International Journal of Technology and Design Education (2020) 30:389–411
https://doi.org/10.1007/s10798-019-09503-x

An exploration of the variables contributing to graphical education students' CAD modelling capability

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Accepted: 5 February 2019 / Published online: 11 February 2019

Abstract

This paper reports on a study exploring the variables that contribute to upper second level students' capability in a digital graphical modelling exercise in the field of technology education. The study evolves previous work in the area conducted in different contexts such as teacher education. Findings indicate deficiencies in second-level students' digital modelling abilities and a significant relationship between students' analytical, strategic and visuospatial abilities are presented. The paper discusses these findings as they relate to pedagogical reasoning processes and present the necessity to broaden the conception of graphical capability within digital CAD modelling contexts. Some key implications for technology education programmes and pedagogical approaches are discussed in conclusion.

Keywords Graphical education · ICT · CAD · Pedagogy · Capability

Introduction

The demand of twenty-first century educational provision emphasises a focus on the development of a broad set of knowledge and skills among student populations. The rationale for this contemporary emphasis stems from societal necessity and calls for individuals capable of operating effectively in dynamic and constantly evolving contexts. This necessity has forced educational providers to reconsider their philosophies for teaching and learning and acknowledge that traditional approaches to provision are misaligned with many of the contemporary goals of modern education (Bell 2010). Within the Irish context this shift in focus is clearly evident in the technology subjects offered at second level. Owen-Jackson (2000) states that from their inception, technological subjects at secondary school level were:

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> concerned only with the passing on to pupils traditional knowledge and skills [where] Pupils were required only to learn the knowledge, not understand it, and to copy and practise the making skills (p. 5).

This master-apprentice model of technology education encompasses the dominant praxis evident within second level education of the past. In Ireland, this focus was challenged and re-envisioned for the twenty-first century in 2007, when the suite of technology subjects offered at upper second level (ages 15–18) underwent significant changes. Two new subjects, Design and Communication Graphics (DCG) and Technology, were introduced as study options. Technology was a new subject for upper second level and DCG replaced the old Technical Drawing syllabus. DCG represented a clear shift away from the traditional, prescribed drafting approaches encouraged in Technical Drawing and towards a more holistic conception of graphical capability through the lens of design driven education (Seery et al. 2011).

A key introduction within the new subject of DCG, and differentiator from Technical Drawing, was the introduction of a design project as part of the core assessment for the subject. A core element of the successful engagement and completion of this design project is being able to successfully utilise parametric computer aided design (CAD) to represent and communicate an assortment of graphical information (NCCA 2007) ranging from the pure observable to the purely speculative in nature. The introduction of CAD to the subject was seen as having huge potential for cultivating a set of contemporary learning experiences in the areas of graphical and design education. CAD is ubiquitous in many design and technology education fields and can be a powerful and versatile tool for communication and reasoning (Field 2004). However, the introduction of this technology (within a new second level subject) to practicing teachers and within a national framework of qualifications brings with it some undeniable challenges.

The overall shift from a vocational conception of technology education in Ireland to a more design driven one was a necessary move and does align with global curricular initiatives and perspectives (Dow 2006). However, there are inherent pedagogical concerns involved in reshaping and redirecting the philosophy of a subject once seen as purely vocational. Namely the concern that prevailing pedagogical practice will be upheld and preserved from the subject's previous incarnation (Dakers 2005; McGarr 2011). In addition there are further concerns relating to the integration of a substantial level of ICT into a subject domain that previously had little to no such emphasis (Levin and Wadmany 2005). Learning to effectively model and communicate with CAD systems is also a complex endeavour in its own right and includes a strong focus on the development of strategic knowledge (Chester 2007). A misalignment between the philosophy of the new subject and technological pedagogic practice could have profoundly negative effects on students' development of such cognitive skills through CAD modelling. Therefore, these concerns warrant an exploration of the current norms and practices around CAD education and learning within Irish post-primary schooling.

This paper presents an exploratory study that investigates the CAD modelling strategies of current post-primary DCG students. In addition, the paper will also explore some of the variables and cognitive aptitudes that are intrinsic to the notion of capability in digital graphical modelling within an upper second level educational context. The paper is motivated by potential concerns associated with the preservation of hegemonic practices as the contemporary ideology of technological education has transitioned and diverged from its once vocational origins. To set the context for the study, the paper will first explore the current philosophical positioning of graphical education at upper second level within the technology education landscape in Ireland before moving on to specifically look at the characteristics of pedagogy associated with CAD modelling. Finally it will look at the core elements posited to comprise CAD modelling expertise in an effort to encompass the multifaceted nature of this element of graphical capability prior to outlining the aim of the research paper.

The contemporary philosophy of graphical education

The origins of Irish Technological Education have its roots in vocational training and craft development. However, aligning with the evolution of technology education internationally, the merits of the subject as a general educational offering are becoming increasingly apparent. Major curriculum reform has resulted in the upper second level subject of Design and Communication Graphics (NCCA 2007) replacing the more traditional subject of Technical Drawing. As a new technology subject, its core objective is to prepare technologically capable students, with a specific leaning towards conceptual design and creative endeavours.

Although, this overview of DCG sets the general arena for the consideration of the use of digital tools in learning, it is the exploration of capability that supports the consideration of practice. Capability is largely a contested construct in design and technology education and is difficult to define (Gagel 2004). Gibson's (2008) model provides structure to a definition by describing technological capability as the unison of skills, values and problem solving underpinned by appropriate conceptual knowledge. Black and Harrison (1985) define it as being able "to perform, to originate, to get things done, to make and stand by decisions" (Black and Harrison 1985, p. 6). The subject values both the development of designerly thinking and technical competencies, with the overarching aim to "prepare [students] to be creative participants in a technological world" (NCCA 2007, p. 2). This translates into an amalgam of skills that encompass "graphicacy/graphic communication, creative problem solving, spatial abilities/visualisation, design capabilities, computer graphics and CAD modelling" (NCCA 2007, p. 1).

A significant aspect of the 2007 syllabus is the development and appropriate utilisation of parametric CAD modelling. The use of CAD is positioned as a system independent competency and the ability to develop cognitive skills and strategies is at the core of the intended application. The function of CAD within the design process is seen as a tool to facilitate the representation and manipulation of complex geometries and features leading to new design ideas. It is this context that qualifies the learning and development beyond traditional views of execution and captures the more contemporary expectations built on a disposition of enquiry, where "the skill does not lie in the recall and application of knowledge, but in the decisions about, and sourcing of, what knowledge is relevant" (Williams 2009, p. 249). Critically, the expectation is that [Students] should be able to distinguish between stages and functions in design graphics (NCCA 2007 p. 20). Therefore, the expected outcome is not only that the learner can use a CAD modelling system, but also that they have the capacity to determine its appropriate function at a specific stage in the design process.

It is the disharmony between the speculative and the technical that shapes (often unintentionally) much of the activity that governs the teaching and learning practices in technology education. From an enacted pedagogy perspective, the balance between design development and acquired technical competency results in complications for practice and sometimes competing educational agendas. Executing and modelling a conception or design is ultimately predicated on a comprehensive skill set being developed in the use of this digital tool. This complication is amplified, by both the prevailing pedagogical practices (McGarr 2011) and the epistemological views that are dominated by traditional subject definitions and origins. It is also further complicated through the implementation of a significant level of ICT into a subject domain that previously had little such emphasis.

