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COGNITIVE LOAD MANAGEMENT AND ARCHITECTURAL DESIGN OUTCOMES

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Abstract: The aim of this study was to analyze the link between the way designers manage cognitive load during the process of architectural design and the outcome of this process, that is, the quality of the creative designs they produce. To this end, we quantitatively measured cognitive load by asking 36 architecture students to perform a secondary task while they were using three classic design media (hand sketch, physical model and Sketch-Up, a modelling program). Then, the students' designs were qualitatively assessed by eight architects acting as judges (four teachers and four professionals). No correlation was found between cognitive load and project quality for any of the three media.

Keywords: *cognitive activity, design media, evaluation*

1. **Introduction**

Design is a complex task composed not only of a single problem, but of several, multifaceted ones (Lebahar, 2007). According to the cognitive approach to creativity and design activities, architecture is a dynamic and iterative process of looking for a "satisfactory" solution that is both original and functional. This iterative process of exploration-generation-evaluation relies on representations, which can be either internal (resulting from cognitive activities or processes) or external (depending on the design medium). These representations are essential to any creative act, as well as in every phase of the design process, as a means of projecting the architect's thinking and know-how.

The activities and cognitive strategies implemented by architects during ideation may consist of (re)interpretation, combination, restructuring, or analogical reasoning (Visser, 2009), and require significant cognitive resources. However, as mentioned by several authors (Bilda & Gero, 2008; Wickens, 2000), cognitive resources are limited, and designers need to externalize their ideas to free up their working memory (Baddeley, 2007). Moreover, the manipulation of design media also requires cognitive resources. We therefore decided to examine whether any particular types of design medium impose additional cognitive load on the designer during the design process, and whether the design outcome is affected.

We begin by defining the concepts evoked above – namely cognitive load and its role in the design process, as well as the assessment of creative productions resulting from this process – before detailing the current experimental method and results.

2. Theoretical background

2.1 Cognitive load and the design process

Owing to its inherently complex nature, the design task is reliant on working memory resources. However, in the field of architectural design, few studies have focused on the management of cognitive load. After defining cognitive load, we look at how it can be measured and its role in architectural ideation.

2.1.1. Cognitive load definition

There are almost as many definitions of cognitive load as there are research areas. Thus, in the field of cognitive ergonomics, Wickens and Holland (2000, p.128), define it as “the difference between the cognitive demands of a particular job or task, and the operator’s attention resources” - a definition reiterated by Cegarra and Chevalier (2008). In educational psychology, for Sweller, who developed the theory of cognitive load in the 1980s, working memory accumulates the information being processed, and it is this that constitutes its cognitive load. By inducing less cognitive load, we can allow more information to be processed, and thus support and enhance learning potential. Following this logic, Eggemeier (1988) asserts that any increase in task difficulty leads to a deterioration in performance.

For the purposes of the present study, we adopted the general definition by Chanquoy et al. (2007, p. 58). According to these authors, cognitive load is “a quantity, a measure of the intensity of cognitive processing engaged by a particular individual, with certain knowledge and resources, to achieve a certain task, somehow, in some environment”.

2.1.2. Cognitive load measurement

Cognitive load measures can be classified as either qualitative or quantitative.

- Qualitative measures

These measures or tests are used to collect participants’ thoughts and feedback on their performance. De Waard (1996) prefers the term “self-assessment measure” (self-report measure), as some physiological measurements can also be subjective. Three tests are particularly widespread in the literature: the Workload Profile (Tsang & Velazquez, 1996), the Subjective Workload Assessment Technique (SWAT; Reid & Nygren, 1988) and the NASA Task Load Index (TLX; Haart, 1988).

