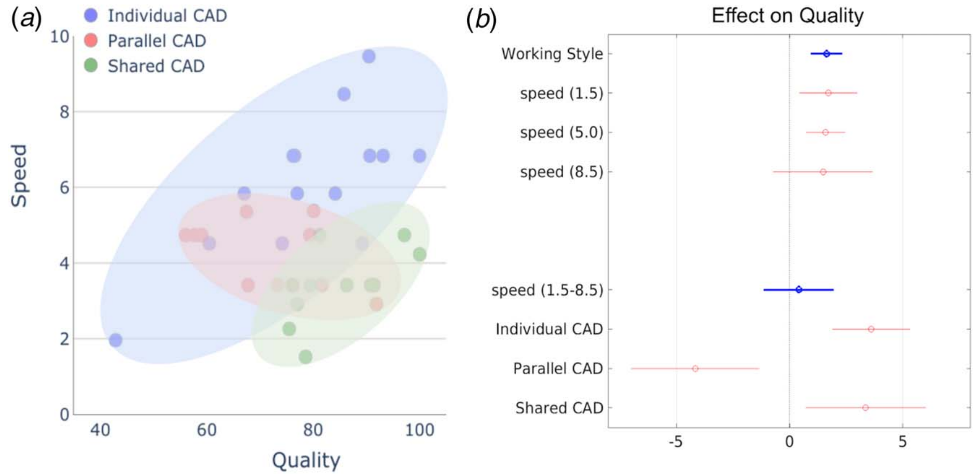

Fig. 8 Plots showing interaction between speed and quality: (*a*) clustering of speed versus quality data points and (*b*) effect on quality from interaction between speed and working style

Table 4 Summary of results elaborating on supporting research questions pertaining to communication, user activity, and satisfaction, with significance of statistical tests of difference

	Parallel CAD	Shared CAD	Individual CAD	*p*-value
Communication (% of 45 min)	41.5%	74.8%	NA	<0.01
User activity (% of 45 min)	60.2%	41.8%	56.0%	<0.01
Satisfaction (1–5, converted from Likert scale)	3.95	3.22	4.13	0.059

two out of the three samples were significantly different. To validate the ANOVA result, a post hoc test, Tukey's honestly significant difference (HSD) was conducted. This analysis showed a significant difference between all combinations, except in the case of user activity between Parallel CAD and Individual CAD.

Lastly, the satisfaction scores were calculated by converting Likert scale responses to a numeric value of 1–5. The difference in satisfaction scores was tested by a one-way ANOVA test. This result was not significant at the 5% level. To summarize, we found support for research questions S1 and S2, but not S3.

Note that audio communication of the participants was assessed at the pair level. Plots corresponding to audio communication and satisfaction can be found in Appendix F and G (Figs. 15 and 16). Extracting audio communication for each participant in a pair individually would entail manual processing of audio data. This process has been further explored in Vella et al.'s publication [65].

Data points of cursor activity for all participants are shown in Fig. 9. As seen, data from Individual CAD and both partners in Parallel CAD appear clustered tightly. However, we see a very clear division in cursor activity in Shared CAD pairs, similar to what we would expect in a driver-navigator relationship, where one user dominates the cursor activity in the pair.

4.3 Results Summary. Table 5 summarizes our findings on the research questions from Sec. 1.1. We found evidence in support of all research questions except S3, where the difference was not found to be statistically significant at the 5% level.

5 Discussion

5.1 Summary of Computer-Aided Design Performance. Our results agree with established norms in small group literature: overheads slow down collaborative work and limit team members from reaching their full individual potential [66]. In the experiment, these overheads manifested likely from coordination efforts,