Pedagogical practices and the role of CAD

In the context of ICT integration within educational paradigms, the literature is abound with evidence suggesting that teachers struggle to effectively integrate and adopt their pedagogical practices to new ICT elements in the curricula (Norris et al. 2003; Orlando 2009). The focus of the current paper is specific to the integration of ICT in the form of CAD modelling software within a technological curriculum concerned with design education and it is therefore prudent to focus more narrowly on literature in this area. As previously discussed, the new conception of graphical education within Ireland, in the form of DCG, evolved from a previous conception of technology education that promoted a vocational focus (McGarr 2011). A national support service was established to provide ongoing continuing professional development (CPD) in pedagogical practices to motivate and support these curricular changes. Such developments highlighted the required shift from the traditional vocational focus of the subject area to an approach that concentrated on a teaching and learning experience aligned with twenty-first century skills.

Major changes were required to the pedagogical practices in the graphics classroom to ensure that this endeavour was fulfilled on the ground. Prawat (1992, p. 357) highlights how “a dramatic change in the focus of teaching, putting the students’ own efforts to understand at the centre of the educational enterprise” is key. He also highlights how teachers are the critical agents whom we depend upon to oversee reform efforts within our education systems. Paradoxically teachers can also be viewed as major barriers to change due to their adherence to outmoded forms of instruction that emphasise factual and procedural knowledge at the expense of deeper levels of understanding (ibid.) This form of instruction is synonymous with conceptions of vocational education which was the prior philosophy of technology education in Ireland (McGarr 2011) and therefore presents potential cultural and hegemonic barriers to successful use of CAD modelling technology within the modern DCG classroom that embraces a pedagogical philosophy framed in the context of design education.

Edwards et al. (2002) outline a dissimilitude between the curriculum and the knowledge that students carry with them into formal education, as well as that needed upon graduation, that memorisation and repetition are prioritised over enquiry and criticality. In a large exploratory study, McGarr and Seery (2011) found that teachers pedagogical approaches to teaching CAD mirrored a primarily traditional approach emphasising procedural execution of software commands to complete specified tasks. This is a akin to what Levin and Wadmany (2005) describe as partial change of ICT usage, which emphasises a rigid approach to pedagogical practice that sees the computer as a technical artefact. This technical rigidity in pedagogical approach has also been highlighted in the wider graphical curriculum at this level of schooling with circumvention of the core cognitive and mental processes critical to achieving graphical capability apparent (Delahunty et al. 2012). In a subject that now promotes creativity and speculative inquiry through design education, an adherence to traditional conceptions of technical pedagogy has the potential to severely limit the development of strategic and adaptable knowledge necessary to effectively utilise CAD for design exploration and realisation.

Rynne et al. (2011) investigated the variables underlying undergraduate student teachers CAD modelling approaches. In this study, student teachers tended to adopt mechanistic Boolean type approaches to the use of the software despite the inappropriateness of such a strategy for the prescribed task, which was in this case a more organic geometric model involving curves. While studies in this particular area are limited the findings available cite a technical and mechanistic adherence to the use of CAD in a design education context. This aligns with the wider literature on ICT use within educational contexts which have found that high levels of effective technological adoption are still overly lacking (Orlando 2009). As discussed by Ertmer and Ottenbreit-Leftwich (2010) several elements can impact on a teachers' mode of ICT adoption and use in their professional practice. These can include inter alia pedagogical content knowledge (PCK), self-efficacy, beliefs and culture (Ibid). In their study, Rynne et al. (2011, p. 176) identify deficiencies in the knowledge bases of participants particularly when it comes to strategic knowledge and application. This work focused explicitly on future technology teachers and consequently presents concerns for pedagogical practice in upper second level technology education. Given the importance of a robust knowledge base, for the effective use and teaching of CAD it is prudent to explore the variables that contribute to this capability.

Cognitive variables contributing to 3D-CAD modelling expertise

Learning to model utilising a CAD system requires an interaction between declarative and procedural knowledge. Chester (2007, pp. 26, 27) defines declarative knowledge as knowledge about the various commands that can be utilised within a CAD system such as extrudes, cuts and mirrors among others. He also defines procedural knowledge as that which enables the user to execute these specific CAD commands (ibid, p. 27). These two types of knowledge have been ubiquitous with conceptions of CAD expertise since the earlier introductions of two-dimensional CAD systems. However, since the introduction and pervasive use of three-dimensional CAD software within industry and education, strategic knowledge has been widely accepted as the critical component of modelling expertise (Chester 2007; Johnson and Diwakaran 2011). Strategic knowledge is housed within the context of metacognitive processes (Pintrich 2002) and includes the planning, monitoring and revising of one's cognition (Garrison and Akyol 2015). Within the context of CAD modelling expertise, the development of strategic knowledge is typically encompassed within the concept of design intent (Johnson and Diwakaran 2011). Rynne et al. (2011, p. 166) summarise the primary cognitive and knowledge components involved in parametric part modelling and this is shown in Fig. 1.

In educational contexts, the teaching of these key skills for CAD are typically centred around an applied modelling activity where participants are required to model various geometries. This problem-based approach to the learning of skills and knowledge is the quintessential approach adopted within technology education fields (Williams et al. 2008). While the various knowledge components, that constitute CAD modelling expertise, have been highlighted it is also important to consider the cognitive components that support the applied CAD modelling process. When a student engages in the modelling of a prescribed task, similar to any other problem centred activity, they engage in a complex

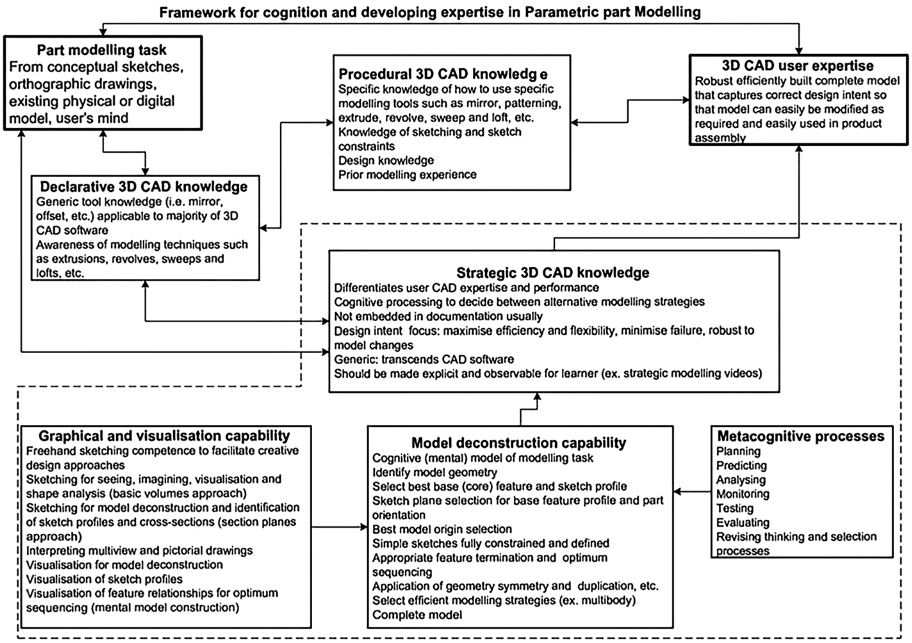


Fig. 1 Cognitive and knowledge dimensions of developing CAD expertise (Rynne et al. 2011)

interaction of conceptualisation and representation of a problem space and heuristic search strategies (Todd and Gigerenzer 2000; Delahunty et al. 2018). In the case of CAD modelling, the analytical deconstruction capabilities and strategic knowledge application abilities theorised by Rynne et al. (2011) (see Fig. 1) are akin to these more general problem solving elements. Considering students' engagement in a part modelling exercise as primarily involving the analytical deconstruction of geometry and the strategic modelling of said geometry highlights the role of several key facets of the human cognitive architecture.

