Digital Processes in Architectural Design: A Case Study of Computers and Creativity
Raid Hanna and Tony Barber
This paper describes the results of a statistical-experimental investigation into the relationship between three variables: design cognition, the computer as a problem solving medium and ‘creativity’. The hypothesis put forward suggests a directional link between the use of ‘CAAD as a cognitive design medium’ and ‘levels’ of creativity in the design process. The hypothesis was tested statistically using first year architecture students as research design subjects.

In order to place the research within a context, develop a thesis and identify ‘operational’ measures for variables, a literature search with special emphasis on ‘creativity’ was conducted.

The statistical findings did confirm that levels of architectural ‘creativity’ in the design process and in the final product were somehow affected by the use of CAAD. Ideation fluency and originality, as ‘creativity’ indicators, correlated positively with CAAD as a cognitive medium with coefficients 3 0.5. The statistics from subjects- group design- revealed that computers’ power of visualisation, slicing and Boolean operations has helped spatial ability and could eventually help novice designers to venture and create complex objects more than they would normally do with conventional media.
1. INTRODUCTION: THE RESEARCH PROBLEM AND METHODS

Computers have made a significant impact on architecture both in education and in practice. The architectural curriculum of almost all schools has changed to allow courses in Computer Aided Architectural Design (CAAD), exploring how best CAAD can fit the mould set by design studio teaching. Some believe that CAAD as a design visualisation medium may improve students’ spatial ability. A number of academic conferences, such as eCAADe, ACADIA and CAADRIA have documented this change and covered these issues.

The architectural practice has also witnessed a revolution in terms of working methods and the design process. Many practices have used and are still using CAAD as a tool to automate the production of architectural drawings and presentations. Others have deployed CAAD programmes as a design medium to generate novel and complex forms. Examples include names such as NOX, Oosterhuis, Decoi, DubbleDam, Lynn etc. [1] This new breed of architects, according to the literature, broke away from the Modern Movement and is working on a different terrain to give city space a new meaning. [2] The architecture produced by the new architects is different both in outcome and process. Quoting Posngratz and Perbellini “it is now possible to develop a certain level of complexity in design, to explore geometries or modalities that were previously impossible to pursue, and realistically experience an unbuilt space.”[2]

However, it is not just the complex geometry generated by the computer that distinguishes innovative CAAD practices from others but also their departure from traditional design philosophies and processes. Rahim maintains that contemporary processes rely on modes of thought that are ‘non-deterministic’ and ‘non-static’. [3] Architectural thinking that relies on ‘material’ processes is rigid, deterministic and in turn non-creative because it relates design to physical reality. Breaking away from pre-existing moulds of experience helps our imagination flourish and explore what is possible.

The philosophical issues born out of the new founded relationship between computers and architecture within the domains of education and practice have been identified and examined rather superficially by Steele. [4] He purports that the difficult concept of ‘cyberspace’, first coined by Gibson [5], is the third stage in the development of architectural space after modernism and postmodernism. On the virtual reconstruction of reality in cyberspace, Steele argues that this notion of reality undermines our relationship with (physical) reality. [4] In contrast one could argue that reality of the material world inhibits our imagination and places limits on what is possible in the immaterial world, where gravity and physical matter do not rule relations. It may be that experiencing the ‘virtual’ may enrich and augment our experience of the ‘real’ world.
Despite the fact that significant progress has been made both in architectural education and practice in terms of deploying computers to tackle a raft of complex issues related to modern design processes, there still remains much to be desired. For instance, will the computer ever become a ‘partner’ and lead the design process? Can we think of CAAD— the subject, the computer (the hardware) and the software—beyond being an expensive drawing and presentation tool? What is the impact of using computers on design cognition—receiving, processing and manipulating design information? In other words do computers help or hold back the design process? More importantly, can computers help rather than hinder ‘creativity’ domains in architectural design?

This paper has tackled some of the above questions, employing two research methodologies. The theoretical method, through the review of relevant literature, intends to identify ‘variables’ and develop a thesis on computers (CAAD), the design process and creativity. The empirical method is experimental as it deals with the measurement of creativity ‘variables’ in a statistically based single group design, i.e. subjects. The data collected from subjects through questionnaires, interviews and direct observations has been analysed using appropriate statistical tests. The analysis then led to interpretations regarding the impact of CAAD on ‘creativity’ domains in the design process. It is worth mentioning here that it is hard to judge and dismiss computers on the basis of creativity enhancement alone since their use brings several advantages to the design process in domains such as accuracy, speed, performance, efficiency and cost effectiveness.