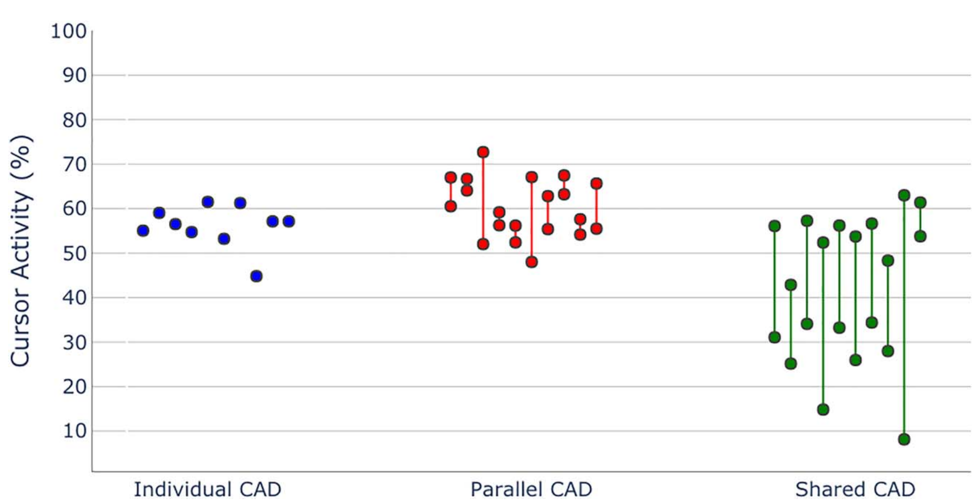

Fig. 9 Plots showing clustering of cursor activity data for all working style

Table 5 Summary of findings on primary and supporting research questions

Primary research questions			
RQ1	On a per person basis, is Individual CAD faster than Parallel CAD and Shared CAD?	Supported ($p < 0.00$)	Although Parallel CAD completed most tasks as pairs, they were slower than individuals and faster than Shared CAD on a per-person basis.
RQ2	Does Shared CAD lead to higher quality compared to Parallel CAD and Individual CAD?	Supported ($p = 0.03$)	Shared CAD participants performed highest quality work followed by Individual CAD and Parallel CAD.
Supporting research questions			
S1	Do Shared CAD participants communicate as much as Parallel CAD participants?	Supported ($p < 0.00$)	Shared CAD participants communicated almost twice as much as Parallel CAD.
S2	Do Parallel CAD participants show more comparable user activity than Shared CAD?	Supported ($p < 0.00$)	All CAD working styles showed significantly different levels of cursor activity.
S3	Are Parallel CAD and Shared CAD participants more satisfied than Individual CAD participants?	Not supported ($p = 0.059$)	The average self-reported scores from the post-study survey assessing user satisfaction did not show significant difference.

communication, and awareness seeking. For example, Parallel CAD participants had to account for additional time to update their collaborator, given the dynamic nature of the CAD file. As a result, they spent less time on CAD modeling and progressed slower than Individual CAD participants. Similarly, Shared CAD participants communicated with each other for 75% of the study time on average, which reduced the time and attention available for CAD modeling activities. However, in the case of Shared CAD, the limitation of lack of dual editing freedom, as expected, was found to curtail speed the most.

On the contrary, CAD quality was expected to improve from having "more eyes" on the same CAD file. This effect turned out to be true only in the case of Shared CAD, where there was directed attention toward a unified modeling experience. This result suggests that a shared visual artifact plays a major role in the communication of CAD work and warrants future work. We conjecture that sharing the CAD visually also led to significantly higher levels of audio communication between Shared CAD participants. We believe the combination of higher/frequent communication and increased awareness led to better CAD quality in Shared CAD.

Driver-navigator style pairing is common in software pair programming. In the experiment, only Shared CAD participants demonstrated such role-play. In Shared CAD pairs, one participant clearly dominated the cursor activity. This also suggests that in each Shared CAD pair, one participant was always focused on overseeing their partner's work and reviewing the requirements. Further, the Shared CAD environment forced pairs to come to a mutual agreement on design decisions before progressing. This two-fold validation process is possibly another reason for the higher quality in Shared CAD.

Conversely, Parallel CAD participants could progress in less structured way, without each other's consent. Cursor activity data showed Parallel CAD participants behaved similar to Individual CAD, alluding to the fact that Parallel CAD participants showed more work equity. We observed that faster Parallel CAD participants produced lower quality work, as would be expected by our traditional understanding of the time-performance tradeoff in product development; yet the opposite relationship was true for Shared CAD and Individual CAD, warranting further investigation.

5.2 Recommendations for Pair Computer-Aided Design Work.

We have demonstrated that CAD style has an effect on the design outcome. However, choosing only one pair CAD style or using pair work throughout the design process might not be the best strategy. A hybrid model which employs pair work in a focused manner, for a specific time, might be ideal. For example, during a crucial design milestone, teams might employ Shared CAD to produce a higher-quality outcome and improve designers' confidence. Once crucial decisions are made and the team is predominantly CAD drafting, they might choose Parallel CAD for its higher speed.

Another approach suggested by a participant in the post-study survey was to provide pairs the ability to transition between Parallel CAD and Shared CAD on-the-fly. This approach will better leverage the advantages of both pair CAD working styles. Although ideal, this warrants an expansive screen size and an elaborate software suite.

Computer-aided design is just one element in the array of tools needed for pair CAD work. We recommend that designers use synchronous collaboration tools like Google Docs, Slack, and Zoom to augment pair CAD tools.

5.3 Limitations.

The results of our experiment are constrained by the nature of the design tasks presented to our participants and the duration of the experiment. This means that our results lay the foundation in this niche research area but do not necessarily generalize to all industrial settings.

Employing students as participants, though common in our field, limits the application of our results in the industry [40]. The short duration of the experiment limited the potential of teams to develop a more mature working relationship. We acknowledge that our results could change if the participants had more than one opportunity to work together. These limitations mean that our results do not directly translate to industry work without further validation.