Clearly, the analysis and representation of the prescribed geometry and the associated planning of a modelling strategy will involve an interaction of working and long-term memory processes. The declarative and procedural knowledge that a student possesses will be stored in the form of cognitive schema within the long-term memory system (Ericsson and Kintsch 1995; Stillings et al. 1995; Sweller et al. 1998). During the analysis of the part to be modelled, an individual will encode the stimulus given and relate this to the content of schema in long-term memory within the workspace afforded by working memory (Baddeley and Hitch 1974; Cabeza and Nyberg 2000). This mental modelling process will form the basis for the task-directed behaviour of the student. Schacter and Addis (2007) describe this modelling process as an interaction between constructive and relational processes and emphasise the importance of flexibly relating and synthesising components of information extracted from past events and encoded from current situations.

Hassabis and Maguire (2007) go on to make a special emphasis on the role of visuospatial cognition during this process where relevant information may be accessed and retrieved from long term memory and combined with new information critical to the imagining and planning of future action. This type of activity has also been highlighted as a potential contributor to problem conceptualisation through differential access to memory subsystems in problem solving (Delahunty et al. 2015). The visuospatial sketchpad of the working memory system has been supported as the locus of such activity during human cognition (Baddeley 2000).

Summary of the literature review

This literature highlights several key elements that underpin the knowledge types (declarative, procedural and strategic) that are critical to CAD modelling skill development. These are interactions between working and long-term memory and the contributory potential of visuospatial cognitive ability. Spatial ability has long been associated with CAD modelling proficiency (Sorby 2000; Branoff and Dobelis 2014). Research looking at the relationship between CAD modelling and spatial ability often emphasised the capacity of 3D CAD systems to improve students' visualisation abilities (Ault 2003). However, research by Sorby (2000) has demonstrated that merely using a CAD system does not lead to any significant improvements in students visualisation ability. This aligns with the literature reviewed here as it is a plausible hypothesis to consider a certain level of spatial ability as prerequisite to support the cognitive processes involved in successfully analysing and modelling a prescribed geometric exercise. Taking cognisance of this literature, the concept of CAD modelling capability presented here and advocated in this paper involves a intricate exchange between various cognitive mechanisms, knowledge and skills.

In addition, evidence suggesting a deficiency in the development of future technology teachers' strategic knowledge base provided by Rynne et al. (2011) presents potential concerns for practice within DCG at upper secondary school level. Strategic knowledge is known to be a prime factor contributing to CAD expertise (Bhavnani and John 1997). Without a high level of strategic thinking, students' modelling approaches will be dictated by command knowledge and representation of a conceptual design will ultimately reach a point where further development and manipulation is not possible (Rodriguez et al. 1998). As Chester (2007) discusses, the learning of CAD modelling through a predominant focus on command knowledge mastery is problematic.

Taking cognisance of these two key areas, it is important to consider the current modelling practices of upper second level students to explore whether these modelling deficiencies permeate second level design education and also ascertain the role of visualisation capacities in the CAD modelling process. Based on these broad themes of exploration, it may be necessary to broaden the conception of capability and knowledge required for successful CAD modelling within technology education. This forms the impetus for the current research study.

Current research focus

In their study, Rynne et al. (2011) concluded that participants (student teachers) lacked the strategic knowledge and metacognitive regulation abilities to analytically deconstruct the prescribed geometry as their knowledge of CAD and visualisation ability was considered to be of high standard. However, a notable limitation of the study by Rynne et al. (2011) is the assumed capacity for visualisation by inference from performance on a graphical examination. High levels of performance on a graphics examination cannot be taken as proof for the development of graphical and visualisation abilities (Delahunty et al. 2012) and a more definitive measure of visualisation ability would have benefited the study.

The study by Rynne et al. (2011) also recommended that strategic CAD modelling ability can be developed with freehand sketching and appropriate focus on metacognition. Freehand sketching also has benefits for the development of spatial ability (Sorby 2009) and the constructive and relational cognitive processes that underpin the analytical and strategic elements of the CAD modelling process. It does this by allowing individuals to extend the capacity of working memory, reducing cognitive load and allowing a dialectical canvas where communication (both external and internal) and manipulation of visual information can take place (Fish and Scrivener 1990; Goldschmidt 2003; Kimbell 2004).

The current study therefore intends to investigate these phenomena within current practice in upper second level graphical education. Namely it aims to explore the relationship between the analytical and strategic components of CAD modelling and the visualisation ability of students when engaged in a prescribed CAD modelling task. Also of considerable interest will be the relationship of spatial visualisation ability as a key process augmenting the constructive and relational processes in strategic cognitive modelling. The previous research cited (Rynne et al. 2011) was concerned with the practice of student teachers. Given the association between teachers' beliefs and their pedagogic practices (Fang 1996), it is pertinent to investigate if similar rigid trends to CAD modelling are also manifesting within current practices at upper second level to advance what is currently shown in the pertinent literature.

Method

Given the focus of this study it was decided to adopt the theoretical framework proposed by Rynne et al. (2011) outlined in Fig. 1 within a mixed-methods approach. The study aimed to investigate the relationship between the analytical and strategic elements of the CAD modelling process and the relationship with spatial visualisation ability in the context of educational practice in graphical education at upper second level. Two principal components of this framework were used to guide the design of the study: model deconstruction ability and the application of strategic 3D CAD knowledge (see Fig. 1). Model deconstruction capability involves the analysis and planning of a strategic approach to modelling a prescribed part and therefore formed one of the key variables of interest. This was an addition, compared to previous work, that also encompassed the necessity for students to utilise their freehand sketching skills to understand the geometry of a prescribed part prior to modelling. The second variable was the use of strategic CAD knowledge in the modelling of a prescribed exercise. The last variable of interest was spatial visualisation capacity.

Pragmatically this involved the design and implementation of two separate but related exercises involving the analytical deconstruction of a prescribed part exercise and the modelling of this part using 3D CAD software. Spatial ability was captured using a well-established psychometric instrument. By tasking participants with an applied analytical CAD modelling exercise, it was proposed that an insight into current pedagogical practices could also be garnered by inference from observation and analysis of their performances.

