CHARACTERIZING COMPUTER AIDED DESIGN MASTERY: WHAT DIFFERENCES EXIST BETWEEN EXPERT AND NOVICE USERS?

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Abstract

The goal of this work is to characterize "expert" student CAD use and examine whether differences from novices are related to factors such as gender, seniority, co-op experience, and spatial ability.

Participants were recruited from a second-year mechanical engineering course and extra-curricular engineering technical teams. The groups were Novice (Year 2, not on a team, n=13), Junior (Year 2, on a team, n=7), Senior (Year 3+, on a team, n=12). Participants completed a spatial task (PSVT:R, Purdue Spatial Visualization Test) and a CAD task while being asked to describe their process (verbal protocol analysis).

Groups were similar in gender composition. The spatial task (PSVT:R) performance was not related to gender, year of study, or use of CAD on co-op. Spatial performance was related to team participation.

Two major differences in process were coded. One was references to past work. Seniors were more likely to reference co-op experience than Novices (p=0.03), Juniors were more likely to reference academic work compared to Seniors (p=0.04). The other significant difference was the method used for construction. Seniors were less likely to use a "cut away" approach to making their part than Novices (p=0.004) or Juniors (p=0.002). Seniors were more likely to trace geometry and extrude their part compared to Novices (p=0.004).

The difference in referenced prior work presents an opportunity for instructors as many more students participate in co-op than in extra-curricular teams. This could be leveraged by encouraging students to contextualize learning from co-op or by creating industrially-relevant assignments. The difference in approach to creating the object suggests that CAD instructors could be introducing students to higher level tools earlier. This could be done through assignments that authentically demand more complicated geometries.

Keywords: CAD, Spatial, Extracurricular Teams

1. INTRODUCTION

When we think about the core academic topics our mechanical engineering students need to master, we often gravitate towards "hard science" topics like math and physics, and applied sciences such as fluid dynamics. Computer Aided Design (CAD) is often viewed as being a less academic topic because it is "just software" and can hence be learned from software-specific documentation. However, students use CAD extensively in their co-op placements and in extracurricular activities, and as we move towards more project-based approaches in engineering education, strong CAD skills will continue to take on more importance academically. Our aspiration should be to help our students achieve competent and efficient performance using these tools so that they can deliver high-quality, ambitious design work that is not limited by their CAD abilities.

Instructors set clear expectations for the standards to which finished CAD work should conform, but often little guidance on *how* that work should be done. CAD tasks are assigned and then assessed summatively or indirectly by grading the output, such as a prototype or drawing. Observing students in class, we often see a group of students who "get it" quickly, and a group of students who continue to struggle with CAD throughout their academic careers. This paper attempts to understand what makes the struggling students different from the ones who "get it", and if those differences might provide clues to how we could better support students who lag behind. Making these process improvements could also indirectly enhance the diversity of extracurricular engineering technical teams and co-ops, as these students may feel more confident pursuing the types of work that they may have self-selected away from in the past.

Part of the complication in studying CAD is that it is a composite task. One element is the software itself (e.g. "Where are the tools within the interface?" "What does each tool do?"), and one element is the mental model associated with constructing a part or assembly (e.g. "How do I make a cube?"). The third element, real world background knowledge about how parts are formed and assembled, is likely the most incomplete element for very novice students. The composite nature of the task is supported and described thoroughly by Chester [1].

Students who are on engineering technical teams, such as Mini Baja or Formula Electric, form an appealing natural experiment for studying CAD mastery. These are students who are at the same academic and maturity level as their colleagues, but have superior skills across all three elements of CAD; they are a group of students who could be characterized as “experts”. This gives us a more informative comparison than industry-level experts with multiple years of full-time CAD experience because the students form a group of “near-peers”.

We have good evidence over a large number of years that the engineering technical teams are a crucible for technical skill acquisition and are a target for recruitment for engineering employers[2]–[5]. Based on the general psychology literature regarding skill acquisition [6] these teams satisfy many of the criteria previously identified for optimal skill development: they encourage distributed practice, develop a rich library of problem spaces, encourage students to explain their actions to others, and are a form of integrative training. What we still don’t know is specifically how or where those skills are acquired, or if superior technical skills are inherent in the students themselves. Previous work suggests that the students’ attitudes and motivations are broadly similar in these groups [7]; this paper builds on that work by investigating how they might differ in their approaches to a specific technical task.