Although not studied in depth, an understanding of a participant's technical background, personality attributes, and learning preferences may also be critical to success in CAD work [67]. These attributes warrant to be studied in more detail.

Lastly, the sample size used in our experiment was limited by financial and time implications of running complex experiments. Although we found statistical significance in some of our results, a follow-up experiment with a larger sample is necessary to reevaluate results with statistical tests of additional power.

5.4 Future Work.

The immediate next step would be to generalize our findings by validating the results in a professional setting. Then, the application of our results would have to be studied over the entire design process as constraints in using CAD are design-phase-dependent [68]. This step could be executed as a case study in the industry. It is important to allow the use of pair CAD for a sustained period of time as that will give participants an opportunity to evolve their preferred working style. Through this work, the results of our work will be translated to professional practice.

The eventual success of pair CAD work will rely on developing design and training supports for pair CAD work. An illustrative example of this within the design research community is ENERGY3D [69]. In Rahman et al.'s work, design supports are added to a 3D CAD environment to integrate design thinking principles into the design decision-making process.

6 Conclusions

In conclusion, are two heads better than one in CAD? As is often the case for research results, it depends. Through this research, we have observed and described the tradeoffs and plausible mechanisms for pair CAD work and set the precedence for future investigation.

A primary analysis of the data investigated the speed versus quality tradeoff. We found that pair CAD did not produce twice the outcome of individual CAD. This can possibly be attributed to coordination overheads in group work. An analysis of CAD model quality revealed that sharing the CAD environment produced the highest quality work. On the contrary, parallel work in CAD produced the worst quality outcome. To be comprehensive, we tested the speed versus quality results with additional variables using a stepwise linear regression model. We found no significant association between our speed versus quality results and participants' incoming CAD skill. However, the correlation between speed and quality was notable. In particular, speed and quality were positively correlated for Shared CAD and Individual CAD but inversely for Parallel CAD.

To expand upon our findings, we investigated supporting research questions. First, we found that Shared CAD participants communicated almost twice as much as Parallel CAD participants. Next, we looked at cursor activity to understand user activity during the experiment. We noticed that Shared CAD participants adhered to clear driver-navigator type role-taking and Parallel CAD participants showed more work equity.

Driven by Industry 4.0, the transformation of design engineering is already underway. The collaborative capabilities of new cloud-based CAD unlock the potential for new and creative ways of working. Our study emphasizes that in order to reap the tailored benefits of new technology, we should consider not only the tools themselves, but the process by which the human designer uses the tools.

Acknowledgment

The authors would like to start by thanking all the participants for their time. Next, we wish to thank Meaghan Vella and Xiangjiu (Jennifer) Wu for their assistance in running the experiments. We thank Professor Dan Frey for his inputs on helping us think through the statistical analysis portion of our work. Lastly, we would like to thank Mitacs Globalink and the University of Toronto's Dean's Spark Professorship for funding this work.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper.