Participants

The participants selected for this study were upper second level school students (N = 17), all between 15 and 17 years of age, from a voluntary secondary school in Ireland and who were currently studying DCG. According to their class teacher, the participants were of mixed ability and had been using the CAD system Solidworks for a single class period (40 min), once a week for 16 weeks (approximately 10.7 h). All participants who took part in the study were male. These students were selected as the study needed to be contextualised in secondary education to gain an understanding of the phenomena and current practices within that context. Previous research has typically been confined to the tertiary sector and it was necessary to observe the phenomena at this level. Also, these students were studying DCG at the time and had experience in using CAD software and developing the requisite capabilities for the prescribed deconstruction and modelling exercises utilised for the purposes of this research.

Design

To gather data relating to students' analytical and strategic modelling capacities a part model was designed for the focus of the problem-based activity. The researcher conceived and modelled this new exercise in conjunction with the class teachers so that students' level of CAD modelling ability was considered. The part model which formed the focus of the applied analytical activity is illustrated in Fig. 2.

In practical CAD modelling terms, the exercise would involve several features such as extrudes, cuts, lofts and sweeps as well strategic sketch and design intent features such as the use of mirroring functions, selecting the correct end conditions of cuts and selecting the correct plane geometry. These elements were familiar to students based on the feedback from the class teachers.

For the analytical deconstruction task, participants were required to deconstruct the piece of geometry shown in Fig. 2 into its basic two and three-dimensional geometries using sketches and annotations. In addition, students were also required to outline their modelling plan by indicating their approach to the modelling of those features in the

Fig. 2 Part model for current study

CAD system. This task was primarily conceived to observe students' cognitive modelling and strategy construction prior to the use of the CAD system and determine if there is a statistical relationship between this element and the actual CAD modelling process of the students.

In addition, by presenting the deconstruction and planning task as a standalone activity, this allowed a more authentic view and quantification of data relating to the cognitive modelling and strategy generation of participants prior to engagement with the software environment. This is an important consideration as within any problem based activity, individuals operate within the bounded rationality of their environment and often implement a diverse set of behavioural heuristic strategies to satisfy a problem situation (Todd and Gigerenzer 2000). While heuristics is a useful framework to investigate problem solving behaviour, in the context of the current study utilising a heuristic framework based primarily on behavioural analysis would make it much more difficult to extrapolate data on the relationship between the deconstruction and CAD modelling elements. Before completing the task, participants were given a presentation and detailed instructions on the analysis and strategic planning of a prescribed part modelling exercise.

Participants were then required to model the part shown utilising the sketch functions and features they judged to be most appropriate within the Solidworks software environment. A working drawing with all key dimensions and information was provided for students during the part modelling exercise (see Fig. 3). The specifics for this were as follows:

1. Successful completion relied on participant's declarative and procedural knowledge coupled with the application of strategic knowledge.

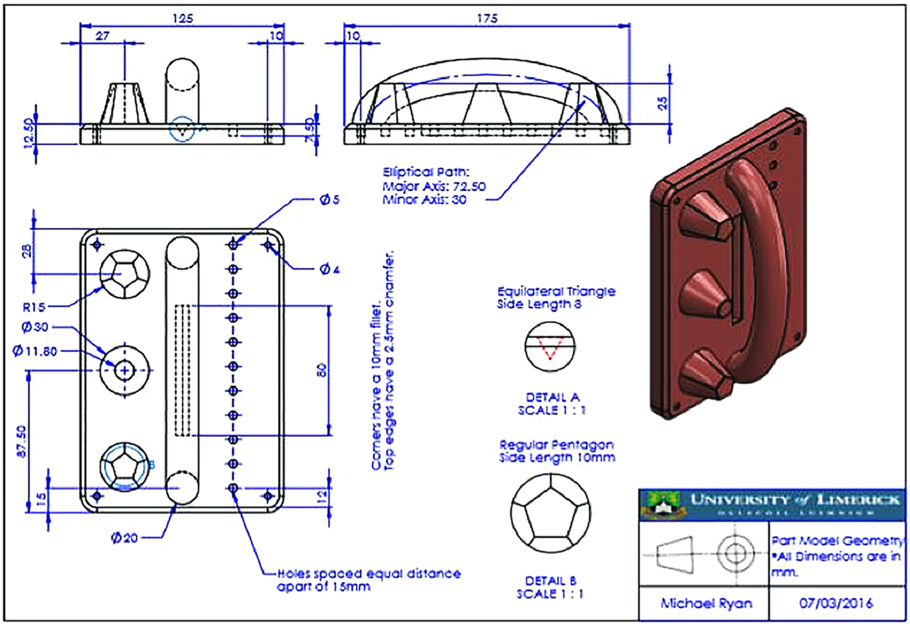


Fig. 3 Working drawing provided to participants

2. Participants were given 50 minutes to model the part.
3. In order to reduce the impact of further complexity variables on the modelling performance of participants, a pictorial view was once again provided on the working drawing. Barr (1999) claims that students have great difficulty in visualising information from presented orthographic views so providing this pictorial view was envisaged to reduce the impact of this complexity and ensure significant participation across the entire sample.

The last variable of interest was spatial visualisation ability and it was necessary to gain a measure of this competency. The Purdue Spatial Visualisation Test: Rotations (PSVT:R) (Guay 1976) was chosen for this purpose. An individual's score on the PSVT: R has been found to be the most significant predictor of student performance in engineering graphics courses (Gimmestad 1985). The PSVT: R is also the standard spatial ability test in graphical education research (Sorby 2007, 2009). Obtaining spatial visualisation performance data in this manner would then facilitate statistical comparisons with the other performance measures already outlined for the study.

Notes on implementation and data analysis

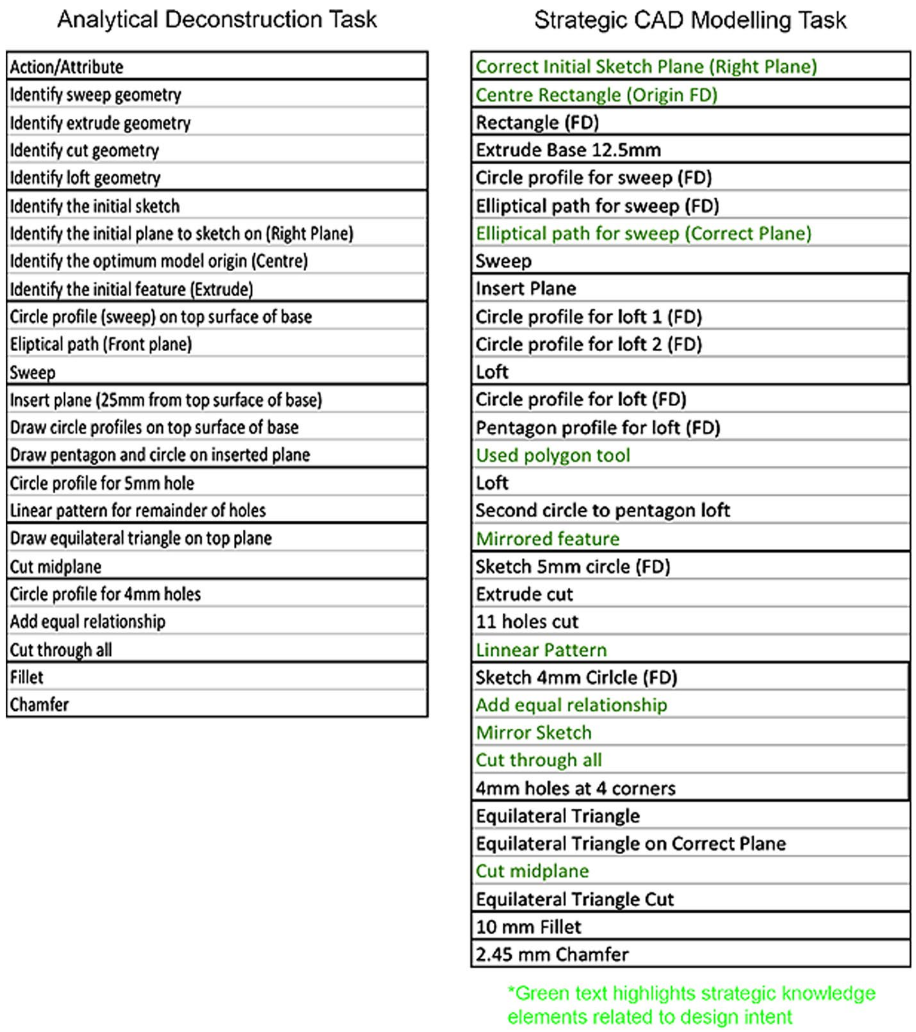
The data was collected in two stages. Initially, participants completed the PSVT:R in their classrooms with their teacher. Both teachers were given clear instructions on how to prepare their classes so that all the students understood what was expected of them on the PSVT:R spatial ability test. The following week participants completed the deconstruction of geometry activity followed by modelling the same piece of geometry on a CAD system in their DCG classes at school. Participants were evenly spaced around the room and the environment was moderated by a researcher and their teacher.