2. COMPUTERS IN DESIGN

Examination of literature on the role of computers in architectural design reveals that there is a gulf in opinion between those who view it as a ‘medium’ that can improve design thinking at a conceptual level and those who are suspicious of its role and regard it as a production ‘tool’ having little or no impact on design thinking and concept formulation.

Furthermore, the gulf of opinion is not only between academics and theoreticians but also between prominent practitioners. For example in his treatise ‘new science=new architecture’ Jencks argues that there is a shift in thought, a departure from the old Newtonian linear science to other forms of science such as that of complexity, fractals and non-linear systems. He calls for architecture as ‘a form of cultural expression’ to have a similar shift in the framework of thought. He then cites three ‘seminal’ buildings of the 1990s to support his thesis of shift. Gehry’s Bilbao, Eisenman’s Aronoff Centre, Cincinnati, Libeskind’s Jewish Museum in Berlin ‘are three non-linear buildings and were partly generated by nonlinear methods including computer design’, maintains Jencks. He goes on to question the role of metaphor in the three buildings and suggests that “new science=new language=new metaphor”.[6]
Critical of the above view is Frampton who advocates a strong link between architecture and building in the ‘material’ world. Digital design on the computer is a ‘fantasy’ unless it conforms to the ‘tectonics’ - material- requirements of the physical world. [7] However, conformity to the ‘material’ world may inhibit the ‘subjective’ experimentation of minds in the ‘objective’ world of computers, to use Popper’s terminology on the three worlds of knowledge.

A similar conflict on the role of computers in design can be detected between two world-class architects by careful analysis of literature. Eisenman’s writing identifies two intellectual themes about computers and architecture. Firstly, he highlights the challenges to architecture from the ‘electronic paradigm’ as ‘reality’ is defined through simulation and ‘appearance’ is valued over ‘existence’. [8] Secondly he acknowledges the creative potential of computers as he asserts that “the computer gives you the possibility of constructing objects that you would never do directly from the mind to the hand. We constantly produce models after having conceptualised them using the computer. It is a process of constant refinement.” [9]

On the other hand Gehry adopts a different position in regard to the role of computers in his office. Although Gehry acknowledges the potential of the computer as a knowledge-based system for structural design, construction and cost analysis, he remains sceptical about its ability to design. He maintains that “the computer is a tool, not a partner, an instrument for catching the curve, not for inventing it”. [10] A slight problem with Gehry’s statement is his unique working method that excludes computers from the early design stages. As to his notion of ‘inventing it’, computers can never become autonomous and improve their design skills to match those of a designer.

In conclusion, recent development in software engineering has furthered the modelling capabilities of some CAAD packages to such a level that increases their creative potential as a conceptual tool for use at an early design stage. New CAAD programmes such as Rhinoceros [11], a NURBS (non uniform rational B-splines) modeller means that 3D free form organic surfaces and solids can be created intuitively and quickly at the early design stage, thus overcoming serious limitations of traditional polygon modellers. This was accomplished by adding two extra coordinates (U,V) to the traditional three coordinates (X,Y,Z), which in turn improved modelling performance and overcame the ‘orthogonal rigidity’ of the Cartesian system, an issue rightly criticised by Gomez for representing another form of modernistic rationality. [4]

Also recent works on ‘genetic programming’ may lead to the possible development of a new breed of ‘evolutionary’ CAD tools that can help designs to evolve from scratch through a process of mutation and constant refinement. An example is GADES- a genetic algorithm designer developed by Bentley, which was used to evolve designs successfully. [12] Evolutionary
CAD tools, according to Bentley, “allow the designer to explore numerous creative solutions to problems, overcoming design fixation or limitation of conventional wisdom by generating alternative solutions for the designer”.

[12] However, it is very unusual to dismiss the use of computers in design even if they were found to hold back creativity as they have attributes that make the design process precise, efficient and cost effective.

3. CREATIVITY AND ARCHITECTURAL DESIGN

Creativity as a concept, which encompasses originality, has appeared in many design definitions. Zeisel’s description of the design process as an embodiment of many intangible elements including creativity, intuition and imagination, which are critical to quality [13], and Archer’s reference to originality are just few examples. [14]

Creativity is the production of ideas, designs, theories and objects that are accepted by experts as ‘novel’ and ‘valuable’. [15] Novel means that the product is uncommon while valuable implies ‘function’- use and practicality.

Examination of literature on creativity reveals that the bulk of research falls within the disciplines of psychology, education and little within design disciplines including architecture. Even less has been cited dealing ‘specifically’ with CAAD and creativity. Therefore it is hoped that this research, despite its limitations, would fill an existing gap in knowledge.