Appendix A: Design Task Examples

An Instruction Page From the Training Phase

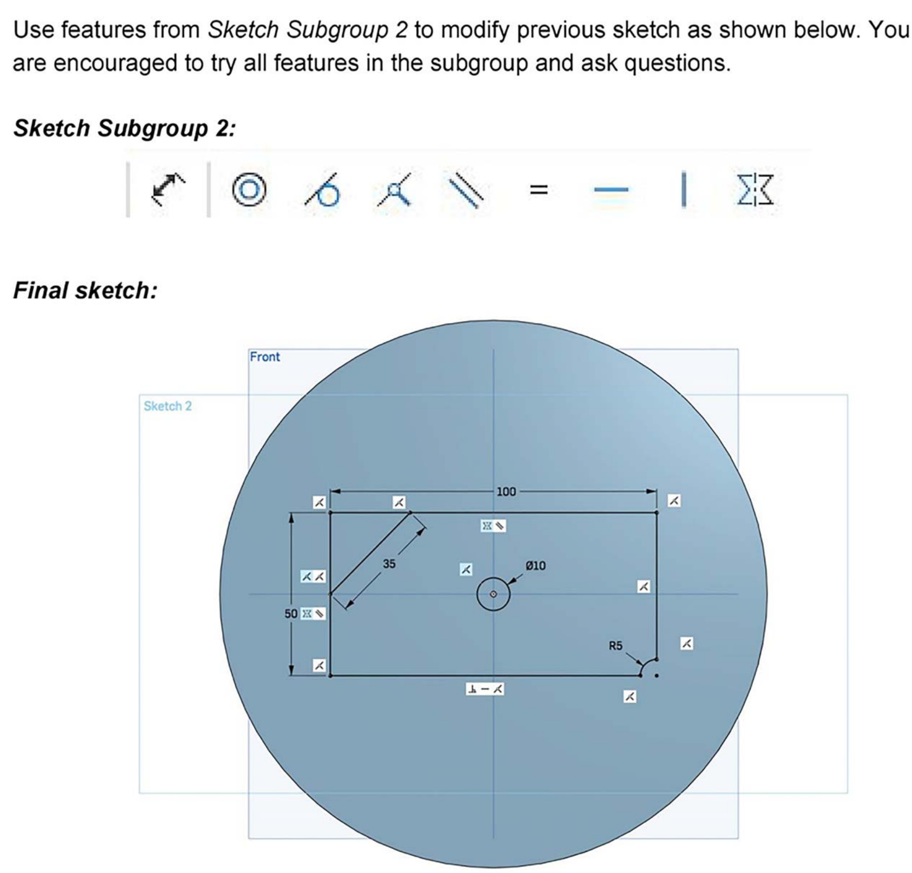

Fig. 10 Example Training phase design task

Image of CAD feature:

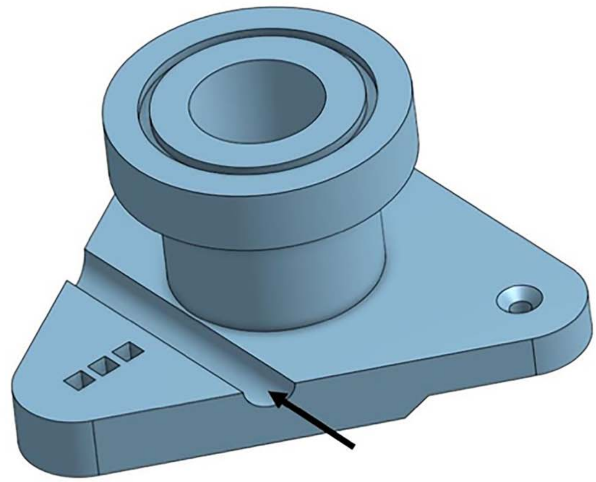

Figure 18. Groove on the baseplate

2D drawing:

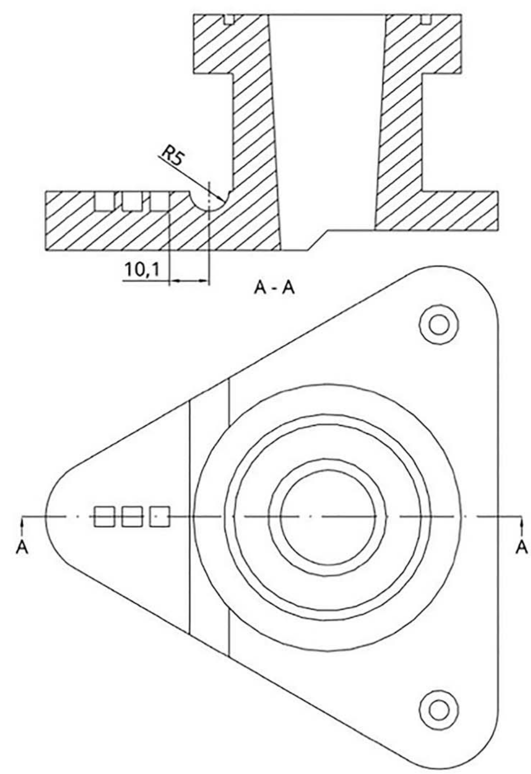

Figure 19. Dimensions of the groove [in mm]

Feature requirements:

- Perpendicular to line A-A in *Figure 19*

Fig. 11 Example Baseline phase design task

An Instruction Page From the Experiment Phase

Renderings:

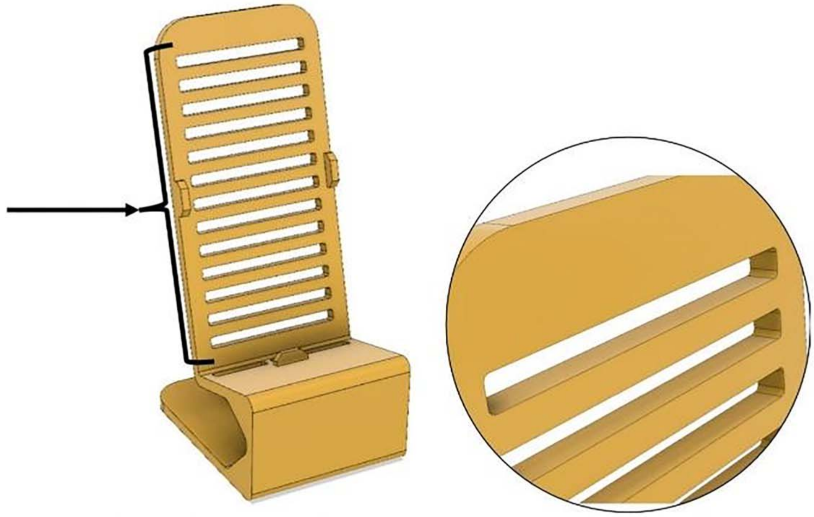

Figure 8. Phone holder with slots for air circulation (left), Closeup (right)