In analysing the data generated from the analytical and strategic modelling elements analytical, observational and grading criteria were adopted. This led to the generation of two separate rubrics which outlined the key components involved in successfully completing the analytical deconstruction and strategic modelling tasks respectively. These rubrics are shown in Fig. 4.

Participant solutions from both task elements were analysed using the rubrics and a binary approach was adopted. The criteria were used to observe evidence of the presence of each element in student generated solutions. The use of the rollback feature within the Solidworks environment allows the researcher to investigate the sketches and features used at each stage of the modelling process. If the feature in question was present students were awarded a mark of one whereas a zero indicated a lack of evidence of that component in either of the tasks. After this frequency analysis was conducted, the counts were standardised and used to assign a performance score to each individual participant in both task conditions.

Findings

This section of the paper will present the findings arising from data collection and analysis. Firstly, the analytical deconstruction task and CAD modelling exercise will be presented detailing both performance trends and strategies evidenced by students during engagement in the prescribed instances.



Analytical Deconstruction Task

Action/Attribute
Identify sweep geometry
Identify extrude geometry
Identify cut geometry
Identify loft geometry
Identify the initial sketch
Identify the initial plane to sketch on (Right Plane)
Identify the optimum model origin (Centre)
Identify the initial feature (Extrude)
Circle profile (sweep) on top surface of base
Eliptical path (Front plane)
Sweep
Insert plane (25mm from top surface of base)
Draw circle profiles on top surface of base
Draw pentagon and circle on inserted plane
Circle profile for 5mm hole
Linear pattern for remainder of holes
Draw equilateral triangle on top plane
Cut midplane
Circle profile for 4mm holes
Add equal relationship
Cut through all
Fillet
Chamfer

Strategic CAD Modelling Task

Correct Initial Sketch Plane (Right Plane)
Centre Rectangle (Origin FD)
Rectangle (FD)
Extrude Base 12.5mm
Circle profile for sweep (FD)
Elliptical path for sweep (FD)
Elliptical path for sweep (Correct Plane)
Sweep
Insert Plane
Circle profile for loft 1 (FD)
Circle profile for loft 2 (FD)
Loft
Circle profile for loft (FD)
Pentagon profile for loft (FD)
Used polygon tool
Loft
Second circle to pentagon loft
Mirrored feature
Sketch 5mm circle (FD)
Extrude cut
11 holes cut
Linnear Pattern
Sketch 4mm Cirlcle (FD)
Add equal relationship
Mirror Sketch
Cut through all
4mm holes at 4 corners
Equilateral Triangle
Equilateral Triangle on Correct Plane
Cut midplane
Equilateral Triangle Cut
10 mm Fillet
2.45 mm Chamfer

*Green text highlights strategic knowledge elements related to design intent

Fig. 4 Analysis rubrics

Analytical deconstruction and planning task

Students displayed a poor level of analytical capacity during the deconstruction task designed to prime an appropriate CAD modelling approach. A mean score of 42.9% with a standard deviation of 18.5% was recorded. It must be noted that these students had significant experience gained within DCG at this point and difficulty should not have been an issue for a task that required basic representational sketching. In order to gain a greater understanding of the components involved in individuals' analysis of the geometry, a frequency analysis was conducted using the rubric outlined in the method (Fig. 4). The result of this process is illustrated in Fig. 5.

As is clear from the result of this frequency analysis, students had little difficulty identifying the extrude and cut geometries with 94% and 100% rates of identification

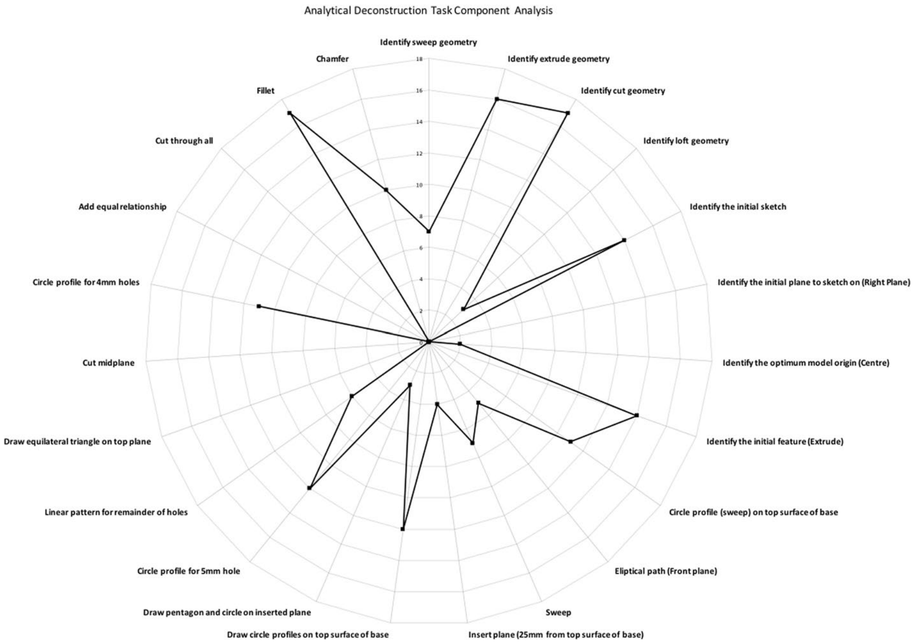


Fig. 5 Analytical deconstruction task strategy frequencies

in the analytical tasks respectively. Identifying the more complex geometry, involving lofts and sweeps, was clearly more difficult with only 18% of students identifying the loft geometry and 42% identifying the sweep geometry. In terms of planning a CAD modelling approach, it is clear that students found identifying the initial sketch features (focusing on extruded geometry) much simpler with identification rates of 82% for the initial sketch and extruded feature. This is contrasted by difficulty planning the sketch approaches for the more complex geometric features such as the sweep sketch profile (65%) and the elliptical path sketch (29%). Figure 5 also illustrates evidence of difficulty in design intent related analysis and planning. For example, no student clearly identified the correct initial plane to begin sketching the first feature, the correct mid-plane cut or the appropriate 'through all' end condition for the linear series of holes.

