THE IMPACT OF COMPUTER AIDED ARCHITECTURAL DESIGN PROGRAMS ON CONCEPTUAL DESIGN IN AN EDUCATIONAL CONTEXT

Abstract

Little research has been undertaken concerning the manner in which students use computer aided architectural design (CAAD) programs for conceptual design. The research aim was to explore the potential impact of CAAD programs as conceptual design tools within architectural design methodologies. Therefore, the study aimed to understand the effect of CAAD on self-reflection using a think-aloud method. The findings demonstrate that participants used CAAD representations for concept development, information visualisation and presentation of design strategies. Results from the detailed analysis of design process are enlightening, particularly in terms of the cyclical nature of conceptual design. Furthermore, the use of a micro-detail protocol study within this context suggests an appropriate methodology for application in further study of the architectural design process.

KEYWORDS:

Architectural design, design activity, computer aided architectural design, protocol analysis, conceptual phase

In recent years Computer Aided Architectural Design (CAAD) has been highlighted as a socio- cultural change in the design professions rather than "*merely a technical issue*" (Pektas and Erkip 2006; Tweed 2000). The emergence of digital design as a new practice has been pioneered by leading architects such as Frank Gehry, Zaha Hadid, Greg Lynn, Ben van Berkel, and Peter Eisenman. The emergence of digital design theory has been mooted by theorists such as Kalay (2004) and Oxman (2006, 2008) who are all predicting new design approaches, methods and processes. However, a perception of the impact of CAAD programs on design practice and education is still fragmented (Al-Qawasmi 2005; Hanna and Barber 2001; Morton 2012). In response to this, attempts have been made by theorists (Oxman 2006, 2008) and studio instructors (Al-Qawasmi 2004, 2005; Dokonal and Knight 2006; Lu 2008; Zuo, Leonard and MaloneBeach 2010; Morton 2012) to change how CAAD is perceived through practical engagement and experimentation.

The study aim and objectives are positioned within the context of advanced (final year) education and CAAD's "professional systems" (Achten 1996) that are used in most schools of architecture and architectural practice, e.g. AutoCAD and SketchUp. This paper aims to understand the impact of CAAD on the micro level of interaction among the student, CAAD, and design brief in the conceptual design process. This will answer the question of "Does CAAD negatively or positively impact student's design processes?

This study explores four design protocols of how architectural design (AD) students and architectural technology (AT) students use CAAD software programs as they solve a design task. In addition to that, we study students' use of CAAD by examining three different coding schemes, these being design micro strategies, level of abstraction and external representations.

1 The framework

Many educational programs were proposed and developed in the field of architecture and engineering disciplines which aim to integrate digital tools in the design curriculum (Oxman 2008) as opposed to the customary approach of integrating CAAD into the IT curriculum. However, at present the teaching in many, if not most, of architectural design schools falls behind in this respect. The project model of design in many of the architectural studios is still firmly based on visual thinking and reasoning with paper media (Oxman 2008; Zuo, Leonard and MaloneBeach 2010; Basa and Şenyapili 2005).

Design studies have focused on sketching and its impact on designing whereas the role of other media, e.g. imagery, discussion, reflection and CAAD, has not been examined in as much detail.

Jonson (2005) argued that currently the primacy of sketching, as a primary conceptual tool requires more evidence. Indeed, Jonson concluded that sketching is not the dominant conceptual tool; instead, he found verbalisation, or the combination of verbalisation and other conceptual tools (Jonson 2005). The combination of different conceptual tools such as modelling, sketching, words and CAAD also reflects that design is a dialogue between verbal and non-verbal methods. Moreover, Jonson (2005) concluded that CAAD emerged as a conceptual tool across different design domains. CAAD is not just a technical drawing tool but also a conceptual tool capable of developing new ways of conceiving and perceiving design. Jonson (2005) concluded that negative views of CAAD perception depends mainly on the surface understanding of the conceptual tools. Quoting Jonson: "*Arguably, then, the view that CAD is inappropriate for conceptualising seems to be based on a preconception of conceptual tools as surface, rather than deep structures*." (Jonson 2005).

Recently, design media and interactivity have been explored in design studies, based on the nature of the designer's interaction with the media. According to Oxman (2006), media has four levels of interactivity. A designer interacts with: (1) A paper-based representation: at this level of interaction, the designer is interacting directly with a representation of the designed object visually through a drawing or physical model. (2) A digital representation construct: at this level of interaction, the designer is interacting with CAAD by means of a digital drawing, either in 2D or 3D format. (3) A digital representation generated by a mechanism: at this level of interaction, the designer is interacting with CAAD through a set of rules and (spatial) relations to form a mechanism to generate a digital structure; this is arguably mediated by information. (4) A digital environment that generates a digital representation: at this level of interaction, the designer is interacting with "the operative part of a generative design mechanism." Where the designer "can interact with the computational mechanism that generates the digital representation." this is arguably mediated by more advanced information and knowledge.

In the first two levels, the designer interacts with the drawn shapes on paper and the emergent configurations. This is further classified as external interaction (Oxman 2006). Oxman (2008) asserts that Schön's conversational characteristics have one aspect that is the "backtalk" of the visual representation. This can be true with the first level of paper–based interaction, but on the second level of interactivity- digital based- this can be argued as the interaction goes beyond the 2D image of a representation into 3D objects. The other two levels are classified as internal interactions meaning that these levels of interactions go deeper than the surface level of the visual aspect of a representation, to manipulate the computational medium in different ways, requiring a different form of action. Hence, the last two levels clearly reflect the new requirement for knowledge requisition of the “toolmaker” (Oxman 2006) designer, and consequently the digital-skill level will vary. Arguably, the last two levels of interactivity are the most challenging in relation to the knowledge (Oxman 2008) that is required and are part of the future direction rather than changes that might occur in the next ten years. There would be a different outcome if computation (programming) became a common knowledge or skill, or if computers became simpler with respect to such (operative) computational mechanism(s). These two are hypothetically “re-introducing a different medium of conceptualisation, replacing paper-based media” (Oxman 2008).

In this study, it is argued that the second level of interactivity has two modes of visual thinking: 2D and 3D. This can be categorised further into passive and active interaction. Passive interaction agrees with Oxman’s (2006) proposition of the visual talk back and active interaction is when the represented objects are manipulated and modified.

As we move towards the other uses and levels of digital interactivity, new knowledge is needed to bridge the gap between the known and unknown. Thus it is argued that the knowledge required will be different from now on and will affect the designer’s role as well as new requirements for practice and education. However, architectural practices are ahead of those in design education (Lawson 1997 and Cross 2001), which is still based on Schön’s framework of reflection to support the thinking process in the studio as well as the self (student), and the role that representations play in the design process, knowledge and methods.

How CAAD would influence a student’s design process is not yet understood. However, it is recognised that the majority of architectural design students, as part of the wider student population, are described as a motivated sample who use CAAD on their own, and where this is the case, it is important to understand how the interaction is taking place. Alongside this, another point which should be taken into consideration is student’s preferences. Therefore, studying a hypothetical interaction in a similar situation is important even if it is argued by some studies as inappropriate. Most studies in CAAD are descriptive in the sense that students have positive attitudes towards the use of computers in design. However, in relation to CAAD practice and impact, investigation should be carried out on specific design interactions on the micro level of self-reflection. The current levels of interactivity have been examined and will be discussed further in relation to design process, level of abstraction and external representation.

2 Methodology

Researchers have used Thinking Aloud Methods (van Someren, Barnard and Sandberg 1994) in the design process to theorise and present the rational structure of the design process. The second workshop, ‘Research in Design Thinking II- Analysing Design Activity’, in 1994, held at The Delft University of Technology, revealed a range of approaches to analysing design activity and was an important milestone for this research methodology. However, it gave another dimension to design studies by which protocol analysis has been validated as a research technique for design (Cross Christiaans and Dorst 1996). The thinking aloud method allows the researcher to collect qualitative data from individual users. As the name suggests, participants should think aloud while performing a specific design task within a medium. These could be paper drawings (Schön and Wiggins 1992), CAAD (Bilda and Demirkan 2003), mental imagery (Bilda 2006), or physical modelling. Moreover, van Someren, Barnard and Sandberg (1994) state that “thinking aloud takes place concurrently with the cognitive process.” By verbalising their thoughts, or what they are trying to achieve, data emerges to help the researcher understand how they solve the design problem in that designing (thinking) medium. The verbalisation acts as a narration of the design process and the subject’s behaviour. This method is also known as “concurrent protocol” (Tang 2001, Ericsson and Simon 1993; van Someren, Barnard and Sandberg 1994). Furthermore, as noted by Gero and Tang (2001), using concurrent protocols reveals details of sequences of information processes reflecting the designer’s short-term memory. Therefore, concurrent protocols reveal the process of design (Dorst and Dijkhuis 1996).