We also know from past literature that spatial ability has been linked to engineering academic performance in general [8], [9]. Past work in the area of engineering student skill acquisition [10] has focused on conceptual design skills, not technical CAD skills. The current study aims to to characterize “expert” student CAD use and examine whether differences from novices are related to other factors such as gender, seniority, co-op, and spatial ability.

2. METHODS

2.1. Participants and Recruitment

This study was approved by the research ethics board. Participants were recruited from a second-year mechanical engineering design communication course (MECHENG 2A03) and from extracurricular engineering technical teams via email and announcements on the course website. Participants were directed to a LimeSurvey [11] form with a series of screening questions, demographic questions and a letter of informed consent. The inclusion criteria were being enrolled in an undergraduate engineering program and either currently taking MECHENG 2A03 or currently using CAD in an extracurricular engineering technical team. Participants were also asked to self-report their confidence reading and creating technical drawings on a 5-item Likert scale (with 1 being “not confident at all” and 5 being “very confident”). Participants who met the screening criteria and were able to complete a data collection with a student assistant received a gift card as a study incentive.

The participant groups were Novices (second-year students currently taking MECHENG 2A03 but not on an engineering extracurricular technical team), Junior Team Members (second-year students currently on an extracurricular engineering technical team), Senior Team Members (third-year or higher students currently on an extracurricular technical team). For brevity, from here forwards in this paper, “Team” will refer to an extracurricular engineering technical team, such as Mini Baja or Formula Electric.

2.2. Data Collection

Data were collected by recording a Microsoft Teams[12] video call. During this call, the participant shared their screen while they completed a standardized spatial task (PSVT:R, Purdue Spatial Visualization Test) [13] and a technical computer-aided design (CAD) task (creating a part, making an assembly with another part and creating a technical drawing of that part). The CAD task, (as shown in Appendix 1) was completed with AutoDesk Inventor software [14]. As participants completed the CAD task they were asked to describe their process, a data collection technique called verbal protocol analysis [10].

2.3. Transcript Data Coding

After the task was complete, a transcript of the call was generated and coded for themes in Dedoose software [15]. Grounded textual coding was used so that themes could emerge from partial or unstructured responses [16], [17]. Two raters coded each transcript against the same coding dictionary, which is included as Appendix 2.

2.4. Data Analysis and Statistics

Likert scale data (confidence questions) by category were assessed with a Mann-Whitney U-Test in MATLAB[18]. A U-Test functions similarly to a t-test, but for categorical data rather than continuous data. Correlations between PSVT:R and confidence questions were assessed with a Spearman Rank Correlation in MATLAB, which functions similar to a linear correlation but without the assumption of continuous data. PSVT:R score by group was compared with a t-test in MATLAB.

Coded transcript data were analyzed by creating a code presence chart in Dedoose [15]. If a code was present in both raters’ versions, it was given a score of 1; if it was not present or only present in one of the rater’s versions, it was given a score of 0. Inter-rater agreement was calculated using Cohen's Kappa[19]. The binary data in the code presence chart were analyzed for proportion with a series of Fisher's Exact tests in MATLAB.

All statistical tests had an alpha (significance level) set to 0.05, which was corrected for multiple comparisons with a Holm-Šidák correction, (p=0.017) [20]. The statistical power of the significant tests was determined post-hoc with G*Power [21]. A power in excess of 0.8 is considered to be a sufficiently powered comparison[22].

3. RESULTS

3.1. Demographics and Likert Scale Questions

There were a total of 32 participants in the study. The groups were similar to one another in terms of in gender composition (p=0.11, using a Fisher's Exact test). Demographic factors are summarized in Table 1.

Table 1: Demographics

Variable	Descriptor	n=
Group	Novice (Year 2, not on a team)	13
	Junior Team Members (Year 2, on a team)	7
	Senior Team Members(Year 3+, on a team)	12
Gender	Female	12
	Male	20
	Non-binary Gender Fluid and/or Two-Spirit	0
Program of study	Mechanical engineering	29
	Mechatronics engineering	2
	Electrical engineering	1
CAD on co-op	Yes	9
	No	23
Year of study	2	20
	3	6
	4	3
	5+	3

There were no significant differences between any group in confidence reading technical drawings. However, Novices were significantly less confident than Senior Team members creating technical drawings. These findings are summarized in Table 2.