However, some interesting studies that deal with the broader spectrum of ‘cognition’ and ‘design computing’ were found in the literature. Examples include: Frazer’s research on evolutionary programming for form generating process [16], Woodbury’s work on ‘design space exploration’- the notion that computers can help designers to represent designs, array them in a network structure, and create new designs by navigating through the network [17], Tan’s study on the role that shape recognition, by the ‘designer’s conceptual filter’, plays in the development of design ideas [18], and Oxman’s framework of a ‘think-map’, which aims at making design knowledge explicit by constructing conceptual map that can be structured and represented by computational media. [19] On the difference between creative and non-creative skills of thinking, Koeastler [20] argues that routine thinking operates on a single plane or context whereas the creative act cultivates more than one plane, what he calls “the bisociation of two mutually incompatible contexts”. In addition he believes that maximum levels of creativity are attained, when our rational thought is suspended. It could be that the rational thought is responsible for the practicality of the creative product whereas the irrational thought deals with the novelty part.

In dealing with design problems Aalto describes similar processes of thought and maintains that the irrational- forgetting the mass of the problem and drawing abstract ‘childlike compositions’- leads to a discovery of a solution.

[21]

However, creative thinking in architecture is the product of past knowledge and experience (learned from others) as well as presumably an
inherent talent (the self, the ego). This makes architectural design a discipline with two dimensions: sociological (learning from others) which is often overlooked and psychological (learning from the self) which is often highlighted. It is reasonable then to conclude that if one is operating within the domains of creativity, the greater his or her knowledge and experience, the bigger the creativity leap will be. This can be supported by the notion that expert designers are better in problem solving than novice ones for experts think in ‘chunks’, larger blocks of information, which already contain the smaller sub blocks - making the thinking process more efficient as smaller blocks, already contained in the chunks require no further thought.

[22] Creativity, as a personality trait, has been thoroughly researched and widely published; an example is the pioneering work of Barron [23]. As research in this area is exhaustive, this paper will only cover research deemed to be of relevance to architectural creativity.

MacKinnon investigated the relationship between ‘personality’ and ‘preferences’ of three groups of architects and their creativity. Architects I (the most creative of the three with a score of 5.64), were found to be preoccupied with achieving their own standard of design excellence rather than making impressions on others. Architects III (least creative with a score of 3.54) seemed to have others as their source of inspiration, the ones they would like to become, and closely followed standard set by their profession and society. [24] Using the Barron-Welsh Art scale, Barron and Welsh administered a 400-item test to a sample of artists and non-artists. They found that artists preferred figures that are “complex, asymmetrical, freehand rather than rules and moving in their general effect”. Artists described them as organic. [25] A concept relevant to creativity and central to design is that of intuition, the immediate apprehension of a problem, which is linked to traits by Gough [26] as “the creative personality is intuitive and emphatic”, and is associated with duration by Bergson [27] who suggests “to think intuitively is to think in duration. Intuition is arduous and cannot last”.

4. TESTING CREATIVITY

A number of tests have been devised, validated and advocated for creativity. One of the most common ones is RAT (remote association test) and word association, where the testee is usually given three words and required to find a fourth word which could provide an associative link between the three unrelated ones. [28] High scores denote high creativity. However, Datta questioned the suitability of this method for all professions. After an empirical investigation, Datta concluded that “the production of remote verbal associations is not as important a component of behavioural creativity for professional engineers (and perhaps architects and scientist) as it maybe for psychology and design”. [29]
Torrance’s seminal work identified four main parameters upon which creativity can be operationalised. These were: fluency (generating a volume of ideas); flexibility (to do with the variety of ideas); originality (uncommonness of ideas); elaboration (progressing an idea). Runco and Chand advanced the above thinking and developed a two-tier model. The primary tier has three components: problem finding, ideation (fluency, flexibility, originality), and evaluation. The secondary tier has two components: knowledge - declarative (of facts) and procedural (know-how), and motivation. Two additional modes of thinking, convergent and divergent, were widely reported in the literature to have influenced creativity in problem solving. Convergent thinking is prescriptive as it follows a single prescribed path to arrive at a single solution to the problem. Divergent thinking on the other hand is speculative and unstructured as it explores ideas and combinations to arrive at ‘possible’ solutions to the problem.