The coded protocols are data in the sense that they can be compared within a coding scheme, between the coding schemes and among various cases. These are quantified numerically in relation to their formal category, sub-categories or duration (Tang 2001; Gero and Tang 2001; Atman, Turns and Adams 2005). This quantitative approach is most common in design protocol analysis (Brereton et al. 1996) and can focus on describing designer interaction through design process acts and design intents (Cardella, Atman and Adams 2006; Ataman 2000; Gero and McNeil 1998). In previously reported research using protocol studies, a sample size of 1-3 has been shown to elicit acceptable results, and to allow for an appropriate level of analytical depth (Jiang and Yen 2009; Cardella, Atman and Adams 2006).

2.1 Experimental Design

To generate CAAD-based design protocols, the following experiment was set and repeated in two runs of data collection. The experimental design follows that defined by Van Someren, Barnard and Sandberg (1994), a similar approach used by others (Bilda 2001; Bilda 2006; Tang 2001). In this research, the level of design expertise was crucial for the theoretical framework (Dorst and Reymen 2004). It was felt that the final year cohort was more likely to perform design using CAAD than earlier stages.

2.2 The design task

An architectural design brief was presented to participating students who then selected their preferred CAAD program (AutoCAD, SketchUp or ArchiCAD) to attempt the design task. Participating students were asked to verbalise their thoughts during the task while being video and audio taped. The digital video camera was arranged to minimise the impact on the participant being recorded (Van Someren, Barnard and Sandberg 1994; Bilda 2006). The researcher sits to one side, observing the process and making notes of the design session, the experimental setting is shown in Figure 1. A two-dimensional AutoCAD drawing of the task site was provided together with a cross-section.

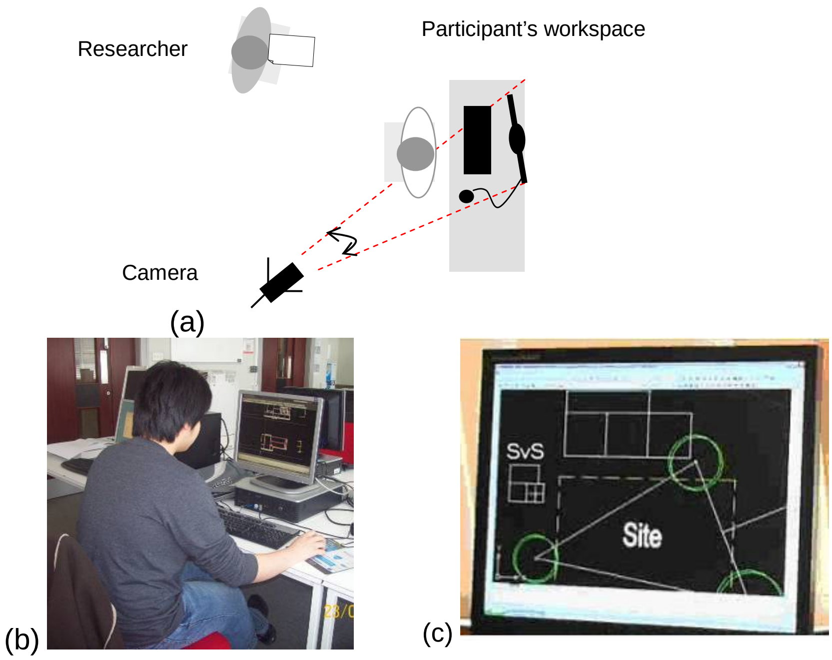


Figure 1 (a) Experimental setting (b) Participant's position (c) Camera snapshot.

The design task was to design a gathering space; the required outcome being a 2D concept and preferably 3D conceptual model while detailed plans, sections, and elevations were optional. All participants stopped designing when they felt that they were satisfied with their design proposal. When the participant felt ready to present the finished idea, the student was asked to provide a brief conceptual explanation of the proposal.

2.3 Software video coding and analysis

In the context of think-aloud protocols, segmentation and coding are the procedural steps of analysis (Van Someren, Barnard, Sandberg 1994). The data from each experiment was prepared to be analysed using Transana software* (version 2.22) for coding video/audio data, Figure 2. The Transana platform provides the ability to quantify the time spent on each code and the number of codes in every protocol.

The pre-analysis data preparation involved six steps: (1) dividing the video recording into three clips, (2) transcribing the parallel modes of thinking, (3) assigning clips by time stamping, (4) segmenting arbitration, (5) data coding by assigning keywords, and (6) coding arbitration. The reader is directed to Appendix A, for the full lists of Gero and McNeill (1998) coding and the adapted list used in the data coding of this study.

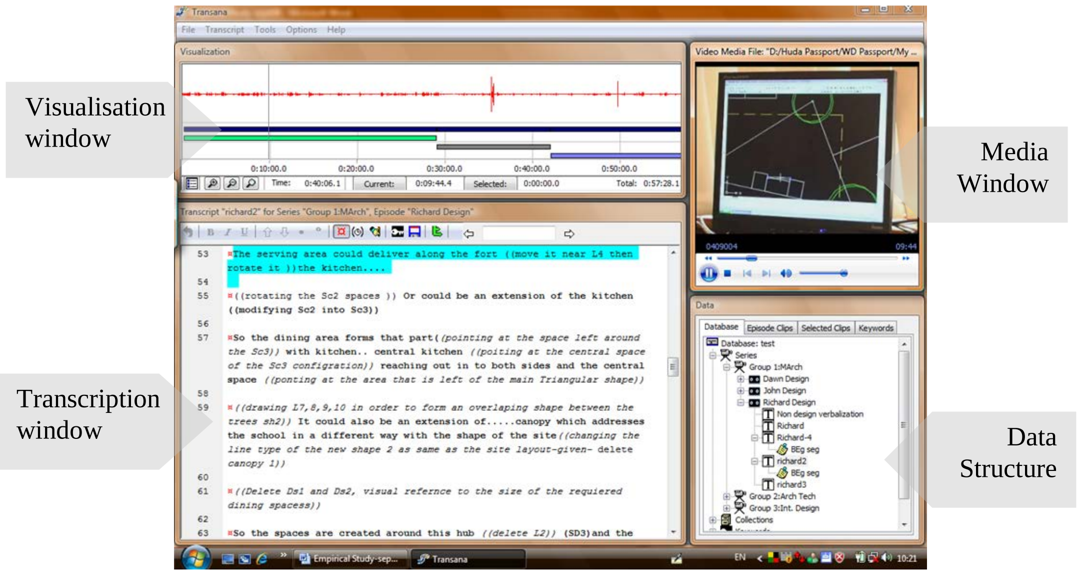


Figure 2 Transana software platform (text, time codes, visualisation window and the protocol study database).

It was first necessary to define the exact duration that the student had spent in conception. This step was important in terms of utilising Transana software as an analysis aid for time calculations, as it calculates time for each coded activity in relation to the total time that the participant spent in designing.

2.4 Segmenting and coding consistency

The agreement percentage is calculated for each protocol by computing the agreement percentage of the coding between the first encoding run (version one) and the second encoding run (version two). An arbitrated version (third) was subsequently reached through comparing the observed discrepancies and selecting the most reliable one (For a full review of the inter reliability coding method, the reader is directed to Purcell et al. 1996).

* Transana: http://www.transana.org/index.htm

Table 1 Arbitration and coding consistency.

Participants	Agreement percentage between	
	1st and 2nd run (%)	3rd and arbitrated coding (%)
SA1	75	90.1
SA2	80	90
ST3	77	89.6
ST4	81	90.3
Average	78.25	89.5

Table 1 shows the agreement percentages between the three versions; first, second and the arbitrated version, and how the agreement percentages were strengthened after arbitration. In the first run, a comparison yielded an average agreement percentage of 78.25, whereas the arbitrated version (third run) compared to the earlier versions yielded a higher average percentage of 88.9%. Other protocol studies (Tang 2001; Bilda 2006; Atman et al. 1999), report agreement percentages ranging from 70% to 94%.