Phone drawing:

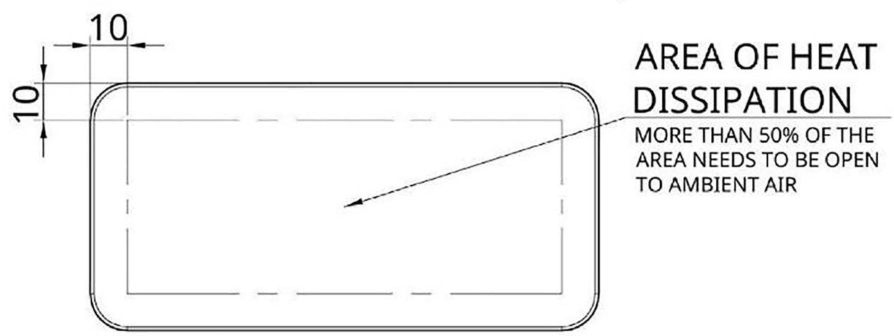

Figure 9. Area of heat dissipation on the back panel of the phone [in mm]

Feature requirements:

- More than 50% phone area is open to air in landscape orientation
- More than 50% phone area is open to air in portrait orientation

Fig. 12 Example Experiment phase design task

Appendix B: Participant Computer-Aided Design Files

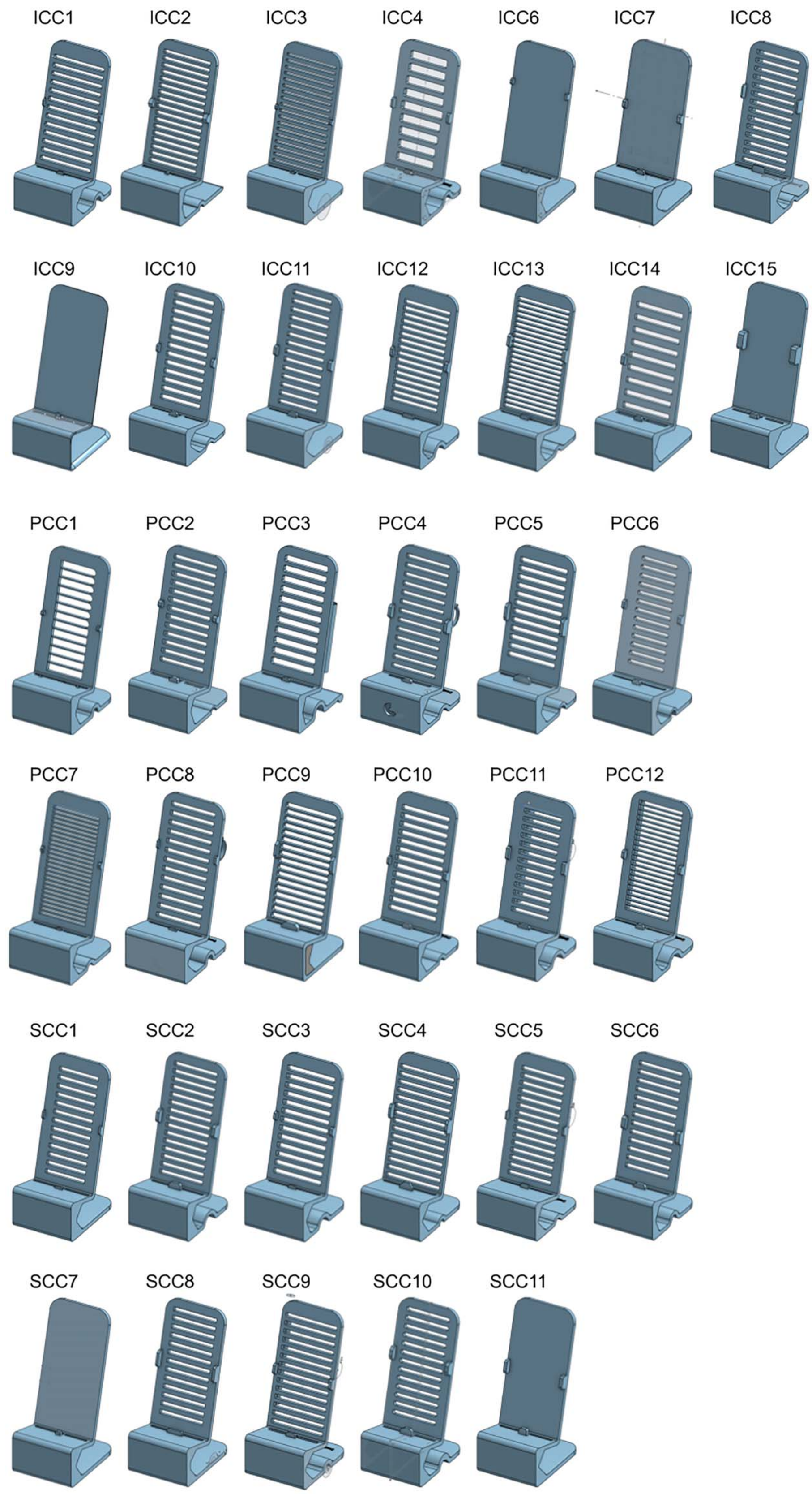

Fig. 13 Final experiment CAD files from participants

Appendix C: Variance Between Design Tasks. Here, we take a closer look at the completion times for each Experiment phase design task. Although we strived to create design tasks with comparable complexity, it was impossible to be exactly consistent as every CAD designer's modeling preferences are unique. Figure 5 captures the variance in design task completion times. As can be seen, each task had a different mean and variance for a given working style. To nullify the random effects from varying complexity of design tasks, we normalized speed metrics on a per-working-style basis.

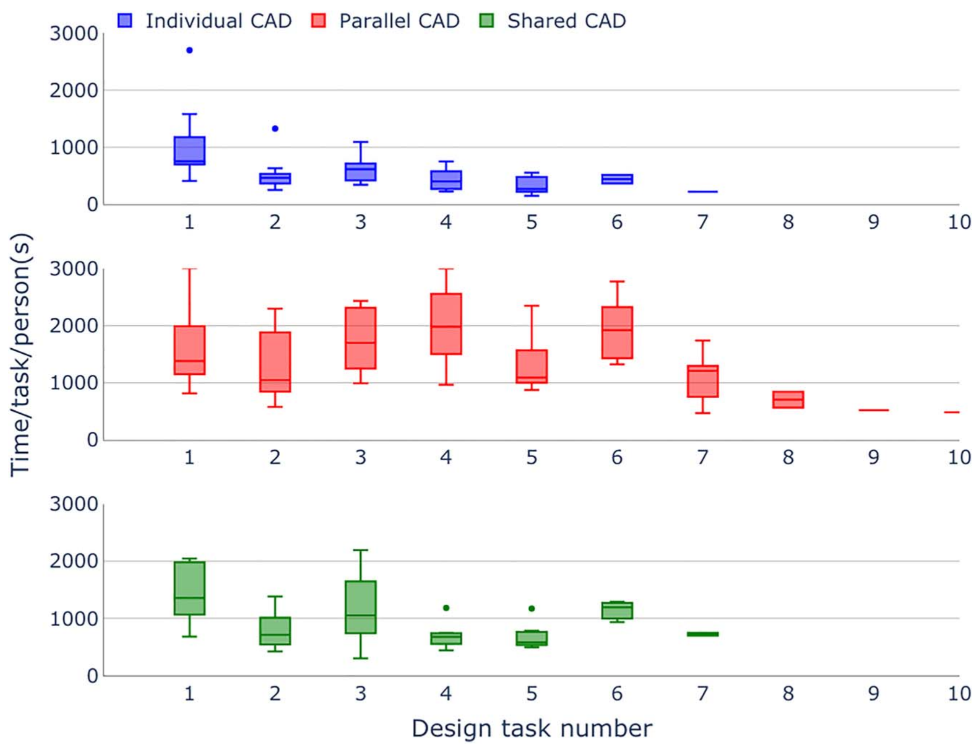

Fig. 14 Variation in task completion times versus working styles

Appendix D: Quality Grading Rubric