Notes were also compiled by the researcher on the general graphical approach to analysis and planning. The majority of students in the study opted to utilise two-dimensional orthogonal sketches with only 29% of students using a combination of orthographic and pictorial representations. In terms of these orthographic representations, most students relied on plan views of the geometric component for their analysis and planning approaches. Students' annotations tended to focus on simplistic commands such as 'sketch circle' or 'extrude' and only 29% of students included dimensional information in their analytical sketches. Only 18% of students illustrated information on the plane selection for their geometries. Examples of student outputs for this element of the study are illustrated in Fig. 6.

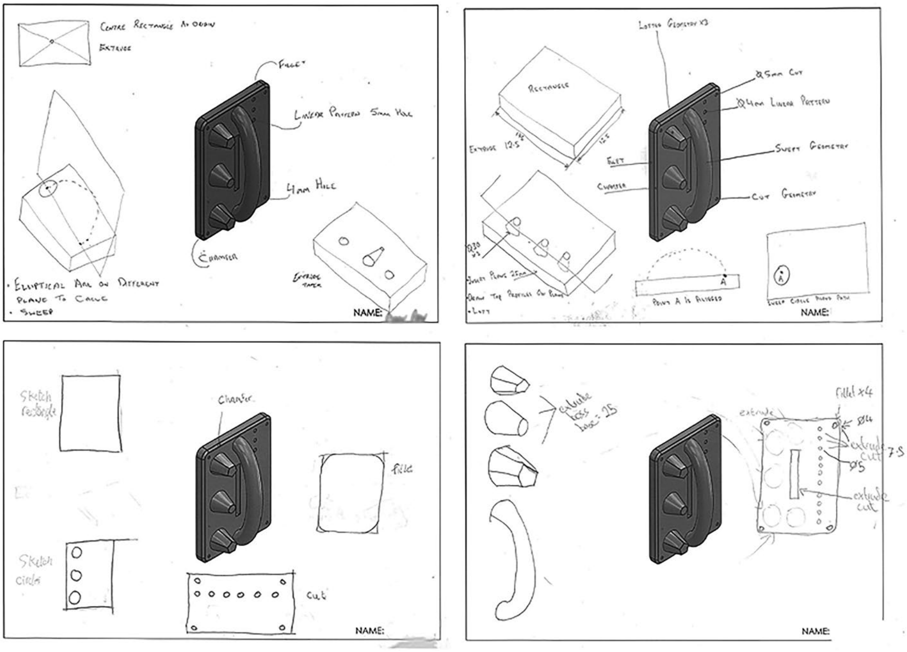


Fig. 6 Examples of student solutions to analytical task

Analysis of CAD modelling solutions

Students performance in the CAD modelling task recorded a mean score of 37.8% with a standard deviation of 21.8% indicating a significant amount of variance between participants' performance scores. This score indicates an overly poor performance on part of the students involved in the study especially considering the experience these students had with CAD usage in DCG. All participants required the full 40 min allotted to the completion of this exercise and no one successfully completed the task. The CAD modelling element of the study was also submitted to a frequency analysis using the rubric presented in the method (Fig. 4) and results of this can be seen in Fig. 7.

Similar to the analytical deconstruction task, students had difficulty modelling the more complex geometry including the swept geometrical elements. Here, only 59% of participants sketched the correct circular profile for the sweep with an even smaller amount (29%) sketching the elliptical path sketch needed to model this element of the specified task. As with the analytical and planning task discussed in the previous section, students did not produce a significant number of the solution elements associated with design intent. For example, only 12% of participants selected the correct initial (right) plane which was a critical element for establishing the correct design intent. Students also had significant difficulty in selecting the correct end conditions for cuts and utilising mirrored and linear pattern functions within sketches. Overall, the elements of the modelling strategy related directly to the application of strategic knowledge were poorly engaged with and illustrate a significant deficiency apparent in these students' strategic development.

Fig. 7 CAD modelling strategy analysis

Overall observations of the student generated models revealed two general overall modelling approaches: orthogonal sketch dominated and Boolean dominated approaches. Participants who opted for the former approach initially created the base feature, they then proceeded to sketch a variety of sketch geomtry on the top face of that feature. Examples of this approach can be seen in Fig. 8.

Participant 6 scored 39.3% in the CAD modelling activity, which was the highest score out of the four examples as shown in Fig. 8. This participant exhibited a good level of CAD sketching skills, and all their sketches were fully defined as can be seen. They also created four features: fillet, chamfer, extrude and cut but these are all confined to the principle base feature. Participant 2 recorded a performance score of 30.3% and again exhibited a good level of CAD sketching abilities. However, this participant failed to produce any cut features on the base element, hence why they scored lower than participant 6. Participants 12 and 14 scored 18.1% and 12.1% respectively. Both participants displayed a poorer level of CAD sketching knowledge and failed to fully define any of their sketches. This contributed to their poorer performance. Overall, the nature of this approach indicates deficiencies in students' procedural and declarative knowledge related to CAD modelling expertise.

The other common approach evident in the students' CAD models was Boolean focused in nature. This is an extension of the first approach mentioned above, where a number of orthogonal sketch profiles were extruded/cut in an attempt to create the required features. Initially, participants created the base feature, after which they sketched orthogonal sketch

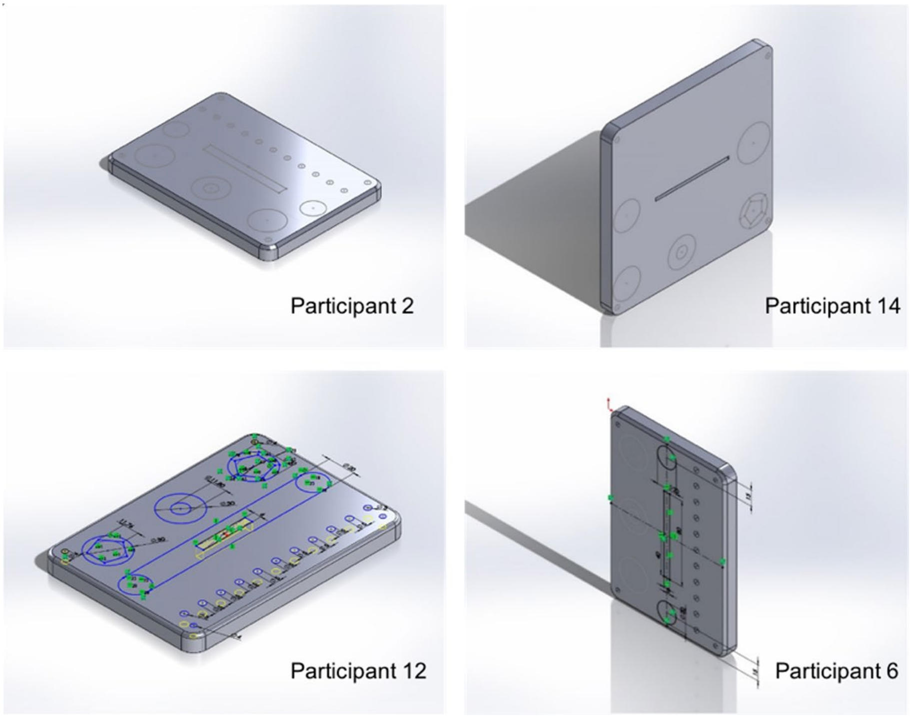


Fig. 8 Sample of student models exhibiting an orthogonal sketch dominated approach

profiles on the top surface of the base feature. They then used cut/extrude functions in an attempt to create the required geometry. Examples of student approaches are illustrated in Fig. 9.