3 Results

Based on the study framework and objectives, four design protocols of advanced year students were selected for analyses. The research recognised that a variation in students background is important, architecture and architectural technology students will be instructed to use CAAD at different stages in design, and perhaps for different purposes. In the study undertaken here, two participants were studying for a Master of Architecture and have been labelled in the study as SA1 and SA2. The other two participants were final year Architectural Technology students, and have been labelled in the study as ST3 and ST4. Table 2 shows the selected protocols.

Participants	Auth/Gend	Age	Stage	Design Clip Duration (hr:min:sec)	CAAD Program (s)
SA1	English /M	23	5 th	00:57:28	AutoCAD
SA2	English /M	22	5 th	00:45:18	AutoCAD/SketchUp
ST3	Asian /M	21	4 th	01:19:41	AutoCAD
ST4	Scottish /M	22	4 th	00:56:55	SketchUp

Table 2 General description of the participating students.

Participants were asked to choose any CAAD program(s) they preferred for carrying out the design task. The selected protocols varied in that respect, and as a result, two distinct CAAD based protocols can be identified. The first type is classified as the use of a single CAAD program throughout the whole session (a *single* CAAD program-based protocol) and the use of more than one CAAD program as a *multi* CAAD programs-based protocol. Figure 3 shows the four proposals created by the participants.

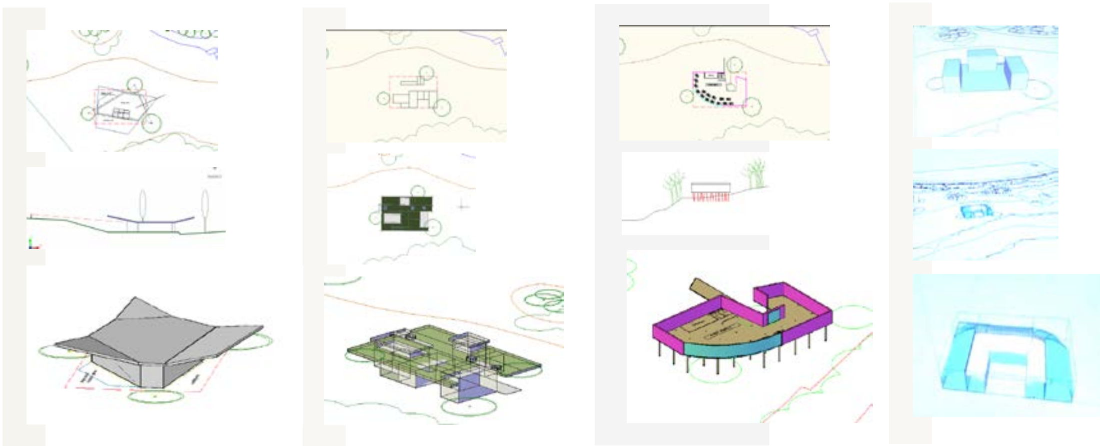


Figure 3 (a) SA1 Proposal(AutoCAD) (b) SA2 proposal(AutoCAD+SketchUp) (c) ST3 proposal (AutoCAD)(d)ST4 proposal (SketchUp).

The analysis is presented in six main sections: the results of segment duration and transition rates in the first two sections; the process oriented coding in the third section which includes a descriptive analysis of the design intervals, coding percentages. The results of levels of abstraction coding are presented in the fourth section; and the results of the external representation acts and explicit strategies are presented in the fifth and sixth sections.

3.1 Segment durations

The period of time spent in design activity has implications for design behaviour (Tang 2001; Adams, Turns and Atman 2003). Within the context of this study, applying segmentation is based on the shift of focus when new information is added to the design context. This means that every segment in the protocol represents one intention of the participant's design process. The total number of segments varied between the four design protocols (69-83), shown in Table 3. The average number of segments for the four design sessions is 74.75 segments. The transition rates for each of the four design sessions were 0.85, 0.54, 1.04 and 0.75, successively.

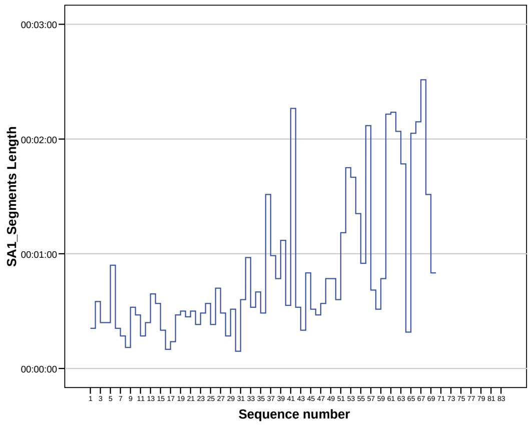
Participants	Designing activity total time (hr:min:sec)	No. of segments (clips)	Mean of segment length (hr:min:sec)	Std. Deviation for mean segment length (hr:min:sec)	Kurtosis for segment length	Std. Error for Kurtosis	Range	Minimum segment duration	Maximum segment duration
SA1	0:57:28	69	0:00:49	**0:00:37**	.590	.570	0:02:22	0:00:09	**0:02:31**
SA2	**0:45:18**	**83**	**0:00:32**	**0:00:23**	6.591	.523	0:02:26	**0:00:04**	0:02:30
ST3	01:19:41	76	**0:01:02**	0:00:36	1.829	.545	**0:03:00**	**0:00:12**	**0:03:12**
ST4	00:53:34	71	0:00:44	0:00:29	-.722	.559	**0:01:46**	0:00:04	0:01:50
AV	**00:59:00** (Total of 238.37 min)	**74.75**	**00:00:47**	**0:00:31**	**2.072**	**0.549**	**0:02:23**	**0:00:07**	**0:02:31**

Table 3 Descriptive statistics of the four design sessions.

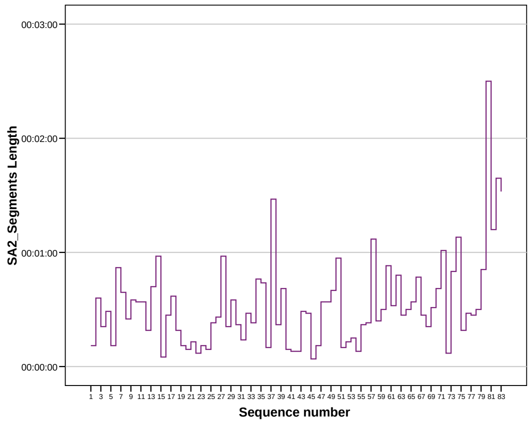
It is interesting that the shortest design protocol duration (45:18 min) had the largest number of segments (83). This suggests speedier shifts of intention and moves compared to the other design protocols. At this level of analysis, this may be related to the user employing a multi-CAAD protocol.

To ascertain how these segments were distributed with respect to the start and end of the design session, plotting the segments duration in sequence (using segment's time series in SPSS sequence charts) provided a detailed visualisation of the length of each segment of the individual protocol and its position along the design process time line, as shown in Figure 4 (a, b, c, and d).

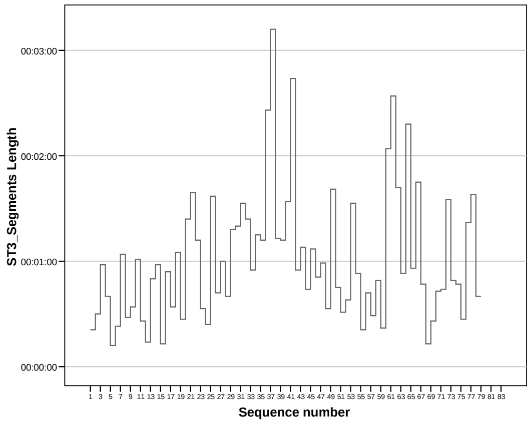
The segments have a progressive nature, in that later segment lengths are longer. This was observed in SA1 and SA2 design protocols with SA1 showing an early progression compared to SA2. This suggests that the segment length in SA1 increases as the design session progresses. The speed of focus shift becomes slower with longer segments. SA2 shows a more balanced interplay between short and long segments along the process, that is fast shifts of intention compared to longer shifts but the longer segments also occur later nearer the end.



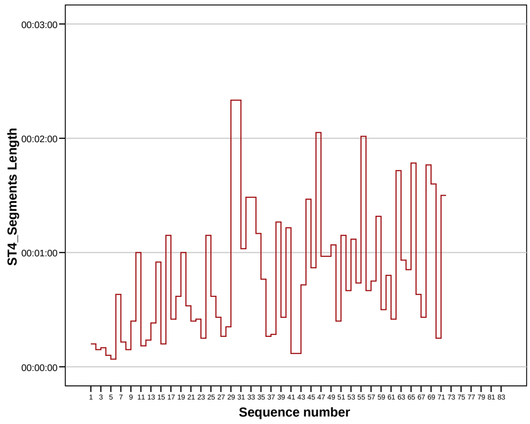
a- SA1 Segments sequence graph.



b- SA2 Segments sequence graph.



c- ST3 Segments sequence graph.



d- ST4 Segments sequence graph.