3.2. Spatial Task Performance

Spatial task performance was correlated with confidence creating drawings, with a higher spatial score (PSVT:R) corresponding to higher self-reported confidence creating drawings, as summarized in Table 3.

The spatial task (PSVT:R) performance was not related to gender, year of study, or use of CAD on co-op. Spatial performance was related to team participation. Senior mean score was 25.63, Junior mean score was 25.57, and Novice mean score was 21.7 (p=0.01). These results are summarized in Table 4.

3.3. Coded Transcript Data

Two major differences in process were coded, as summarized in Table 5. One was references to past work. Seniors were more likely to reference co-op experience than Novices (p=0.03), and Juniors were more likely to reference academic work compared to Seniors (p=0.04). However, these differences did not meet the corrected significance level or sufficient power level.

The largest and most well-powered differences were features used for construction. Senior Team members were less likely to use a "cut away" approach to making their part than Novices (p=0.004) or Junior Team members (p=0.002). Senior Team members were more likely to trace geometry and extrude their part compared to Novices (p=0.004).

4. DISCUSSION

It is interesting that the previously published gender difference in spatial performance (PSVT:R) [23], [24] was not replicated in the current study. The most likely reason for this departure from past work is a difference in the population studied. Our group had a higher average PSVT:R score than Duffy *et al* [9] and Onyancha *et al*[25], a higher academic year than Hsi *et al* [8] and Sorby *et al* [26] (although the average score was similar to Sorby *et al*). Our study recruitment was self-selected; students with exceptionally poor spatial or CAD skills likely would not choose to participate, and students with strong skills were specifically recruited by our study. The current study was predominantly mechanical engineering students, not students in a general first year [8]. Overall, compared to previous work, our students are likely stronger and more senior, which may obscure a gender difference in spatial ability.

The current data suggest that spatial task score (PSVT:R) is associated with Team membership. These findings suggest that time on the Team does not affect the spatial task performance, since the Junior and Senior spatial scores were similar to each other and higher than the Novice scores. Therefore, Team membership may select for inherent spatial ability, rather than spatial ability being developed through Team activities, a finding that is supported by the past work by Chester [1].

Table 2: Self-reported confidence reading and creating technical drawings by group. These were compared with a Mann-Whitney U-Test; significance (alpha)=0.05, significance threshold corrected to 0.017 with Holm-Šidák Correction. Comparisons that met corrected threshold indicated with '*'

Comparison	P-value	Interpretation
Confidence reading drawings		
Novice vs Senior Team Members	0.29	No difference
Junior vs Senior Team Members	0.50	No difference
Novice vs Junior Team Members	0.73	No difference
Confidence creating drawings		
Novice vs Senior Team Members	0.009*	Novices less confident
Junior vs Senior Team Members	0.37	No difference
Novice vs Junior Team Members	0.30	No difference

Table 3: Correlation between PSVT:R score and self-reported confidence. This was calculated with a Spearman Rank correlation (alpha)=0.05; p-values that met the significance threshold indicated with '*'.

Correlation	Correlation Coefficient	P-value	Interpretation
PSVT vs Confidence Reading	0.16	0.40	No correlation
PSVT vs confidence Creating	0.45	0.01*	Moderate correlation

Table 4: Differences in PSVT:R Score by group. These were compared with a t-test; significance (alpha)=0.05, significance threshold corrected to 0.017 with Holm- Šidák Correction. No comparisons met the corrected threshold or sufficient statistical power.