$$(\text{Quality})_k = \frac{\sum_{i=1}^{m}\left(\sum_{j=1}^{n}\frac{x_j}{n}\right)}{m}$$

Table 6 Categories of scores used in quality calculations, adapted from Company et al. [63]

Metric category	Definition	Indicator
Complete	Replicates drawing accurately	• Replicates size accurately • Replicates shape accurately
Concise	Replication features used (e.g., use of offsets and mirrors)	• Replication features used when available
Consistent	Fully constrained and dimensioned with no new parts	• Fully constrained Dimensioned in reference to the model
Valid	No failed instances	• No errors in the model tree

Table 7 Partial view of quality grading rubric

#	Description	Cat.	ICC1	ICC2		ICC15
	CAD visually resembles rendering	Cmp	1	1	⋯	1
	Charging cable fits through center-hole. D (MIN) is 3 mm.	Cmp	1	1	⋯	1
	While the phone is on the holder, center-hole is directly below the charging port. MAX 2.05 mm.	Cmp	1	1	⋯	0
	Replication feature used correctly (i.e., correct feature, direction, and/or number of times)	Cnc	1	1	⋯	1
	Sketch is fully defined (i.e., black)	Cns	1	1	⋯	1
1	Quality score for feature # 1		100%	100%	⋯	70%
	⋮		⋮	⋮		⋮
	Average quality score for participant		100%	76%		60%