Figure 4 (a, b, c and d) Segments sequence graph of the four design sessions.

On the other hand, ST3 and ST4 show another pattern of succession, as the interplay between short and long segments occurred at an early stage and continued as the main pattern throughout the later stages of the design process.

3.2 Transition Rate

The change in design intention from one segment to another is reflected in how many transitions the participant made during this process. The number of transitions is a measure of the number of times a participant moved from one design/representation activity to another (Adams, Turns and Atman 2003; Atman et al 1999). Figure 5, illustrates the number of transitions in percentage for every 10 min interval.

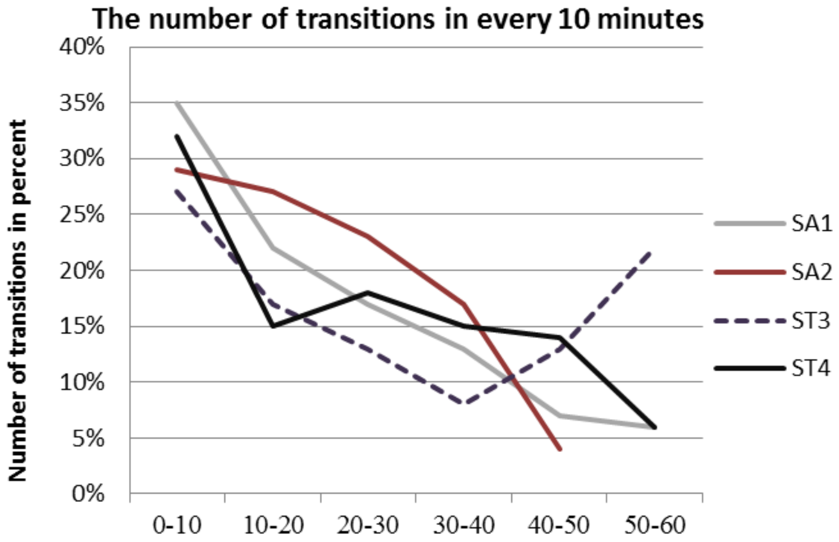


Figure 5 The number of transitions (percentage) every 10 minutes.

These results show that the intervals of the design protocol varied in the number of segments upon the phase of the design process, whether at the early phases of the design or in later phases. In addition, it showed that speed of thought decreased during the later phases, with the exception of one student.

3.3 Design Process Oriented Coding

The design session segments were coded using the process oriented coding scheme and studied qualitatively and quantitatively accordingly. Through Transana's platform, the total time spent in each micro-strategy was documented. Hence, the total time for each strategy can be detected and compared throughout the four protocols. All the segments are coded with only one code, thus every segment refers to one micro strategy.

3.3.1 *Architecture student (SA1)*

Participant SA1 started design by evaluating the design problem and analysing the problem (AS) considering the design brief requirements. He then moves from the problem space to propose a partial solution regarding the shape of the site layout and again starts to analyse the given problem with respect to the changes he has made. Afterwards, he engages in proposing a solution (PS) for an extensive period of time; moving between a number of proposing a solution micro strategies, for example clarifying a solution by adding details or by exploring a proposed solution graphically which enabled him to decide the functional and spatial layout of the proposed building. This was followed by another period of proposing a solution and analysis (see figure 6). He ends this phase by making a design decision regarding the building structure.

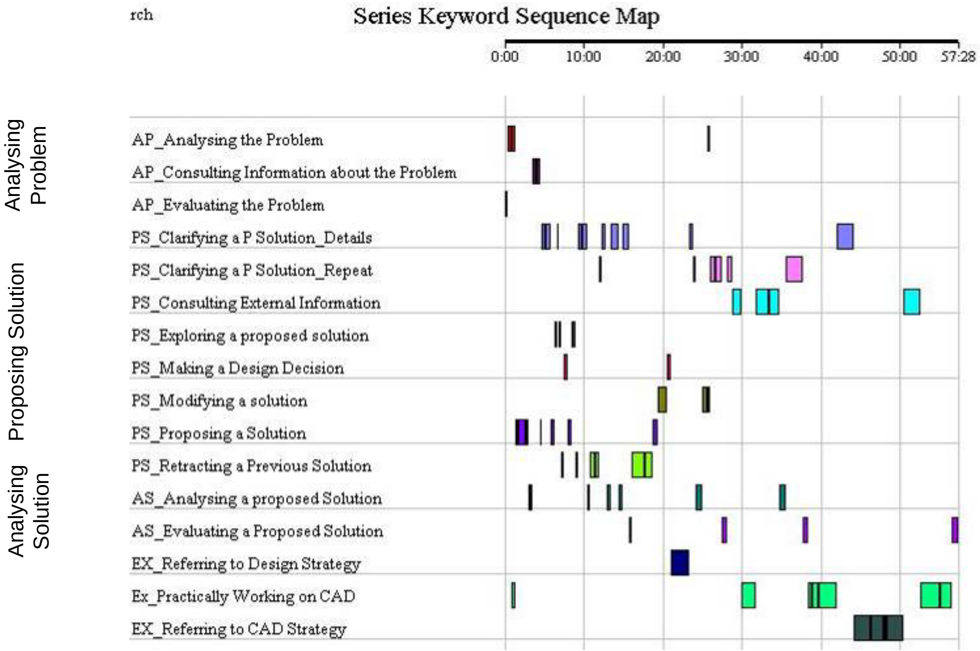


Figure 6 SA1 design micro strategies along the design session timeline.

In general, in this protocol the prevalent trend of micro strategies transition was the transition between proposing a solution and analysing it for most of the design process.

3.3.2 *Architecture student (SA2)*

Participant SA2 engaged in rapid transitions of proposing solution (PS) micro strategies; clarifying it by adding detail, evaluating, modifying and analysing the proposed solution (see Figure 7). This was followed by the final phase of considering the design building on a detailed level of visualisation to explore the design massing by lighting and shading. The student was engaged in proposing a solution (PS) more than any other analytical strategy.

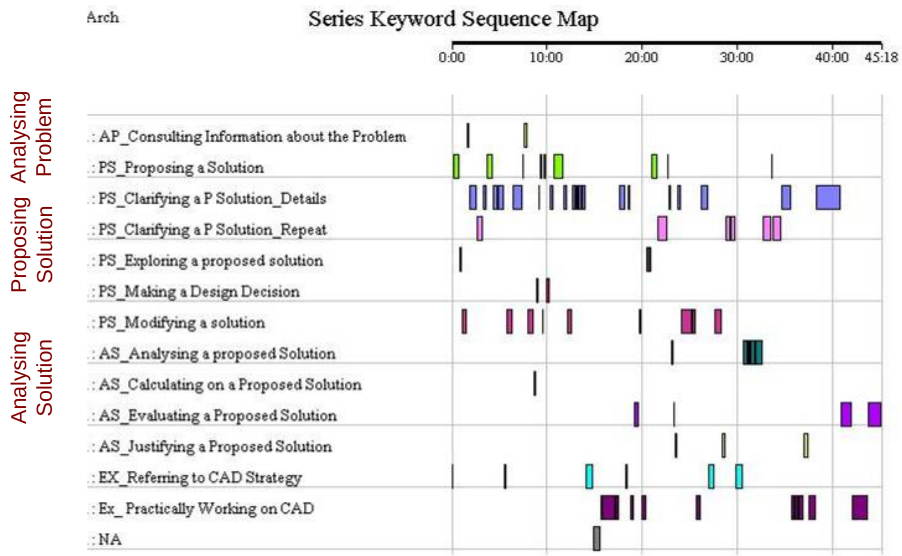


Figure 7 SA2 Design micro strategies along the design session timeline.

This participant provides an example of “aha moment” or sudden insights - seeing something he did not intend to draw or create - and illustrates the automated intersection between the created volumes in 3D (SketchUp) which made him pause, think and evaluate. Instead of correcting the resulting configuration, he continued analysing it and went on to justify the new configuration in terms of the conceptual framework of his design to confirm his previous intentions.

> Seg 53 “(0:23:18.4) *now I just come across that without thinking about it but from the way the software works it made me think*”.