Comparison	P-value	Power	Interpretation
Female and non binary vs male	0.27	0.16	No difference
Year 2 vs Years 3, 4, 5+	0.11	0.22	No difference
Novice vs Senior Team members	0.04	0.35	Higher score for Senior Team Members
Junior vs Senior Team members	0.62	0.33	No difference
Novice vs Junior Team members	0.04	0.05	Higher score for Junior Team Members
No CAD Co-op vs CAD Co-op	0.16	0.17	No difference

Table 5: Significant differences in code presence by group. These were compared with a Fisher's Exact Test; significance (alpha)=0.05, significance threshold corrected to 0.017 with Holm-Šidák Correction. Comparisons that met corrected threshold and were sufficiently powered indicated with '*'

Code and comparison	P-value	Power	Interpretation
'Referencing AcademicWork'			
Sr. vs Jr Team members	0.04	0.64	Less common for Senior Team members
'ReferencingIndustryorCoop'			
Sr. Team members vs Novice	0.03	0.65	More common for Senior Team members
'CutAway'			
Sr. vs Jr. Team members	0.002*	0.96*	Less common for Senior Team members
Sr. Team members vs Novice	0.004*	0.91*	Less common for Senior Team members
'TraceandExtrude'			
Sr. Team members vs Novice	0.004*	0.90*	More common for Senior Team members

There seem to be two major differences in how Novices and Experts approach the CAD task. The first is in the past knowledge they use as a reference. Senior Team members referenced their industrial work or co-op experience more than Novice participants. This is logical because a majority of the Junior participants would not yet have had a co-op placement. Senior Team members did not reference academic work nearly as frequently as Novice participants.

The second and most significant and well-powered difference between the groups was how they constructed the object. Novice participants were more likely to use a "cut away" approach, creating the object by starting with a solid block. More proficient participants were more likely to "trace and extrude" geometry to create extrusions; the difference between these approaches is shown in Figure 1. This difference exists between Junior and Senior members as well, indicating that duration on a team may enhance

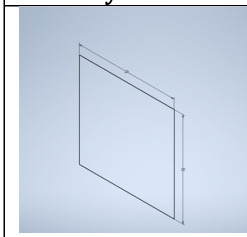
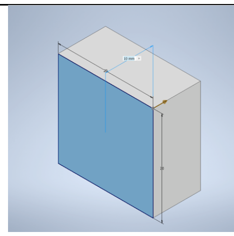
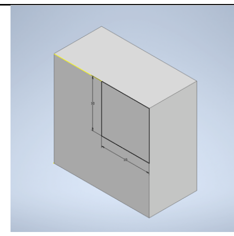
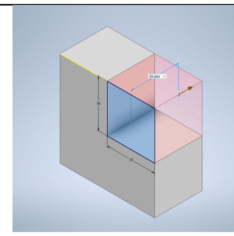
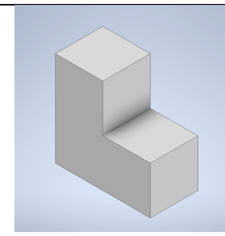
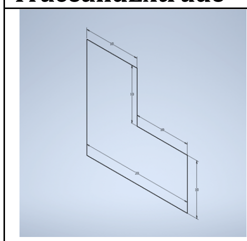
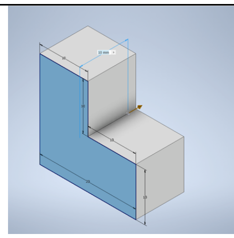
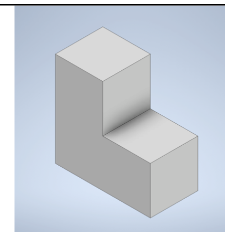
Step: 1	**2**	**3**	**4**	**Final Result**
CutAway				
				
Draw a rectangle the size of the overall part	Extrude the specified depth	Draw a smaller rectangle to create the finished profile	Cut the smaller rectangle from the part to create the final shape	
TraceandExtrude				
				
Draw the profile of the finished part	Extrude the specified depth			

Figure 1: Summary of steps for "CutAway" compared to "TraceandExtrude". Final result is identical but 'Trace and Extrude' requires two fewer steps.

CAD process quality or "CAD hygiene" in terms of commands and tools used. A "cut away" approach is less preferable due to the reduced efficiency and suitability for more complicated geometries in the future. This difference points to the potential of a more complete mental model of how the object is formed, or superior advance planning by the Senior Team members. Atman *et al*[10] noted that more experienced students tend to plan their design work more in advance. The current work may support that finding since trace and extrude involves more mental planning, although codes associated with planning were not significant differences on their own.