Authors such as Finke, Ward & Smith placed more emphasis on non-verbal constructs of creativity, i.e. images and imagery based cognition, and introduced the ‘Geneplore’ model, a problem solving model, which has two phases: generative and exploratory. In the generative phase one constructs mental representations, pre-inventive structures, to promote creative discovery. The pre-inventive structures and their properties are then interpreted in the exploratory phase to arrive at desirable solutions and products. Similar models of visual perception in relation to the structuring of information, called schemata, are reported in the literature. For instance Bartlett maintains that external visual stimuli from objects are related to pre-existing structures in the brain to provide useful information for creative problem solving.

Karlins, Schuerhoff & Kaplan examined some variables related to architectural creativity. Seventeen graduating architectural students from Princeton University were rated in terms of creativity by two professors familiar with their work, and the scores were correlated with a battery of creativity tests. The researchers found that rated architectural creativity did not correlate with “measures of academic aptitude” such as class rank and grades, but was related to the “quality of their design projects and their performance on the spatial factor test”. The spatial factor involves two parameters: spatial orientation and visualisation. It is therefore reasonable to conclude that using CAAD within the design process is bound to affect both parameters and by implication architectural creativity. Research is also needed to examine whether the influence of CAAD on architectural creativity is positive or negative.

5. CASE STUDY: CAAD AND ARCHITECTURAL CREATIVITY

Previous research by the authors on CAAD and the architectural design process revealed that students reported a statistically significant difference
(p<0.05) in attitude toward the design process variables at two points in time: ‘before’ and ‘after’ using CAD.[36] In contrast, the main focus of this paper is to examine the relationship between architectural creativity and CAAD within a design studio setting.

In the current experiment, Sixty first year architecture students were taught Rhinoceros (a CAAD package) during the 2003 academic session. At the same time they started a design project with a brief to design a Sitooterie within a given site in Scotland. We took students to survey and analyse the site. They were taught ‘scripting’ in Rhino to automate and advance both the creation and the editing process. We also dealt with the gulf in perception of materials and gravity between the ‘virtual’ and the ‘physical’ world by performing a series of exercises. These were: full size build (making part of design in real materials to provide an understanding of construction, joints and detailing); body building (teaching mock up structures in the studio using the body as a vehicle); paper structures; and physical model making.

During the process of designing on the computer both authors made observations in relation to the number of design layouts generated and the variety between these layouts. These observations, which were used to evaluate fluency, originality and variety, were coded statistically and deployed as a cross checking mechanism to flag out any inconsistencies in students’ response to the questionnaire, which were administered to students after they completed their designs. The questionnaire encompassed concepts and ‘variables’ associated with architectural creativity, which were culled out of the reviewed literature and adapted to the context of design. The meaning of the factors and their relevance to creativity were fully explained in a lecture that took place earlier. They were not given any information on the impact or the loading of factors on creativity in order not to influence their answers. Twenty-Nine students returned the questionnaire and the returns were then analysed using SPSS (Statistical Package for Social Sciences). [37] The completed projects were rated using the two dimensions found in most creativity definitions: novelty and appropriateness. The first dimension denotes ‘newness’ or ‘originality’ whereas the second one represents ‘function’ and ‘use’. The rating, on a seven-point bipolar scale, was intended to cross-examine students’ response and validate the results rather than establish a measure for the creativity of the ‘product’.

6. FINDINGS

6.1. Ideation

This section deals with ‘ideation’ fluency, originality and flexibility. Students were asked whether the use of CAAD during the design process of the Sitooterie had influenced the volume of design layout generated and the variety between these layouts and the originality of the layouts. Fig 1 shows that almost half of the sample (N=29) recorded category 3- helpful and 4-very
helpful (N-number of respondents scoring >2), which implies that CAAD has helped them regarding the three parameters of ideation. The slicing and sectioning power of CAAD makes the generation of layouts (plans), sections (including 3D live sections) and elevations from 3D mass an easy and quick process that can be repeated frequently. In the case of using physical models during the design process one has always to detach him or her from the object and go back to the drawing board to generate the plans. However on further examination of the three variables in relation to the type of CAAD user (intensive or occasional), a marked difference between the two user groups was found.
Fig 2 describes the difference between the mean score of both groups on a 4-point scale (1 = unhelpful & 4 = very helpful). This is expected as an intensive user of CAAD would develop an intimate engagement with the computer and become detached from the surroundings, which is a necessary condition for successful problem solving. It could also be due to the fact that being an intensive user means one could do more with the computer and produce more 3D design objects and layouts. From observations, some students, who were fully engaged, wrote script files in order to automate the modelling of landscape terrains. Although the average difference between the three means is around 0.6, further analysis is needed to determine whether or not it is statistically significant.