Appendix E: Input to Regression Models. Legend for Tables 8–10:

A = number of tasks completed in the Baseline phase
B = Baseline phase speed score
C = Baseline phase quality score
D = number of tasks completed in Experiment phase
E = Experiment phase speed score
F = Experiment phase quality score
Z_B = z-score equivalent of Baseline phase speed score
Z_C = z-score equivalent of Baseline phase quality score
Z_E = z-score equivalent of Experiment phase speed score
Z_F = z-score equivalent of Experiment phase quality score

Note that for Parallel CAD and Shared CAD participants, data in columns D, E, and F are repeated for both participants of the same pair.

Table 8 Individual CAD performance data

Code name	A	B	Z_B	C	Z_C	D	E	Z_E	F	Z_F
ICC 1	5	7.8	0.8	100	0.7	5	6.8	1.6	100	1.7
ICC 2	4	6.7	0.2	100	0.7	5	6.8	1.6	76.5	−0.1
ICC 3	4	6.7	0.2	75	−2	4	5.8	0.9	77	−0.1
ICC 4	1	1	−2.8	100	0.7	7	9.5	3.3	90.5	1
ICC 6	4	6.7	0.2	87.5	−0.6	3	4.5	0.1	74.2	−0.3
ICC 7	4	6.7	0.2	100	0.7	3	4.5	0.1	89.2	0.9
ICC 8	5	7.8	0.8	90	−0.4	6	8.5	2.6	85.8	0.6
ICC 9	4	6.7	0.2	87.5	−0.6	1	2	−1.6	42.9	−2.7
ICC 10	3	5.1	−0.6	100	0.7	5	6.8	1.6	76.2	−0.1
ICC 11	5	7.8	0.8	90	−0.4	4	5.8	0.9	84.1	0.5
ICC 12	4	6.7	0.2	87.5	−0.6	5	6.8	1.6	90.6	1
ICC 13	4	6.7	0.2	100	0.7	5	6.8	1.6	93.1	1.2
ICC 14	4	6.7	0.2	100	0.7	4	5.8	0.9	67	−0.8
ICC 15	3	5.1	−0.6	100	0.7	3	4.5	0.1	60.5	−1.4

Table 9 Parallel CAD performance data

Code name	A	B	Z_B	C	Z_C	D	E	Z_E	F	Z_F
PCC 1-1	5	7.8	0.8	100	0.7	5	3.4	−0.6	76.2	−0.1
PCC 1-2	2	2.9	−1.8	100	0.7	5	3.4	−0.6	76.2	−0.1
PCC 2-1	3	5.1	−0.6	75	−2	7	4.7	0.2	59	−1.5
PCC 2-2	4	6.7	0.2	66.7	−2.9	7	4.7	0.2	59	−1.5
PCC 3-1	4	6.7	0.2	100	0.7	7	4.7	0.2	57.7	−1.6
PCC 3-2	4	6.7	0.2	100	0.7	7	4.7	0.2	57.7	−1.6
PCC 4-1	5	7.8	0.8	75	−2	8	5.4	0.6	67.5	−0.8
PCC 4-2	4	6.7	0.2	90	−0.4	8	5.4	0.6	67.5	−0.8
PCC 5-1	1	1	−2.8	100	0.7	5	3.4	−0.6	67.7	−0.8
PCC 5-2	4	6.7	0.2	87.5	−0.6	5	3.4	−0.6	67.7	−0.8
PCC 6-1	5	7.8	0.8	100	0.7	5	3.4	−0.6	73.2	−0.4
PCC 6-2	3	5.1	−0.6	70	−2.5	5	3.4	−0.6	73.2	−0.4
PCC 7-1	4	6.7	0.2	75	−2	5	3.4	−0.6	81.6	0.3
PCC 7-2	3	5.1	−0.6	100	0.7	5	3.4	−0.6	81.6	0.3
PCC 8-1	4	6.7	0.2	100	0.7	9	5.4	0.7	80.1	0.2
PCC 8-2	4	6.7	0.2	100	0.7	9	5.4	0.7	80.1	0.2
PCC 9-1	1	1	−2.8	100	0.7	4	2.9	−0.9	91.9	1.1
PCC 9-2	4	6.7	0.2	100	0.7	4	2.9	−0.9	91.9	1.1
PCC 10-1	2	2.9	−1.8	75	−2	7	4.7	0.2	58.9	−1.5
PCC 10-2	4	6.7	0.2	100	0.7	7	4.7	0.2	58.9	−1.5
PCC 11-1	5	7.8	0.8	100	0.7	7	4.7	0.2	79.4	0.1
PCC 11-2	4	6.7	0.2	87.5	−0.6	7	4.7	0.2	79.4	0.1
PCC 12-1	5	7.8	0.8	90	−0.4	7	4.7	0.2	56	−1.7
PCC 12-2	4	6.7	0.2	87.5	−0.6	7	4.7	0.2	56	−1.7