There were a relatively modest number of statistically significant differences identified. It was initially surprising that codes for confusion or misunderstandings were not more prominent in Novices, but given the timing of the study and the course from which the Novices were recruited, it is possible that their confusion was reduced by proximity to the relevant course material. Similarly, more codes for verbal reasoning were expected from Senior Team members, but they may not have thought the steps were notable enough to describe; their processes may have been more automatic. Senior Team members were expected to exhibit more use of advanced tools like patterning, similar to the enhanced use of "Trace and Extrude", but this difference did not reach significance. It is possible that the study task was not sufficiently complicated to demand the use of the more advanced tool.

4.1. Suggestions for Instructors

Examining these findings for actionable insights for instructors, the first is that Novice participants not currently on a Team tend to have reduced spatial ability, as measured by the PSVT:R. While our study cannot separate correlation and causation, it appears that quality of CAD process improves with time on the Team, but spatial ability does not. Team members appear to self-select for spatial ability, so efforts to train for improved spatial ability, such as reported by Hsi *et al* [8], may be a means to improve the diversity of those teams, or to enhance mastery in academic work.

The finding regarding past work referenced, although underpowered, presents an interesting opportunity because many more students participate in industrial co-ops than extracurricular engineering teams. Instructors could leverage this insight by encouraging students to contextualize learning from co-op or by creating industrially relevant examples or assignments. These could involve asking industrial partners or research groups for non-confidential drawings to work from, or making assemblies of solid models of common commercially available parts. This would have the additional benefit of fostering discussion of structure and function of these parts, which encourages students' curiosity about mechanical engineering in general.

The significant finding regarding enhanced CAD process ("cut away" vs "trace and extrude") by Senior Team members suggests that CAD instructors could be introducing students to higher level tools earlier through assignments that authentically demand more complicated geometries and tools. For example, more elaborate fastener arrangements, geometries that demand parametric modeling or parts with mating features. It also may support the use of assessments that explicitly grade process, such as practicums or grading the CAD part files themselves rather than the finished drawing or prototype. These present major challenges in terms of assessment time and therefore may be an appealing target for machine learning automated grading in the future.

The relatively modest number of statistically significant differences in process and themes in this study show that even amongst proficient participants there are individual variations in approaches. This suggests that a conceptual, critical thinking model of CAD instruction may be warranted over a "click-by-click" approach.

5. CONCLUSIONS

Our forthcoming follow-up paper will examine whether the spatial task score (PSVT:R) is well-correlated with specific aspects of CAD task performance (quality of the design solution and completeness of the technical drawing produced). The current data support the previous work pointing to the importance of spatial ability in CAD mastery, but indicates that technical team participation may recognize that ability rather than develop it. We suggest that instructors explore more industrially relevant assignments and more complicated geometries earlier in students' careers to encourage CAD mastery.

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All procedures performed in this study involving human participants were in accordance with the ethical standards of McMaster University Research Ethics Board per clearance number 4958.

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Appendix 1: CAD Task Instructions and Image

CAD Task Instructions

Thank you for participating in this study. The research assistant is not an engineering student and cannot offer technical help about CAD or dimensioning, but they can offer clarifications on the task itself. If you do not finish the task, that's perfectly alright, just submit the files that you do complete.

The task has the following steps:

1) Design a part that mates with the provided part and forms a rectangular shape that is 40x40x70mm.
    a. This part should be joined with the provided M5 screws.
    b. These parts are provided in .ipt format (Inventor 2021) and .stp format (other CAD systems). You will be given the dimensioned drawing of this part via Microsoft Teams, it is also provided on the following page.
2) Join the parts in an assembly (.iam) file (your part, provided part, fasteners)
    a. You do not need to provide specific tolerances or GD&T
3) Make a properly dimensioned technical drawing of your designed part.
4) Make an assembly drawing of your assembly of both parts and fasteners.
    a. Show your assembly with parts together (not exploded view)

At the end of the session please submit the following 4 files via Microsoft Teams:

- An .ipt (or similar) part file for the part you design
- An .iam (or similar) assembly file with your designed part, the provided part and fasteners
- A .pdf file of your dimensioned technical drawing of your designed part
- A .pdf file of your assembly drawing of your assembly of both parts and fasteners