- Quantitative measures

The first category of quantitative measures relies on physiological indicators to measure cognitive load, such as a pupil dilation, eye movement, electrocardiography (blood pressure, blood volume, etc.), electroencephalography (rhythms in the brain associated with cognitive demands), and brain imaging (functional magnetic resonance imaging, fMRI). These physiological indicators are useful because they allow us to measure cognitive load during task performance, but they are both intrusive and expensive. Another quantitative method consists of administering primary tasks (PTs) or secondary tasks (STs), also referred to as behavioural or performance-based measures. In PTs, cognitive load is measured in terms of response times to the PT. STs however, are more widely used (see, for instance, Bonnardel & Piolat, 2003, in the context of design activities). The basic principle is that a more demanding PT leaves fewer cognitive resources available for the ST, which is then reflected in ST performance.

2.1.3. Cognitive load and design media

Few studies have investigated the cognitive load management in the field of architectural design (Côté et al. 2011). Bilda and Gero (2008; see also Bilda, Gero, and Purcell, 2006, and Dorta, 2008) sought to establish whether mental imagery or medium type impose additional cognitive load on designers, using mainly qualitative or subjective methods. Results suggested that the externalization of cognitive activities (e.g., visuospatial information processing) is needed to free up WM so that other tasks can be carried out effectively. For this reason, external representations (i.e., design media) play a key role in architectural design. Hand sketches and ideation are two inseparable acts for most architects. The use of sketches has always been considered a medium of choice for the externalization of visual mental images: "designing involves the interplay of sketching and imagery” (Goldschmidt, 1995, p.3). However, there has been little empirical research on ideation using 3D digital tools such as Sketch-Up, which allows objects to be manipulated in 3D and interactions to take place in realtime. Thus, cognitive load, which is a measure of designers’ cognitive activities, depends on several factors, both including the cognitive strategies and the media used by designers to represent their ideas. No studies in the field of architectural design have made the connection between the management of cognitive resources by designers engaged in the architectural design process and the resulting quality of creative designs.

2.2. Design assessment

Assessing creative productions (here, architectural designs outcomes) is a complicated objective, because it is essentially based on the judges’ subjectivity. Howard et al. (2008) investigated the creativity measures used in several studies. Allthough the precise semantics varied from one author to another, Howard et al. (ibid). found that two key characteristics of creative products were generally emphasised: novelty and adaptability or functionality, While it seems feasible to explore the adaptability or functionality of creative works by establishing objective criteria (compliance with prescribed constraints, such as surface area and number of rooms, planning regulations, disabled access, etc.), the judges’ subjectivity comes to the fore when examining the innovative or original aspects of designs. In the field of architectural design, studies addressing the assessment of architectural solutions in academic or professional contexts have always been based on “qualitative” methods since they rely upon expert assessments (Bilda & Gero, 2008; Casakin, 2008; Yukhina, 2008). Amabile (1983) has theorized about and empirically documented this method for over thirty years, calling it the "Consensual Assessment Technique” (CAT) when applied to the field of creativity. The CAT is based on the idea that the best measure of the level of creativity of a work, a theory, or an artefact, results from a combination of expert assessments in this area. According to Hennessey (2003), researchers using this technique must meet four criteria: (1) the judges must have expertise in the field, even if their levels of experience vary; (2) judges must assess the designs/artifacts independently, without being influenced by the experimenter; (3) judges must assess productions by comparing them and not by measuring them against a standard; and (4) each judge must assess the artifacts in random order, to avoid any order effects. The main advantage of the CAT is that it is not based on any theory of creativity, and its validity was established empirically (Baer et al., 2004).

Assessment criteria vary, depending on the domain and the judges assessing the creative products. In the field of industrial design, Wojtczuk and Bonnardel (2011) asked a panel of 20 experts to assess creative productions (computer mice) according to criteria of aesthetics, originality, functionality, and marketing. In the field of architectural design, Yukhina (2008) submitted participants' products to three experts, who rated their compliance with a number of prescribed constraints (12 design criteria), as well as criteria of originality, complexity, flexibility, functionality and sketch quality. Similarly, Yukhina(2008) and Casakin (2008) based their earlier assessment on prescribed constraints, as well as criteria of usefulness, originality and aesthetics.

To our knowledge, there has not been any research in the architectural design field on the possible connection between the cognitive load experienced by designers and the quality of creative designs generated.