The three variables were also correlated with the variable ‘CAAD on overall creativity’ and Table 1 confirms the presence of some significant correlation coefficients between them at both $P < 0.01$ & $0.05$.

A correlation coefficient that is significant means that both variables are associated, i.e. appear together. A significant coefficient that is positive means that an increase in one variable, usually the independent, will be matched by an increase in the other, the dependent variable. The highest correlation coefficient calculated is between ideation fluency and overall creativity. This implies that CAAD was seen as an aid to the exploration of a number of design strategies and in turn the production of a number of generic layouts. Also the ability to deform and manipulate objects in CAAD— and see the changes instantaneously— might have enabled the production of unusual objects (forms) giving a sense of uniqueness and novelty. The whole process—described as creative— could be very liberating giving an increasing sense of adventure. The strongest correlation found was between ideation ‘fluency’ and overall creativity. As to the nature of this relationship, a scatter-plot has been calculated and presented in Fig 3. The Rsq of 0.3082 to the right of the figure implies that 30 percent of the overall creativity was influenced by ideation fluency.

<table>
<thead>
<tr>
<th>Table 1: Correlation coefficients and significance levels for ideation variables &amp; overall creativity</th>
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</thead>
<tbody>
<tr>
<td><strong>Correlations</strong></td>
</tr>
<tr>
<td><strong>Spearman’s rho</strong></td>
</tr>
<tr>
<td><strong>Sig. (1-tailed)</strong></td>
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<tr>
<td><strong>N</strong></td>
</tr>
<tr>
<td><strong>Correlation Coefficient</strong></td>
</tr>
<tr>
<td><strong>Sig. (1-tailed)</strong></td>
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<td><strong>N</strong></td>
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<tr>
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<tr>
<td><strong>Sig. (1-tailed)</strong></td>
</tr>
<tr>
<td><strong>N</strong></td>
</tr>
</tbody>
</table>

*Correlation is significant at the 0.05 level (1-tailed).
**Correlation is significant at the 0.01 level (1-tailed).
Further statistical tests are needed to determine the cause of the other 70%.

6.2. Knowledge
This part examines the impact of CAAD and the Internet on two variables, which are secondary to creativity: declarative and procedural knowledge. The former deals with facts and information about materials, light, climate, etc., whereas the latter concerns the know-how of how buildings are put together. The chart, Fig 4 shows that the mean score (3.0) for intensive users was high on the four-point scale used (2= slightly helpful, 3= helpful, 4= v helpful). The Internet being an instant source for design information surely contributes to this response. Both variables were tested for correlation with overall creativity. The results found no significant correlation between knowledge and overall creativity. This is in line with some models of creativity that regard knowledge as a secondary rather than the primary tier of creativity. [30]

6.3. Design: analysis, synthesis and evaluation
Here the focus is on the influence of CAAD on a raft of issues such as design synthesis (the ability to formulate design hypotheses), design analysis (testing of light, texture, materials, geometry and structure), and design evaluation (choosing between alternatives at the early design stage). The results, Fig 5, confirm that the majority (24 of 29) scored 3 (helpful) and 4 (v helpful) for CAD on design analysis. The unusually high score could be
explained by the power of CAAD in testing light both natural & artificial and experimenting quickly with textures, materials, etc.

However the correlation results in Table 2 provide a totally different picture; the highest correlation coefficient (0.607) is between design synthesis and creativity rather than design analysis and creativity. A plausible interpretation could be that the cognitive strategies to synthesise a solution are closer and more important to creative thinking than those of analysis. In synthesising design solutions we use intuition, which is reported to be a mark of creative thinking. Hence, according to Gough [26] the creative personality is intuitive.
A further non-parametric test was carried out to cross check the results and detect any significant difference between intensive and occasional users. The results confirm significances of difference between the two groups in terms of ‘CAD on design synthesis’ and ‘CAD on design evaluation’ - P=0.001 & P=0.046, both less than 0.05.

6.4. Preference for complexity and asymmetry

The aim of this section is to assess the impact of CAAD on traits of personality: preferences for complexity, asymmetry and non-linear forms. Figure 6 shows that over 60% of returns confirm a preference for complexity because of using CAAD. Around 40% believe that CAAD has also influenced their preference for objects and layouts that are both organic and asymmetrical. The ‘site’ itself being an open site in the countryside could also have influenced students’ preference. Further analysis on user type reveals that intensive users scored higher than occasional users on all the three variables - a mean of 3.3, 2.5 and 2.6 for complexity, asymmetry and non-linear geometry compared to 2.0, 1.7 and 1.7. However, since the response is clustered around certain scores rather than distributed randomly, it is felt that the