After this “aha moment” the transition has changed rapidly from being between the same category to two main categories PS and AS micro strategies. In general, in this protocol the prevalent trend of micro strategies transition was the transition within the same design strategy that is proposing a solution (PS) for most of the design process.

3.3.3 *Architectural technology student (ST3)*

Participant ST3 micro strategies stretched along the time line as this was the longest protocol session. The student was engaged in analysing the problem (AP) and consulting information about the problem (AS) and proposing a solution (PS) more than any other design strategy, while he was engaged to propose a building layout for the site and a spatial functional layout, this is shown in Figure 8.

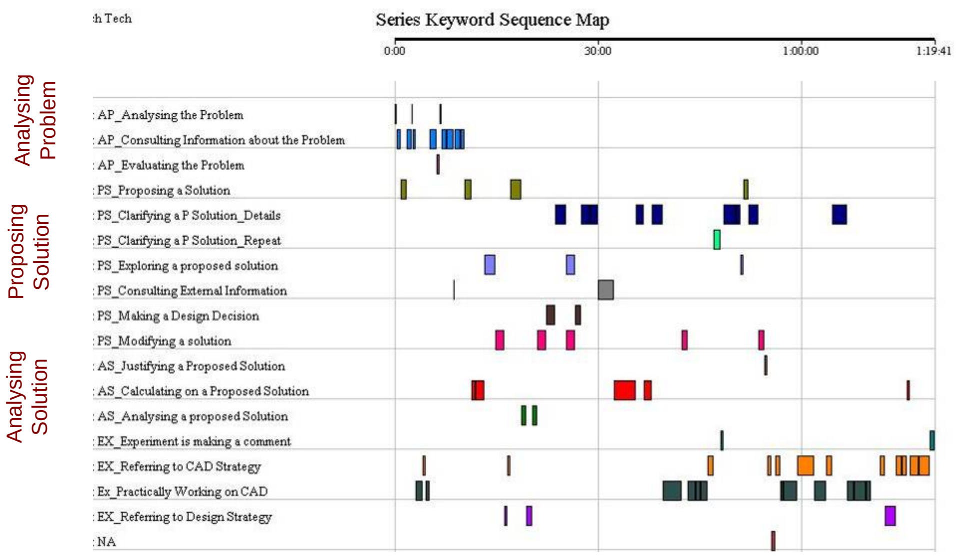


Figure 8 ST3 Design micro strategies along the design session timeline.

In general, in this protocol the prevalent trend of micro strategies transition was the transition between proposing a solution (PS) and analysing it (AS) for most of the design process.

3.3.4 *Architectural Technology Student (ST4)*

Participant ST4 single CAAD (SketchUp) design protocol (shown in figure 9) the participant's design strategic cycles showed that the first interval continued for about 12:39 minutes, which was identified as the richest and the most extensive phase with respect to the micro strategies' variation and number of transitions.

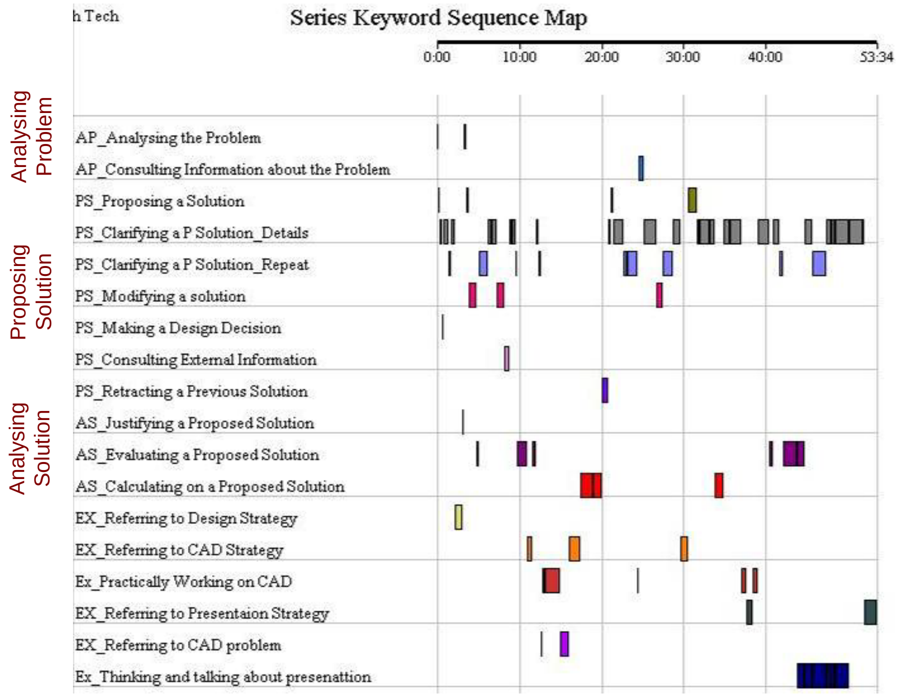


Figure 9 ST4 Design micro strategies along the design session timeline.

The student was engaged in proposing a solution (PS) most of the time, especially clarifying a solution (PS) more than any other analytical strategy while he was engaged in 3D to propose a "volumetric" spatial layout. The prevalent trend is the transition between the same design micro strategies, i.e. proposing a solution (PS), and between proposing a solution (PS) and analysing a solution (AS), with a very little focus on analysing the problem (AP).

3.3.5 *Summary*

Figure 10 presents the summary of general categories of the micro strategies. Two of the students, SA2 and ST4, bear a resemblance in the general categorical percentages of the total time spent on a certain category.

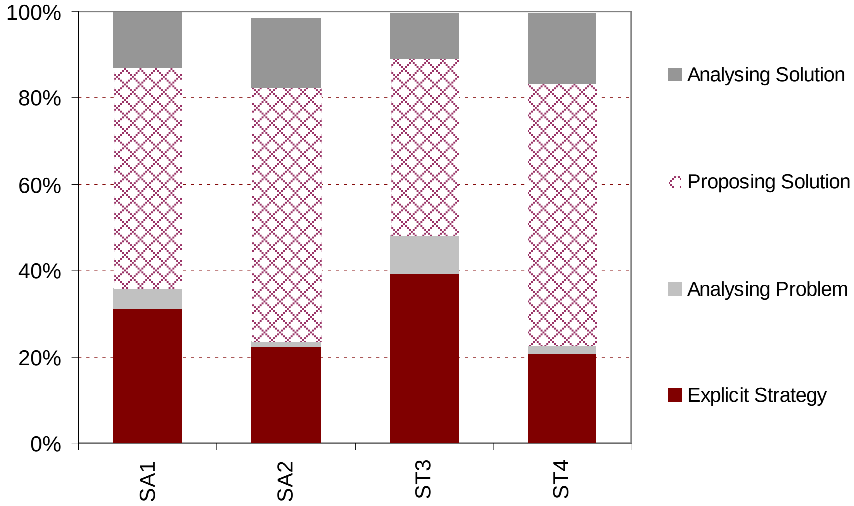


Figure 10 Design process micro-strategies as a percentage of the elapsed time.

Most of the protocol duration was spent on proposing a design solution (59% and 60.5%), spending 22% and 20.7%, respectively, of that duration on analysing the design solution, with only 1.4% and 2.1% respectively, of the duration spent on analysing the design problem. However, nearly a quarter (22% and 20.7% respectively) of the design protocol was spent on explicit strategies as they are concerned with codes other than the design process, Having said that, the detailed analyses of SA2 and ST4 of the design micro strategies demonstrate the many differences that each student exhibited during the design protocol. This makes the modelling of a design process on a lower level of detail difficult, if not impossible.