Table 10 Shared CAD performance data

Code name	A	B	Z_B	C	Z_C	D	E	Z_E	F	Z_F
SCC 1-1	4	6.7	0.2	100	0.7	5	3.4	−0.6	91.4	1.1
SCC 1-2	5	7.8	0.8	90	−0.4	5	3.4	−0.6	91.4	1.1
SCC 2-1	5	7.8	0.8	83.3	−1.1	5	3.4	−0.6	86.3	0.7
SCC 2-2	3	5.1	−0.6	100	0.7	5	3.4	−0.6	86.3	0.7
SCC 3-1	6	9.5	1.7	87.5	−0.6	6	4.2	−0.1	100	1.7
SCC 3-2	4	6.7	0.2	94.4	0.1	6	4.2	−0.1	100	1.7
SCC 4-1	5	7.8	0.8	100	0.7	5	3.4	−0.6	79.4	0.1
SCC 4-2	2	2.9	−1.8	100	0.7	5	3.4	−0.6	79.4	0.1
SCC 5-1	6	9.5	1.7	94.4	0.1	7	4.7	0.2	97.1	1.5
SCC 5-2	5	7.8	0.8	100	0.7	7	4.7	0.2	97.1	1.5
SCC 6-1	4	6.7	0.2	100	0.7	5	3.4	−0.6	75.9	−0.2
SCC 6-2	4	6.7	0.2	100	0.7	5	3.4	−0.6	75.9	−0.2
SCC 7-1	4	6.7	0.2	87.5	−0.6	2	1.5	−1.8	78.6	0.1
SCC 7-2	2	2.9	−1.8	100	0.7	2	1.5	−1.8	78.6	0.1
SCC 8-1	3	5.1	−0.6	83.3	−1.1	4	2.9	−0.9	77	−0.1
SCC 8-2	5	7.8	0.8	100	0.7	4	2.9	−0.9	77	−0.1
SCC 9-1	5	7.8	0.8	90	−0.4	7	4.7	0.2	81.3	0.3
SCC 9-2	5	7.8	0.8	100	0.7	7	4.7	0.2	81.3	0.3
SCC 10-1	4	6.7	0.2	100	0.7	5	3.4	−0.6	90.8	1
SCC 10-2	2	2.9	−1.8	100	0.7	5	3.4	−0.6	90.8	1
SCC 11-1	4	6.7	0.2	87.5	−0.6	3	2.3	−1.4	75.5	−0.2
SCC 11-2	3	5.1	−0.6	100	0.7	3	2.3	−1.4	75.5	−0.2

Appendix F: Plot Showing Audio Activity Difference for Pair Working Styles

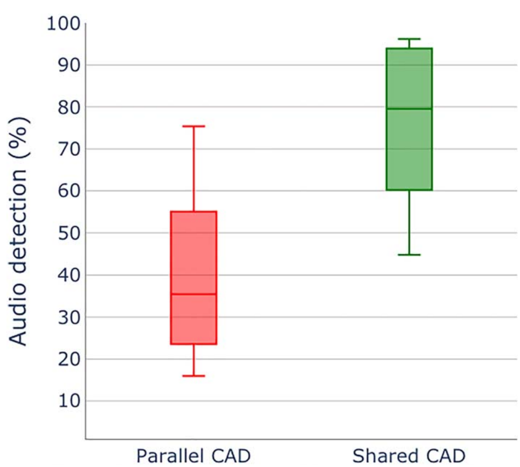

Fig. 15 Audio activity versus working style

Appendix G: Plot Showing Satisfaction Scores for All Working Styles

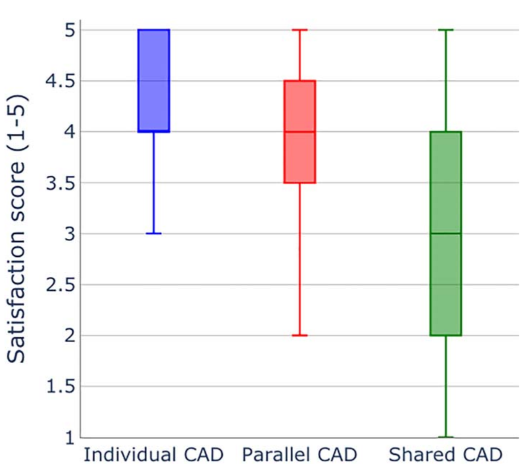

Fig. 16 Satisfaction score versus working style

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