Table 2: Correlations between design variables and overall creativity

<table>
<thead>
<tr>
<th>Variable</th>
<th>CAD on ideation synthesis</th>
<th>CAD on ideation analysis</th>
<th>CAD on ideation evaluation</th>
<th>CAD on ideation creativity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s rho</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>1.000</td>
<td>3.24</td>
<td>4.13</td>
<td>6.07**</td>
</tr>
<tr>
<td>N</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Mann-Whitney U</td>
<td>33.500</td>
<td>88.000</td>
<td>61.500</td>
<td></td>
</tr>
<tr>
<td>Wilcoxon W</td>
<td>138.500</td>
<td>193.000</td>
<td>166.500</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>-3.291</td>
<td>-1.802</td>
<td>-1.997</td>
<td></td>
</tr>
<tr>
<td>Asymp. Sig. (2-tailed)</td>
<td>.001</td>
<td>.046</td>
<td>.046</td>
<td></td>
</tr>
<tr>
<td>Exact Sig. (2-tailed sig )</td>
<td>.001</td>
<td>.477</td>
<td>.057</td>
<td></td>
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</tbody>
</table>

*a* Correlation is significant at the 0.05 level (1-tailed).

**Correlation is significant at the 0.01 level (1-tailed).**
The mode of intensive users is on points 3 & 4 of the scale whereas the mode of occasional users is on point 1 of the scale. Correlation tests were also carried out between the three variables. The results confirm correlations at accepted levels of significance, $P<0.05$. For example a correlation coefficient of $0.801, P<0.001$ was computed between the variables: preference for complexity and preference for non-linear geometry. The implications of this are that in terms of design cognition, both concepts did have similar psychological dimensions and were very closely matched and perceived almost as one concept.

![Figure 6: Line graph showing percentage score](image)

![Figure 7: Mode of response by user type](image)
6.5. Creative cognition

In here the emphasis was on the relevance of creative cognition, as facilitated by CAAD visualisation, to overall creativity. The correlation test revealed a positive linear relationship between the two variables, a coefficient of 0.477, sig. 0.004. A Scatter plot (Fig. 8) results present the linear relationship; 23% of variance in overall creativity was determined by a variance in creative cognition. It appears that having a creative cognition is an important precursor to generate preinventive structures, strategies and elaborate them to produce a useful object (design). The power of visualisation in CAAD could help to assemble and synthesise visual patterns—one can call the DNA of geometry.

6.6. Project assessment

This part deals with the rating of projects (products), using a ten-point scale, on two domains of creativity—reported in the literature: novelty and appropriateness. Ten projects were randomly chosen for assessment using the lottery method of sampling. For measuring appropriateness two indicators were used: functionality—relationship between issues such as site, access, circulation and spaces; tectonic issues—environmental control and construction. For novelty, two measures were used: form—structural and geometrical configuration in three dimensions; façade aesthetics, i.e. how various parts of the object relate to each other and to the overall composition. In addition an overall mark for creativity was also established. Measures for ‘appropriateness’ and ‘novelty’ each was correlated with the ‘overall mark for creativity’. The latter variable was also correlated with
variable ‘CAAD on overall creativity’. The aim was to cross-examine students’ return for validity rather than establish an independent test to predict the creativity of a ‘product’. The first author, who acted like a judge, performed projects’ rating. The correlations between the measures and overall creativity and between were computed with SPSS. Table 4 presents the outcome of rating.

<table>
<thead>
<tr>
<th>Appropriateness</th>
<th>Novelty</th>
<th>Creativity (Overall perception)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality</td>
<td>Tectonics</td>
<td>Facade</td>
</tr>
<tr>
<td>1</td>
<td>7.0</td>
<td>7.1</td>
</tr>
<tr>
<td>2</td>
<td>6.9</td>
<td>6.8</td>
</tr>
<tr>
<td>3</td>
<td>7.4</td>
<td>7.2</td>
</tr>
<tr>
<td>4</td>
<td>6.0</td>
<td>7.6</td>
</tr>
<tr>
<td>5</td>
<td>6.5</td>
<td>6.7</td>
</tr>
<tr>
<td>6</td>
<td>7.4</td>
<td>7.9</td>
</tr>
<tr>
<td>7</td>
<td>4.1</td>
<td>5.0</td>
</tr>
<tr>
<td>8</td>
<td>7.4</td>
<td>7.4</td>
</tr>
<tr>
<td>9</td>
<td>6.3</td>
<td>6.1</td>
</tr>
<tr>
<td>10</td>
<td>4.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>

To make sense of the rating statistically, two additional tests were carried out, a correlation test between the five variables, and a cluster analysis test. The correlations (Table 5) show that ‘creativity’ rating correlated significantly, at the 0.01 level, with both ‘functionality’ and ‘tectonics’, most strongly with ‘facade aesthetics’ (coefficient= 0.972, Significance=0.000, much smaller than the required 0.05), and not significantly with ‘form’. This implies that creativity related to both measures of ‘appropriateness’, it related with only one of the measures of ‘novelty’, i.e. façade aesthetics.