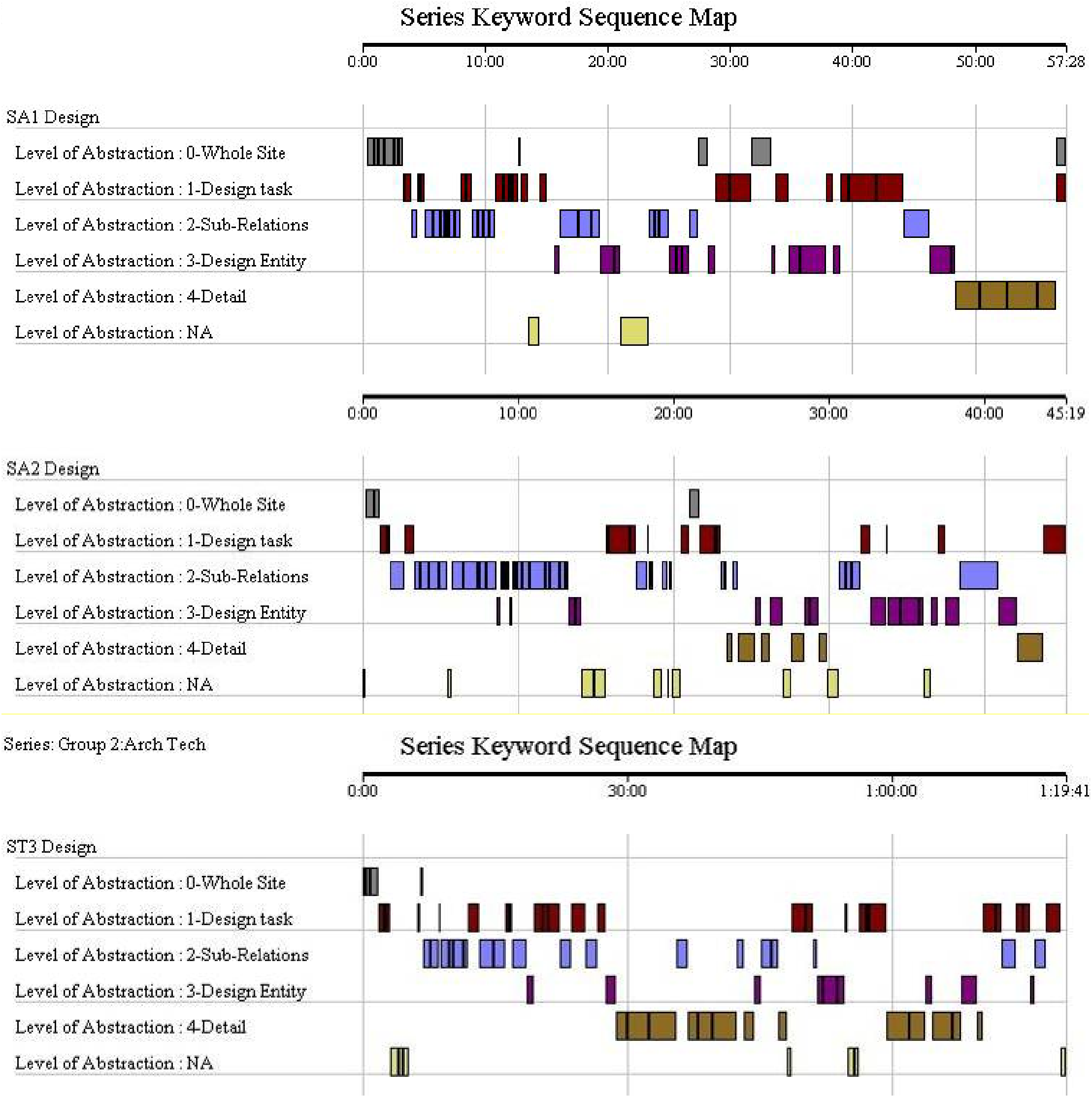
On the other hand, SA1 and ST3 percentages are different (to SA2 and ST4). However, most of the design protocol duration was spent on proposing a design solution (51% and 40.9%), spending 13% and 9.6% respectively, of the duration on analysing the design solution, with only 4.3% and 8.8% respectively, of the time spent on analysing the design problem. However, more than quarter (32%, 39.8% respectively) of the design protocol was spent on explicit strategies, as they were concerned with codes other than the design process. This is explained in section 3.6. In general, these results show that the majority of the time participants spent designing in CAAD was based on proposing a solution (PS) more than any other design solving behaviour.

3.4 Level of abstraction

The objective of coding different levels of abstraction was to ascertain whether the CAAD medium would affect the level of abstraction in a certain way, that is, whether using CAAD in conception would prompt one level of abstraction, with an emphasis on detailed design.

Transana software was used to create keyword sequence maps (Figure 11). These were studied as a separate coding scheme and in relation to the other schemes.

In Figure 11, each level of abstraction is shown in relation to the whole design process for each participant and refers to the level of abstraction the student is considering at any point in the process for each segment. Observing the sequence of the level of abstraction the students engaged in through the process shows two things: (1) the students were able to navigate through the different levels without restricting their vision to a certain level, and (2) the students were able to think of the overall design and at the same time think of more design-specific aspects while progressing into considering detailed aspects of either levels 3 or 4, which would influence the final design.



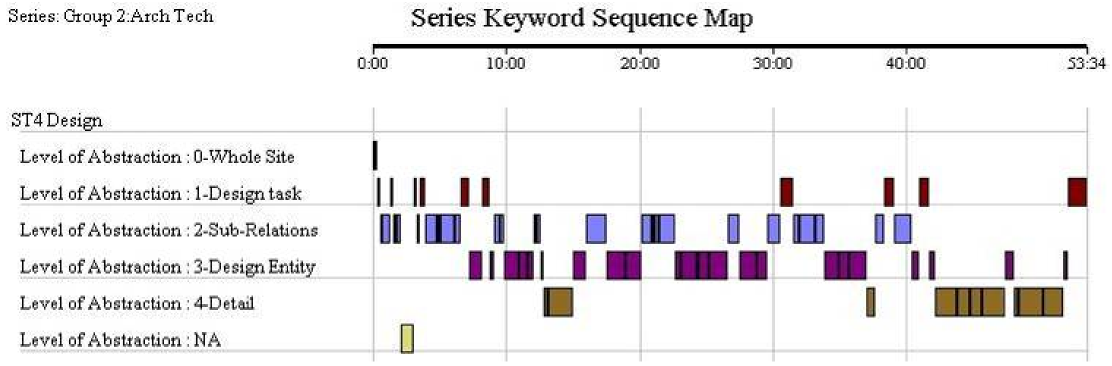


Figure 11 The level of abstraction along the design process timeline.

As shown in figure 11, on a basis of 10 minute intervals, participants considered a minimum of 2 to 3 levels and rarely considered the design on 5 levels of abstraction. It also shows that to allow the consideration of the design at a certain level, more than one segment or several segments may be required. The results of how much time each student spent on every level of abstraction as a percentage of the whole duration are presented in figure 12.

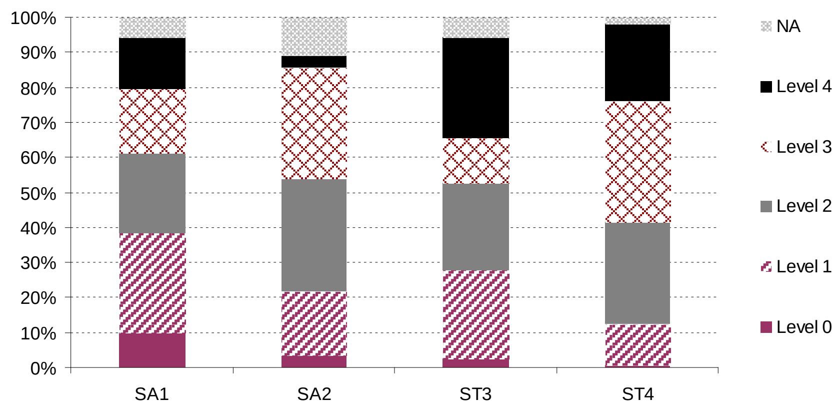


Figure 12 The levels of abstraction that each student considered while designing.

SA1's design session time was distributed across the levels but was dominant on level 1, while spending relatively less time considering the design at levels 2, 3 and 4 consecutively. When compared to the other levels, the design consideration at level 0 was the shortest. SA2's design session time was spent considering the design on two dominant levels of abstraction, 2 and 3, while spending relatively less time on considering the design at level 1 and a very small portion of time on the two contrasting levels of 0 (whole) and 4 (detailed CAAD). ST3's design session time was spent considering the design on three dominant levels of abstraction: 4, 1 and 2 consecutively. ST3 spent less time considering the design at level 3 but very little time on level 0. ST4's design session time was distributed across the levels but was dominant on level 3, and level 2 consecutively while spending relatively less time considering the design at level 4 and 1 consecutively, with a limited abstraction scope on level 0.