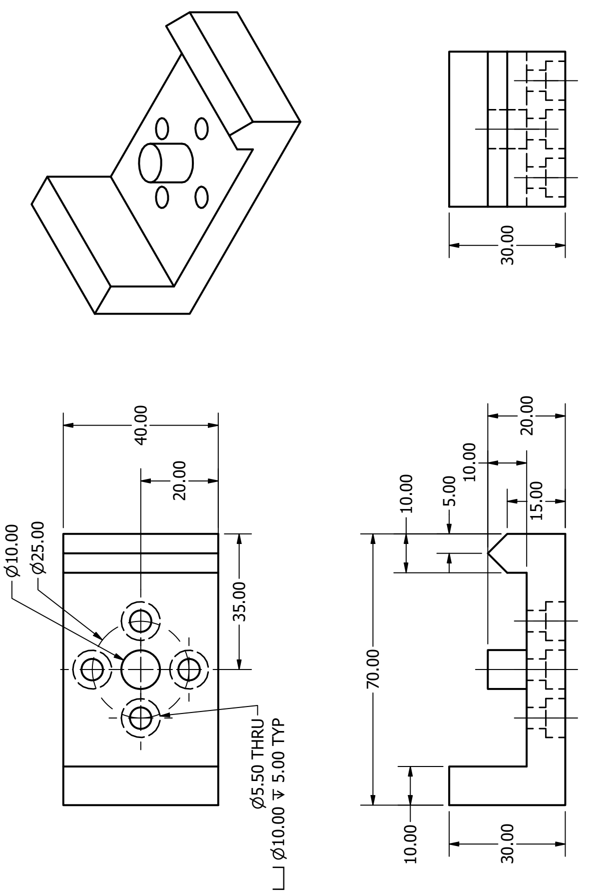

Figure 2: CAD task provided drawing

Appendix 2: Coding Dictionary

- Confusion: The participant was either outwardly confused or was confused by what was asked and so did a step wrong
- Assembly Drawing Confusion: Confusion about what an Assembly drawing is, how to make one, or what elements to include. eg. "I'm not sure whether to dimension this or what is supposed to be in an Assembly Drawing"
- Misunderstanding the Problem: Not understanding what the instructions are asking which results in the wrong piece being made. eg. Makes just a box that is 40 by 40 by 70
- Screw Hole Confusion: Confusion surrounding the screw holes including the depth, form, or fasteners. eg. "I am not sure how deep to make these holes"
- Start over: A participant starts making their piece before quickly realizing they have made an error and decides to restart from scratch
- Explaining why: Explaining why are they doing this step.
- Just because: Explain why they are doing that step with a vague answer. ie. "I am doing this because you should always do it"
- Reasoning: Giving a reason for why they are doing something that does not relate to academic or co'-'op ie. It is easier to read the labels if they are horizontal so I will make them horizontal
- Referencing Academic Work: Explaining why they are doing something by referencing previous academic work or standards given in class. eg. "this is expected in 2A03"
- Referencing Industry or Co'-'op: Explaining why they are doing a step by referencing a previous job, co'-'op, or industry standards. e.g. "this should be done because it is necessary for manufacturing"
- Google: Using Google to assist them in completing the study. eg. "Let me just Google how to do that"
- Handwritten Notes: When a participant uses a piece of paper to create a handwritten sketch of the part they have/the part they are making.
- Previous design projects: Participant references previous design projects to assist in current design project
- Youtube/Video: Used a video or Youtube video to help them complete the study. eg. "I'm just going to watch this video on how to do that"
- Filler words: eg. "um", "ah"
- Instruction Approach: The way a participant reads the instructions
- Check back: Quickly checking back at instructions throughout the process
- Read the whole thing: Longer, quiet reading of the instructions
- Start right away: Jumps into designing without finishing reading instructions. eg. Only reads until step 1 and then starts the step
- Does not pattern holes: Creates each screw hole individually without using the patterning tool
- Does not pattern screws Inserts each screw individually instead of patterning them
- Pattern holes: Use the patterning tool to create the 4 screw holes
- Patterns screws: Uses the patterning tool to add screws instead of placing each one individually
- Cut Away: Participant creates a block and cut extrudes to form final shape
- Trace and Extrude: Participant approaches designing the mating part by creating a sketch or the side view and extruding to the correct size
- Task Switching: Switches between tasks without fully completing the one before