Table 4: Rating of student projects on a 10-point scale

<table>
<thead>
<tr>
<th></th>
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<td>2</td>
<td>6.9</td>
<td>6.8</td>
<td>7.0</td>
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<tr>
<td>3</td>
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<td>7.4</td>
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</tr>
<tr>
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<td>6.3</td>
<td>6.1</td>
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<tr>
<td>10</td>
<td>4.5</td>
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</tbody>
</table>

Table 5: Correlations of creativity with measures of appropriateness (functionality+ tectonics) and measures of novelty (form+ façade aesthetics)

<table>
<thead>
<tr>
<th></th>
<th>Functionality</th>
<th>Tectonics</th>
<th>Form</th>
<th>Facade</th>
<th>Aesthetics</th>
<th>Creativity</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Pearson Correlation</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>Sig (2-tailed)</td>
<td></td>
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<td></td>
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<tr>
<td>N</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Correlation is significant at the 0.01 level (2-tailed).

Correlation is significant at the 0.05 level (2-tailed).
Fig. 9 shows a cluster analysis dendrogram in which the data is reduced to clusters. There seems to be two main clusters: one between function and tectonics and another, a two-step cluster, between façade aesthetics and creativity with ‘form’ joining in at the second step.

Finally, the 10 project creativity ratings—the ‘product’—were correlated with the ‘subjective’ response to the variable ‘CAAD on overall creativity’, from questionnaire returns for the same students. The computed correlation coefficient was both positive and significant with a coefficient of 0.731 and significance of 0.00, i.e., \( P < 0.001 \). This implies that rating on creativity of the ‘process’ related to rating of creativity on the ‘product’.

7. CONCLUSIONS

A single case study, that is based on attitude analysis of students after exposure to CAAD, that has a limited number of variables, can at best refine a theoretical proposition rather than establish a new one. This study has limitations as it dealt with a small sample size; a larger sample would produce more fruitful results, allow more empirical generalisations to be made and increase research validity. In addition, the study’s aim was to ‘explore’ the relationship between variables that relate to design and the design process. If the study were to achieve the other two goals of knowledge, that of ‘control’ and that of ‘prediction’, the influence of one variable on another, then the experiment has to be repeated under different conditions. In addition, research which aims at measuring creativity, usually follows a pattern of employing established batteries of tests for creativity using ‘question and answer’ procedures. This, as a research methodology, one could argue, is more objective than our creativity tests, which were based on questionnaire returns and personal observations. The study carried out an experiment with a CAAD programme that can be regarded as traditional in nature compared to a more cutting edge technology, such as virtual reality (VR) which currently is at the forefront of architectural
computing. The sense of ‘immersion’ in VR settings could produce different results. Nevertheless some tentative conclusions can be drawn from this investigation.

Generally the study found a significant correlation between the use of CAAD in design and four of the five domains of architectural creativity of the process. With ‘ideation’ the study found that CAAD has helped in generating more generic design layouts (solutions) with a significant variety (richness) and novelty (part 1). Overall creativity correlated significantly with fluency (0.547), flexibility (0.371) and originality (0.351). Also a significant difference was observed between intensive and occasional users of CAAD in attitudes towards creativity and each of the three aforementioned variables. Intensive users recorded a mean vote ranging from 2.6-3, compared to a mean range between 2.2-2.6 for occasional users.

Part 2 of the findings describes the influence of design knowledge, procedural and declarative, through the use of CAAD on creativity. Knowledge, both declarative and procedural was found to have little influence on architectural creativity. This was in line with surveyed research that found knowledge as being the secondary tier in creative thinking. Also tests of creativity have shown that intelligence has little influence on creative thinking. Also creative people were found to tolerate ambiguity more than noncreative ones.

This part also found a difference between the two types of user as intensive users gave a higher rating (a mean of 3 out of a possible 4) than occasional users (a mean of 2.3) for the influence of CAAD and the Internet on their design knowledge and in turn on their creativity.