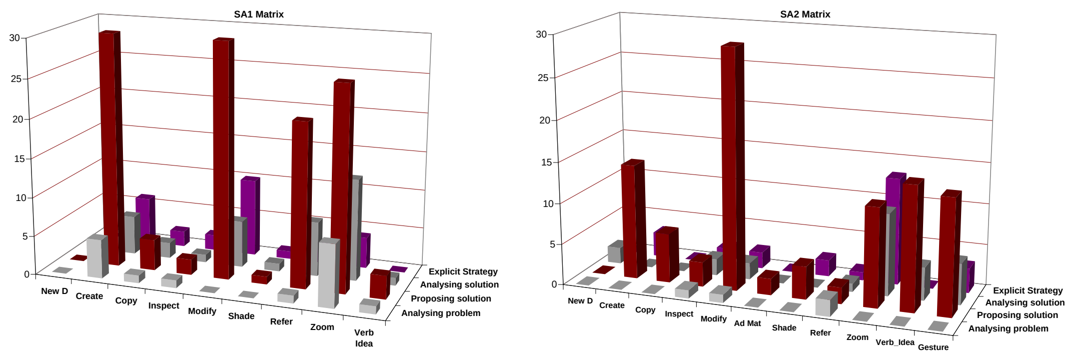
The small amount of time that students spent considering general concepts suggests that CAAD's level of detail has shifted the participant's design focus primarily from overall to consider more detailed levels.

3.5 External representation occurrences

This study further investigated how design representational activities supported individual design processes in architectural design. Mapping the micro representation strategies shows how and when these were used as the main source for visual information in relation to what design micro strategies were used during the session. While drawing was the main focus of problem solving, documenting the use of other types of external representation was important, such as verbal ideas, which are ideas mentioned with no visual support or documentation, gesture and referring to a drawing or inspecting a drawing with a cursor or hand.

While the student is engaged in one design micro strategy, he is also engaged in a multiple mode of external representation acts; therefore, each segment is coded with at least two external representation codes. For this reason, a matrix was sought to reveal the relationship between the occurrences of external representations in relation to design strategies. The matrices of the four design protocols are presented in Figure 13.

In all protocols, the students covered most of the external representations, however proposing a solution occurred with the most common external representations, which were: (1) create (mainly creating new drawing, or by adding to a drawing, continuing on a previous drawing and moving parts to make another composition) and (2) modify (modify by variables, 3D or by moving parts). These were followed by copy, inspect, refer and verbal ideas. This was observed in all protocols.



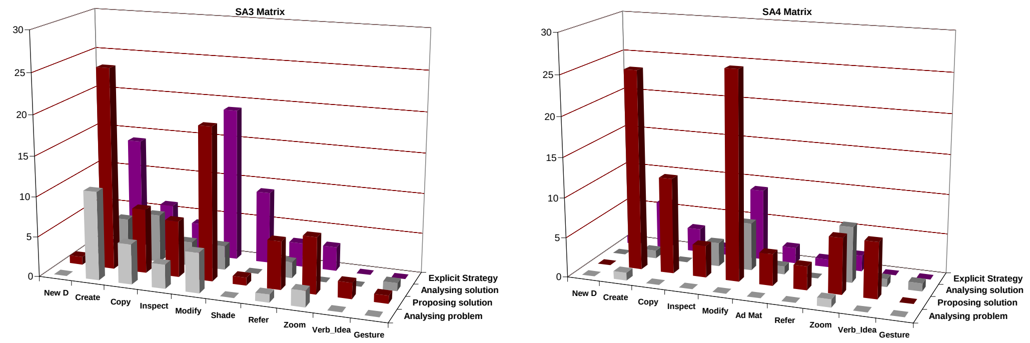


Figure 13 The matrices between main external representations activities and main design strategies.

Analysing the problem was intersected with the lowest number of external representations in SA1, SA2 and ST4 protocols. However, ST3 had the highest occurrence of create, modify, copy and zoom.

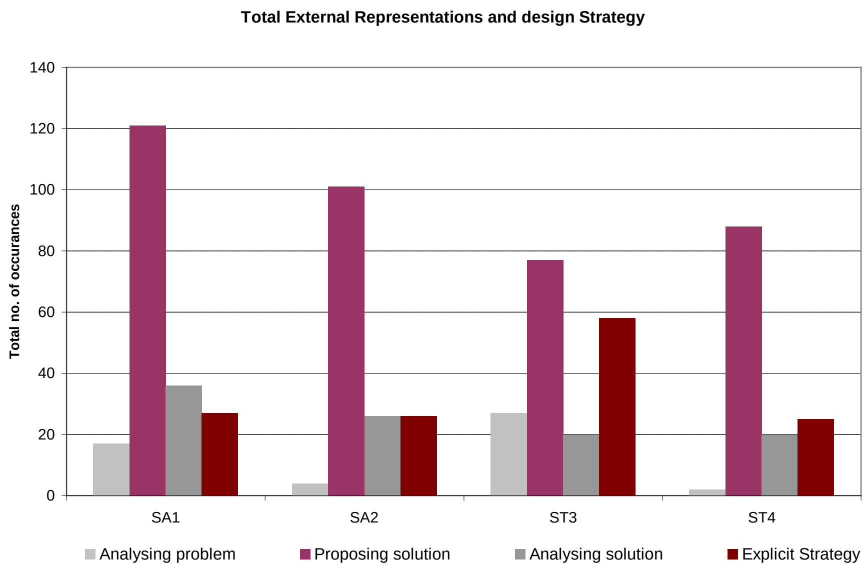


Figure 14 The matrices between external representations and design strategies.

On the other hand, explicit strategy (EX) intersected with various external representation activities, which refers also to the verbalising style of the participants. The most frequent occurrences were observed in ST3 protocol, shown in Figure 14. This is mainly because of his verbalising style as he frequently described CAAD strategy in drawing things. It is obvious that while students are engaged in externalising and reflecting on representations, they are also using other types of external representations with lower levels of certainty and this might help to overcome the complexity of CAAD compared to other types of externalisation.

As a result of the analyses carried out in the previous sections, the longer segments were likely to occur in the following conditions: while drawing in 3D mode and 3D presentational modelling, considering levels 3 and 4 of abstraction; that is working on the details of the proposed design; using a design strategy of proposing a solution through clarifying the solution in detail or through repeat. These were further categorised and presented next.

3.6 Explicit strategy codes

In terms of the coding schemes some of the segments could not be coded under the process-oriented coding scheme (Gero and McNeil 1998; Tang 2001). Participants deviated from design to express or to explain CAAD's ways of doing things. "The interpretation of a single phrase may be influenced by the context in which it appears." (Gero and McNeil 1998). This was important in a CAAD design protocol, in terms of continuity and engagement of the conceptual design process. Its influence was observed through the four participants, as there were many instances where they explicitly mention CAAD. These were identified either via the student's verbalisation or CAAD representation, when the designer is explicitly referring to some aspects of CAAD use: presentation, problems and appraisal. "These correspond to times when the designer is not directly engaging [in] the design task." (Gero and McNeill 1998). Consequently, the longer segments that were coded as explicit strategies (ExS) in all protocols were either coded as Practically Working on CAAD (total frequency of 37 segments) or Referring to CAAD Strategy (total frequency of 24 segments). The former related to the way CAAD shifts conceptual intentions into operational fulfilment, whereas the latter refers to the verbalising style of the participant, when his verbalisation goes into describing the program or the way things should be done. Such incidents can affect the total time spent in active designing and breaks the continuity of conceptual cycles. However, from analysing these successive segments, we can conclude that the occurrence of such technical incident did interrupt the continuity of the design activity but when the failure was solved, the students worked on the same intention of the former segment.

4 Discussion and conclusions

A CAAD design protocol was characterised by a low number of segments with higher durations suggesting that students designing with CAAD will have relatively longer shifts of intention compared to sketching protocols. Another feature was the frequency of intention shifts which varied within the same protocol and among participants, so there is no distinct mode. One design protocol showed a different behaviour in terms of these measures, which was a CAAD multi design protocol. Using more than one CAAD program that is different in their characteristics broke down the lengthy segments. In general the early intervals of CAAD design protocols witnessed higher transition rate than the latter intervals.

CAAD representations were used for three main purposes: conceptual, informative, and presentation. The analyses of ‘design micro strategies’ coding highlighted individual differences among students. This showed that students spent relatively low percentages of time on analysing the design problem (AP) and most of their designing time was spent on proposing a solution (PS) but predominantly through clarifying a solution by adding more details rather than repeating a solution or modifying a solution. Students spent less time on analysing the design proposal (AS) as perhaps they were not motivated to do so. This agrees with previous studies (Lawson 1979; Restrepo and Christiaans 2004; Kruger and Cross 2006) that describe design in general, and novice design process, in particular, as solution-oriented. A recent study (Liikkanen and Perttula 2009), found that designers tend to refer to solutions explicitly rather than problems in the collected protocols. Comparing the time spent in problem analysis in Tang and Gero (2001) also shows a similar trend of less analysing activity (AP) compared to the other two micro activities (PS and AS).