Participants who opted for this approach created extruded geometry where lofted geometry should have been. Participants 4 and 7 then sketched the top profile of the lofted geometry on the top surface on the extruded cylinders. Presumably this was in an attempt to create the profile by further accretion or subtraction attempts.

Participant 7 scored 42.42% in the CAD modelling activity which was the highest out of the participants who demonstrated evidence of a predominately Boolean modelling strategy. This was still an overly poor performance score in this activity and demonstrates the ineffectiveness of such a strategy in terms of a modelling approach for this task. Participant 4 recorded a score of 39.3% and as can be clearly seen in Fig. 9, the student sketched profile features on the top face of the cylindrical extrudes they created. This demonstrates a significant difficulty on part of the student in visualising the approach to create the lofted geometries. Participant 11 scored 18.1%, and participant 10 scored the lowest out of the entire cohort, with 9%.

Students in general, tended to adopt either of these predominant approaches and as mentioned earlier in the section, no participant successfully completed the activity in its entirety. This indicates a significant lack of visualisation capacity in terms of analysing and planning a strategy for modelling in 3D CAD and in addition the approaches identified during observations illustrate an incapacity on part of the students to strategically model the

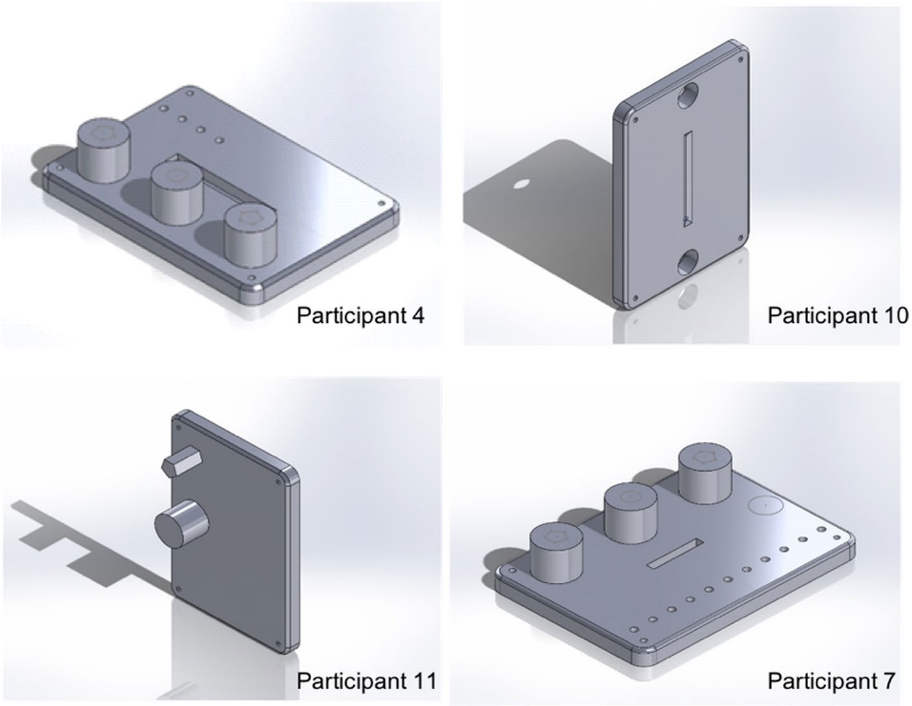


Fig. 9 Examples of Boolean modelling approach

component geometry and lack of consideration of design intent. Given, that the solutions indicate a lack of visualisation ability and also a lack of analytical and strategic competency it is necessary to explore the potential relationship between the variables.

Relationships between variables

To explore this relationship performance data for all participants across the three variables of the study were graphed and are presented in Fig. 10.

As can be seen in the figure, there is a clear variance evident in students' performance. This aligns with the class teachers' description of the sample cohort as being mixed ability. All three performance variables (analytical deconstruction, CAD modelling and spatial visualization) exhibited good levels of normality ($p=0.09$, $p=0.2$ and $p=0.12$ respectively) which is considerable given the relatively small sample size. This indicates a good representation of the typical secondary graphical education classroom demographic in general.

All three variables were subsequently submitted to a correlational analysis to determine any statistical relationships between the variables. Pearson product-moment correlation was conducted on all three variables as data met the assumptions of normality. The results of this are shown in Table 1.

Correlation coefficients show a strong relationship between all variables in this study. This conclusion is based on Cohen's (1988, pp. 79–81) guidelines on interpreting the strength of the coefficient relationship with values above 0.5 indicating a large/strong relationship. The data indicates that performance on the analytical deconstruction and strategic

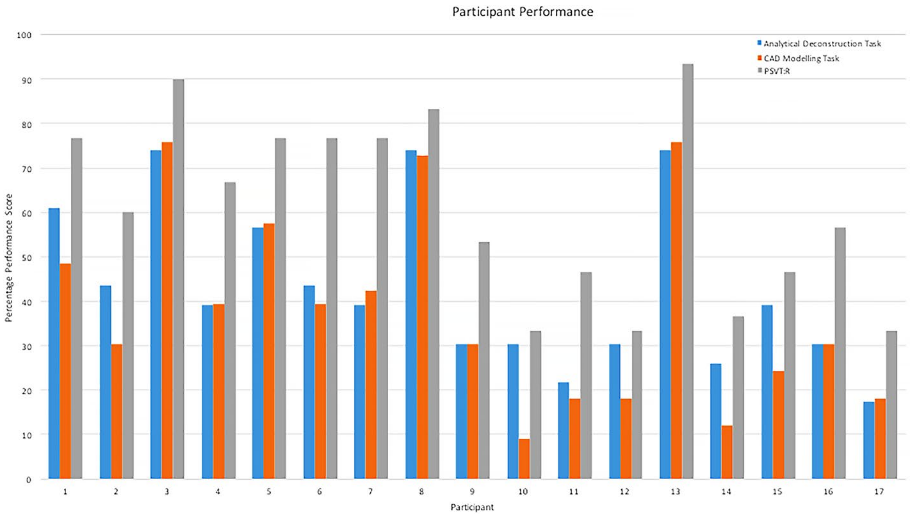


Fig. 10 Participant performance across all study elements

Table 1 Results of correlational analysis

Variable	Analytical	Strategic model	PSVT:R
Analytical	–		
Strategic modelling	0.941**	–	
PSVT:R	0.878**	0.942**	–

**Correlations are significant at the $p < 0.01$ level

CAD modelling tasks are highly related. In addition, the relationship of both elements to participants' spatial visualisation ability is evident.