On the impact of CAAD on design synthesis, analysis and evaluation and in turn on creativity, the study found that 24 students found CAAD helpful regarding the three aforementioned domains of design (part 3). Creativity vote correlated significantly with two of design domains: evaluation (0.47) and synthesis (0.60). The design synthesis rather than analysis significant correlation with creativity suggest that ‘intuition’ may play a larger role than intellect in formulating preinventive visual patterns and structures which both are regarded as a necessary ingredient for creative thinking. Part 4 analyses the influence of CAAD on personality traits related to creativity such as preference for complexity, asymmetry and non-linear organic geometry. 60% of the sample reported that CAAD has helped them in dealing with and pursuing design complexity whereas 40% recorded an impact on pursuing organic and non-linear shapes.

It appears that with CAAD students produced objects, which were complex and organic- both qualities could be more difficult to achieve with traditional means of sketching and physical modelling. This generalisation may seem plausible when the designer is a novice one, like our subjects. Experienced designers, on the other hand, can achieve complexity which is independent of the medium they work with. For instance, Gaudi’s deep imagination achieved levels of surface complexity based on third order
geometry (of an ellipse rather than an arc) using scale models and mathematical calculations. Gehry used the computer to achieve wall and volume complexity in Bilbao and help the construction process to keep the overall cost within budget. As computers cannot be autonomous at present the human dimension of imagination takes an extra significance in the area of human-computer interaction.

Part 5 reports on the fifth domain of creativity - that is creative cognition which is a precursor for creativity. Again students’ response highlighted the usefulness of CAAD visualisation and generative tools such as arrays in the assemblage and synthesis of visual patterns and imagery. The correlation between creative cognition and creativity was significant with a coefficient of 0.47. Part 6 examines the product and rated them on a 10 point scale. The cluster analysis used was a visual mean to observe the proximity between creativity of the product and its two constituents (novelty and appropriateness). Novelty variables of façade aesthetics (with a correlation of 0.875) and 3D geometry (with a correlation of 0.712) formed a cluster with creativity whereas appropriateness indicators of tectonics and function formed another cluster.

In conclusion the findings do support the notion that the use of CAAD within the design process has affected levels of creativity and complexity in the design process and the product. However it also highlights the need for more IT-based design experiments, to be conducted in architectural education, that are empirically oriented. Furthermore it would be extremely helpful if some of the ‘theoretical’ assumptions in the literature regarding the concept of ‘cyberspace’ such as those cited in [38] and their influence on both the designer’s perception and the design of physical space, are operationalised and empirically tested. It seems that there is too much of a theoretical debate going on at the moment on the impact of CAAD on architectural representation, which requires verification through various empirical means and case studies.

From the ‘internal’ validity of this paper, an ‘external’ validity is drawn to propose some guidelines for digital education in architecture. Firstly, the integration of CAAD with design studios in architectural education requires the formulation of a CAAD theory in parallel to the well-established design theory. The current strategies in CAAD education should also place emphasis on conceptual issues of CAAD as well as teaching computing skills. Perhaps a better outcome can be achieved if CAAD is taught both ways: as a knowledge-based subject as well as skills. Secondly, psychological theory on creativity, visualisation, design cognition, and architectural education can be brought together through computing to form a combined system with new educational objectives. Thirdly, architectural theory courses, which are usually conventional in nature, should evolve and cover issues related to the current influence of information technology on architectural ‘style’ and ‘aesthetics’.
Acknowledgement

The author would like to thank First Year students at the Mackintosh School of Architecture, Glasgow for participating in this experiment, allowing observations and completing the questionnaire returns.

References

1964

Appendix:
Selected Illustrative Examples of Students Work

A.1 Student A. The student used the computer to design a project and explore issues of surface ‘complexity’ and topology based on elliptical curves. Ideation variety (flexibility) is manifested through changing the geometry of the basic ellipse, the generator of the ‘deformed’ surface.
A.2 Student B. This is a good example on the use of CAAD for 'ideation
variety'. The student wrote a script in Rhino to generate a variety of roofs
and curved surfaces from which he selected an optimum. The louvres were
inspired by Calatrava's elements in the concrete pavilion, Swissbau. Again
CAAD was used to generate 'various' arrays of louvres along splines before
choosing a scenario ideal for light and view.
A.3. Student C. The student used CAAD to explore form and structures. Ideation 'novelty' was arrived at via the creation of a 'novel' structural system that led to the final design layout.
A.4 Student D. The student used CAAD to generate a ‘novel’ and ‘efficient’ detailing system, which led to the creation of a ‘novel’ design statistically infrequent. The creativity of the ‘product’ stems from its construction efficiency and ‘appropriateness’ for use.