The potential impact of CAAD on the design process can be further categorised into; interrupted protocols, deviated protocols, shift of intention, and a discovery moment. The analysis shows there were instances where all four participants deviated from content towards CAAD operative moves; however, the thought sequence was completed afterwards. Shift of intention occurred when participants had considered lower levels of detail of the representation, i.e. engaging in non-conceptual design activity. This may include pausing moments as a result of mental tiredness by doing menial task i.e. adding text. This was also reported by previous studies, Bilda and Demirkan (2003), and Dokonal and Knight (2006) although the investigation conditions and settings were different. The analysis also shows that discovery moment came when the change of the program occurred (in one of the analysed protocols). The visual interaction with CAAD representations helped one participant to visualise new configuration. However, the result of this was argued by the participant with respect to authorship and CAAD automated effect. It was not acceptable in terms of who did the action. This was the first time that the student encountered such an experience. However, the immediacy of CAAD’s visual feedback led the student to change and alter his thought and further build on it conceptually.

Observations of the methods used by the students suggest that CAAD may change the design process, which also suggests that CAAD is different to sketching. If students used it regularly in their design processes, they might develop new strategies and change their familiar strategies into unfamiliar. This supports Coyne, Park and Wiszniewski’s (2002) study with respect to the combination of traditional and digital methods in drawing, each are valued rather than replacing one another. This gives some insight into the potential change in the design process using CAAD or digital media with regards to supporting the theoretical propositions of theorists like Oxman (2006, 2008), and studio instructors like Al-Qawasmi (2005, 2004) and Dokonal and Knight (2006). On that basis, interacting with CAAD visual representations can be accepted as a conceptual medium and the use of CAAD alone for externalisation. However, advanced students gained skills are only enough to interact with the digital media on the surface level of the visual representation (Oxman 2006), imitating the traditional methods of designing.

5 Limitation and future research

Protocol study methodological limitations can be in the time required not only for analysis but also data collection (Salman 2011). Although the same procedural steps are followed, and the same level of expertise is targeted, it is problematic to obtain numerous design protocols with the same or similar degree of quality. Therefore, the generated protocols will tend to vary qualitatively and quantitatively. In addition, recruiting students with an interest in using CAAD for concept design was one of the limitations within the school; the other limitation was non-native speaking students who found it difficult to think- aloud during designing. However, a sample size of 1-3 is acceptable in most published protocol studies (Jiang and Yen 2009).

To some extent, the research undertaken in this study bridges the gap between CAAD passive research and design active research. Further research would necessitate a continuation of CAAD research to enable comparative studies, which would reduce the subjectivity of the used methodologies in studying design activities. In order to carry out more in-depth study, it might be necessary to recruit participants with certain design behaviours that will reflect on the other two levels of media interactivity. As such, it would require a longitudinal systematic study that focuses on the new skills and behaviours and would provide new insights for educators, and how CAAD may help to overcome students’ differences.

Understanding the differences between the two media will shift the argument further to explore the switch between various digital media programs and a combination of other tools for design thinking.

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Appendix: Coding schemes

Micro strategies used in the Gero & McNeill (1998) design episodes

	Analysing Problem	Relate to actions involving analysis of problem.
Ap	*Analysing the Problem*	Indicates that the designer is analysing, qualitatively or quantitatively, a design problem. This may be in the form of calculations or as a run through of expected behaviour [Functional aspect of users or the artefact?]
Cp	*Consulting Information about the Problem*	As above but using external information[as a n example he mentions the brief as an External information]
Ep	*Evaluating the Problem*	That is an important feature, strong constraint
Pp	*Postponing Analysis of the Problem*	Relating the current status with the latter or a future one. I can find that latter.
	Proposing Solution	refer to the proposal of a solution or partial solution.
Ps	*Proposing a Solution*	is self-explanatory[refer to the proposal of a solution or partial solution.]
CI	*Clarifying a Solution*	indicates that the designer is repeating a previously proposed structure and perhaps elaborating the details of the structure.
Re	*Retracting a Previous Solution (D Dc)*	means that the designer has rejected a whole proposed solution as opposed to modifying a solution by varying parts of it.
Dd	*Making a Design Decision*	comes at the end of a period of considering alternatives. It is characterised by a decision without further elaboration of the proposed structure.
Co	*Consulting External Information for ideas*	is used to denote that the designer is consulting other information to look for options for the solution It is not used when the designer is analysing some aspect of the external information to gain a greater understanding of a structure's behaviour.
Pp	*Postponing a Design Action*	indicates that a need for some structure has been identified but its elaboration has been postponed in favour of another, perhaps easier, task
La	*Looking Ahead*	it means the designer is identifying some future structure that will be required
Lb	*Looking Back*	Modifying a solution by varying parts of it
	Analysing Solution	relate to actions involving analysis of some behaviour.
An	*Analysing a Proposed Solution*	indicates that the designer is analysing, qualitatively or quantitatively, a solution idea. This may be in the form of calculations or as a run through of expected behaviour.
Ju	*Justifying a Proposed Solution*	does not involve calculations or a run through but the designer makes some comment that indicates that some assessment of the behaviour of a proposed solution has been made.

Ca	*Calculating on a Proposed Solution*	
Pa	*Postponing an Analysis Action*	
Ev	*Evaluating a Proposed Solution*	differs from the other categories in that it involves some type of value judgement of the proposed solution.
	Explicit Strategies	*to indicate that the designer is explicitly referring to something. These correspond to times when the designer is not directly engaging the design task.*
Ka	*Referring to Application Knowledge*	*refers to knowledge of the application or environment in which the artefact is to be used.*
Kd	*Referring to Domain Knowledge*	*refers to knowledge of the domain of the design,*
Ds	*Referring to Design Strategy*	*identifies when the designer is commenting on the progress of the design episode or is assessing his own design strategies.*

Level of abstraction coding scheme adapted from (Gero & McNeill's 1998) and Purcell, Gero, Edwards, and McNeill (1996) studies.

Level 0	0 is used to denote the top level of abstraction where the designer is considering the problem as a whole
Levels 1,2,3	is used to refer to the sub-problems identified by the designer.
Level 4	Was used in this study to denote the detail level of abstraction, where the designer is considering a technical problem

External representations coding scheme. This coding scheme has been developed using Transana

ChVw A	Changing the view into another drawing or design entity. or be defined upon the continues nature of using CAD commands
ChVw S	Changing the view in the same drawing or design entity in out=inspect global relations out in =inspect local relations
Copy G.	Copy a given diagram or design entity into other location in the aim to start new modifications-Equivalent to starting with a new sheet
Crt A	Create by adding a new design element or entity to a former design entity after a time gap (relating two different segments).
Crt C	Continue drawing on the same part(s) or design entity in successive segments. no conceptual gap same segment or related elaboration
Crt G	Group created elements; it is either by creating adjacent entities or by duplicating (copy) an object (or drawn object) in one segment duration.
Crt N	Create by drawing a new design element or entity, or inserting an object into the environment.
Discv R	Discovering a relation: an organizational relation between two spaces unintentionally, resulted from inspecting new relations by moving objects or design elements
Discv S	Discovering a space as ground unintentionally, resulted from the appearance of other surroundings.
Insp G	Make calculations and reading information (height, width, diameter, etc,) off

Insp P	Make calculations and reading information (height, width, diameter, etc,) off his drawn entities. It is either inspect or observe!
Mod D.	Erase or delete a design element or a design entity results in modifying the design composition
Mod G.	Modifying a composition by moving previously created objects or entities
Mod M	Move element or entities around the objects after they are created. This is to align them, or to carry them for using in another location.
Mod VA	Orientate/Rotate/change their arrangements, resizing or changing the shape. Changing its visual attributes: shape, angles and sizes
Pres	Applying hatch or colour and texture.
Ref G	Looking at the Given representation and refer to its parts (object or entity) using hand gesture over the screen or the mouse curser (referring to a representational part or design aspect
Ref N	Looking at the new representation and refer to its parts (object or entity) using hand gesture over the screen or the mouse curser (referring to a representational part or design aspect)
Text	Labelling spaces
Zo IO	zooming in & out: inspecting global relations
Zo OI	Zooming out & in: inspecting local relations