Discussion

This research set out to explore the CAD modelling strategies of secondary students during a prescribed problem-based task and also consider the underlying variables comprising the notion of capability within this domain of graphical education. In doing so, the paper uses the proposed theoretical framework of Rynne et al. (2011) and evolves the approach to investigate upper second level education. Rynne et al. (2011) highlighted deficiencies in student teachers' CAD modelling capacities, particularly in the application of strategic knowledge. In addition, the authors posited that including analytical deconstruction strategies in pedagogical approaches directed at developing CAD modelling expertise may partly address these deficiencies. The data in this study, collected from a post-primary student sample, displays some of the same deficiencies in strategic CAD modelling, which poses serious questions of the nature of current pedagogical practice within upper second level graphical education. The data here highlights students adopting approaches either dominated by an over emphasis on orthogonal sketching or Boolean modelling. Figures 8 and 9 illustrate examples of these approaches and when compared to the performance scores

(Fig. 10) it is clear that there is an inefficacy in participants' CAD modelling strategies. Students exhibited a good knowledge of declarative and some procedural elements of the CAD modelling process as shown by the frequency analyses in Figs. 5 and 7. Here students could identify basic geometric features and the associated sketch geometries. However, these figures highlight a significant lack of consideration of the strategic knowledge related to design intent. This is most clearly substantiated by the fact that not a single student identified the correct sketch plane to begin their modelling strategy with.

These findings highlight some considerations relating to pedagogical practices within upper second level graphical education. There is a consensus within the pertinent literature that the practices of teachers, with regards the use of ICT, is still housed within a paradigm of direct transmission (Chester 2008). These types of didactic approaches tend to focus on surface learning that emphasise declarative an procedural knowledge and skills. This can be seen manifesting itself in the modelling approaches adopted by students within the current study that tended to be procedural in nature and predominantly focused on the achievement of a product resembling the perceived solution rather than the strategic application of CAD knowledge. When taken in light of the deficiencies already cited with student teachers (Rynne et al. 2011), there are apparent concerns for the current state of pedagogical practice at upper second level. It is well documented that teachers' beliefs are sculpted, in large part, by their prior educational experiences (Fang 1996). Given the style of utilisation of this graphical ICT software with a lack of strategic awareness and application it is plausible that beliefs surrounding the use of CAD, and associated conceptions of capability, within graphical education are malformed and potentially crystalizing during their teacher education programmes. If this is the case, then the style of activity that has been uncovered within this study is evidence of the manifestations of such beliefs within professional pedagogical practice at secondary level. This is a worrying hypothesis as it highlights a potential misconception of the notion of capability, on the part of the educator, which could be limiting second levels students' development of graphical and technological capability. It also highlights the potential existence of an inimical cycle of hegemony where secondary students who go on to enter ITTE are reinforcing, through their third level experiences, a narrow conception of graphical capability, leading to the preservation of outmoded pedagogy.

The subject of graphical education may still suffer from a hegemonic preservation of past practices associated with vocationalism (Seery et al. 2011) as well as a national assessment mechanism catering for university matriculation that emphasises standardisation and performance grades as its apotheosis. This clearly brings with it a number of pressures for practicing teachers. This coupled with the integration of a significant amount of ICT into a subject where little emphasis (in prior incarnations) was previously placed has led to a potentially narrow conception of capability associated with the development of CAD modelling expertise.

By way of challenging this potential issue, this paper presents data illustrating the multifaceted construct of modelling expertise. This is particularly clear when considering the strong statistical relationship found between the analytical deconstruction and CAD modelling tasks and the additional robust relationship of spatial visualisation ability to both of these activities (see Table 1). Successfully analysing and planning an approach to modelling a prescribed task within a CAD system requires an initial set of representational processes that are predicated on an interaction between working and long-term memory processes. It is clear in previous work by Rynne et al. (2011), that there are significant deficiencies in students teachers' abilities to transfer graphical knowledge to the domain of digital CAD modelling which, as this paper has now demonstrated, also permeates the

CAD modelling capacities of second level students as well. This deficiency may be mediated by the cognitive processes that support the conceptualisation and representation of the prescribed part model. Data presented in this paper demonstrates a correlation between spatial reasoning scores and the analytical and strategic exercises. Visuospatial processing has been shown to be a key contributor in successfully representing a strategic approach (D'Argembau et al. 2010) and so it is plausible to posit the unique contribution this ability may have within the notion of proficient CAD modelling skills.

These findings have potentially significant implications for teacher education within the context of technology enhanced graphical pedagogy. Firstly, it is clear that there exists deficiencies in second level students' modelling capabilities. The exact reason for these are not clear and are likely multifaceted. However, this paper also captures additional data relating to the visualisation and analytical deconstruction skills of students. Consequently and as a second core finding of the paper, the data also expands our understanding of the cognitive processes involved in successfully modelling with a CAD system. Literature in the field of STEM education has consistently highlighted the relationship between visuospatial ability and academic success (Wai et al. 2009). In addition, specific studies have supported a correlational relationship between spatial skill level and CAD modelling success (Sorby 2000; Branoff and Dobelis 2014). The present study highlights that spatial ability has a specific relationship to both the analytical and strategic skills necessary to successfully engage in CAD modelling.

Taken together, these two key elements of the paper highlight a need to reconceptualise the notion of graphical capability within a technology enhanced paradigm. Highlighting this within the field of teacher education is extremely important as it is well established that a teachers' prior beliefs influence their pedagogy (Fang 1996) and specifically play a mediating role in the manner in which they adapt their pedagogical approaches to the integration of ICT (Hermans et al. 2008). This recommendation aligns with Shulman's model of pedagogical reasoning and specifically the transformation of knowledge for pedagogic malleability (Shulman 1987). By broadening the conception of capability within digital graphical modelling this transformation within the pedagogical reasoning process will be enhanced. The paper also presents empirical data that supports a relationship between the deconstruction of geometric data using freehand sketching and strategic parametric modelling performance. Therefore, a recommendation for current practicing teacher arising from the paper is the utility of hands-on sketching activities to deconstruct and plan modelling strategies prior to engagement with the software itself.

Conclusions and future work

This paper highlights deficiencies in secondary students' digital modelling ability within a CAD software system. Unique relationships between the analytical and strategic components of the notion of ability in this area are demonstrated along with a further relationship to visuospatial ability. This work advances related work in the field and presents a need to reconceptualise the construct of graphical capability with regards digital CAD modelling. This has potential benefits for teacher education and subsequently enhancing pedagogy in second level graphical education.

There are some limitations that need to be acknowledged. Firstly, the sample size reported in this study is small and future work in the area needs to take this into account. However, this was controlled for as much as possible by liaising with the class teachers in selection of the participants and can be seen in the reasonable normality of performance scores recorded. Secondly, the contribution of spatial ability is confounded by the reliance on correlational data and work by D'Argembau et al. (2010) highlights the contribution of auxiliary cognitive elements, such as executive function and working memory capacity, to the analytical and strategic components addressed in this paper. Future work will therefore aim to include these variables within more tightly controlled regression analysis approaches to isolate the unique contribution of visuospatial ability. It is also necessary to further develop sketching based activities focused on the deconstruction and planning of modelling approaches and investigate their longitudinal effect in augmenting students' development of strategic modelling skills.

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