3. Experiment

Can cognitive load potentially influence the outcome of the design process, that is, in a general sense, the quality of the design? If a designer has too few cognitive resources to develop visual mental images and externalize ideas, does he or she produce poorer-quality designs? If a design medium requires more cognitive resources and thus increases the designer's cognitive load, does it influence the quality of the resulting design? To answer these questions, we conducted a study across two academic semesters with architectural students. We adopted a mixed methodology to determine the participants' cognitive load, and took care to respect the ecological validity of the architectural design process. Inspired by experimental psychology, we used a combination of quantitative and qualitative measures. However, whereas experimental psychology studies are generally conducted in the laboratory, we believed it was crucial to take the dynamic and complex nature of architectural design into account. Thus, although we could not analyze all the interactions involved in such a process, we were able to ensure a degree of ecological validity by creating a minimally intrusive protocol for a "traditional" design environment.

We adopted a repeated-measures design for our data analysis, as there is only a limited pool of students in architecture, and this design allowed us to compare the use of three design media: hand sketch (HS), physical model (PM) and Sketch-Up (SK). To avoid order and practice effects, the participants had to randomly produce three different designs using the three design media.

3.1. Participants

Thirty-six architecture students took part in this study. We chose to undertake accidental (nonprobabilistic) sampling, one of the most widespread and least expensive sampling techniques. The sample consisted of 22 men and 14 women, with a mean age of 24 years (SD = 3.03). Moreover, to ensure that all participants had some experience of undertaking small design projects, only students who had completed at least four academic semesters were recruited. In addition, on a five-point Lickert scale, all participants rated themselves as proficient in the use of the three design media, especially the modelling software (SK) (Mean responses: PM = 3.88; HS = 3.48; and SK = 3.97; N = 36).

3.2. Procedures and materials

The experiment comprised two phases:

1. The first one concerned the production of three designs in three experimental sessions, during which each participant used a specified design medium. Each experimental session took about 30 minutes. First, the participants had 3 minutes to come up with a design of their own choice, to allow them to become accustomed to wearing headphones (needed for the ST). Then, after reading the guidelines and the criteria for the design project (±5 minutes), each participant had 22 minutes to complete the main (or primary) design task on a drawing board that allowed them to sit in an upright posture. For each medium, the participants performed randomly a task to design either a bus station (BUS), a recycling station (RS) or a public restroom (WC).

   To measure cognitive load, we administered an ST (performance-based task) to participants. This task was tested in a previous design context (Bonnardel & Piolat, 2003) and it seemed appropriate to working conditions in design activities.This task was conducted as follows. Throughout the 22-minute design period, numbers ranging from one to five were played randomly over the headphones, at a rate of one every five seconds. The participants' task was to press on a foot pedal as quickly as possible whenever there were two consecutive ascending digits. The use of a foot pedal minimized interference with the main design task that required the use of both hands. Before each experimental session, participants received a list of written instructions that clearly indicated that the design project took priority. We analyzed the percentage of correct responses (CR) and mean response times (RT).

The second phase consisted of the assessment of the participants' designs. A panel of four professional architects (at least five years' experience) and four architecture teachers assessed these projects on four criteria: overall assessment, aesthetics, originality and functionality. A definition of these criteria was given to the judges in order to reduce differences in interpretation. In addition, as recommended by Amabile (1996), the judges assessed the projects independently and in random order.

4. Results

4.1. Secondary task results

As some participants completed the design task in less than 22 minutes, in order to compare their results with those of the other participants (and given that there was a maximum of 25 correct responses), we computed the following ratio: % of correct responses (for x minutes) = (no. correct responses/25 - no. of missing responses) x 100.

Two one-way ANOVAs were run on correct responses and response times (Fig. 2). The assumptions of normality, homogeneity of variance, and sphericity were met. The results for the correct responses showed that there was no significant difference between the three media, $F(2, 65) = 2.068$, $p = .138$ (see Fig. 1). Concerning response times, no significant difference was observed between the three media, $F(2, 56) = 1.983$, $p = .155$.

The results of these quantitative measures showed that none of the media imposed a relatively higher cognitive load than any other. This result is in contrast with the theoretical assumption that hand-sketching, with its potential for generating alternative solutions faster, induces less cognitive load.

To find out whether there was a link between CR and RT, whatever the medium used, we performed a correlation analysis between the CR and RT measures. Results indicated negative correlations between CR and RT for HS ($N = 36$, $r = -0.456$, $p < 0.005$), PM ($N = 36$, $r = -0.467$, $p < 0.006$) and SK ($N = 36$, $r = -0.607$, $p < 0.001$). Thus, participants who took longer to respond also made more errors, regardless of the medium used. The next section will allow us to determine whether cognitive load has an influence on the quality of projects generated, depending on the medium used.

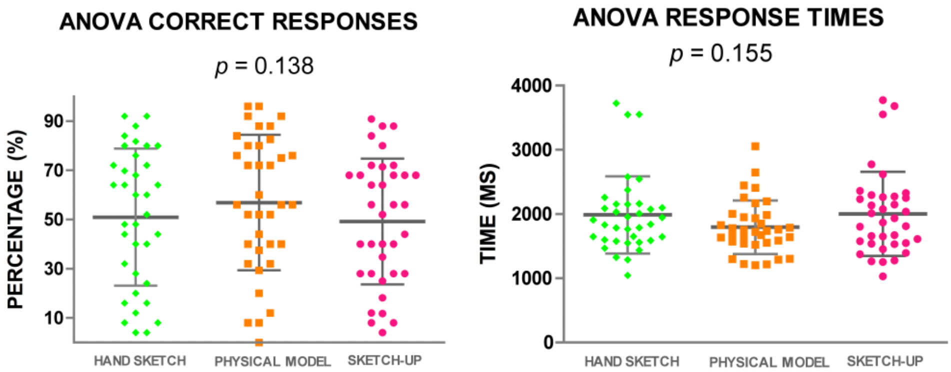

Figure 1. Scatterplots of correct responses (%) and response times
Legend: The scatterplots illustrate the data clustering based on three statistics: lower quartile, mean and upper quartile.

4.2. Design assessment results

The 8 judges had to assess all the participants' final productions, such as the ones presented in Figure 2.

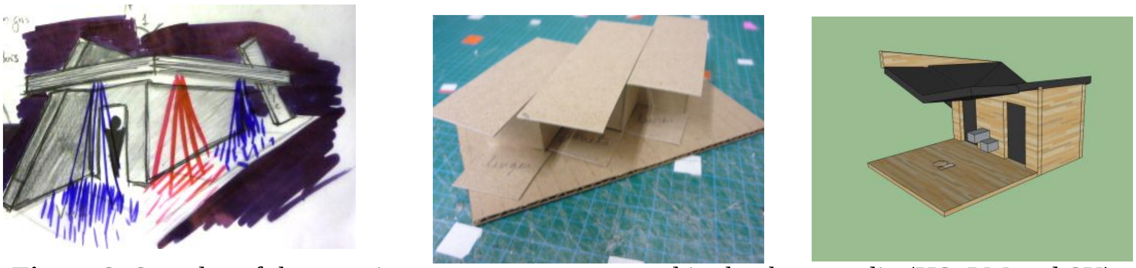

Figure 2. Samples of three project outcomes represented in the three media (HS, PM and SK)

The descriptive statistics performed on scores attributed by the judges showed that for overall quality and aesthetics, SK seemed to have better ratings than the other two media. For originality, PM received the best ratings; while for functionality, HS came top (see Table 1).

Table 1. Means and *SD*s of assessment scores

Assessment (*N* = 36)	Hand sketch	Physical model	Sketch-Up
Overall	2.12 (σ=.70)	2.20 (σ=.48)	2.23 (σ=.62)
Aesthetics	1.85 (σ=.79)	1.99 (σ=.57)	2.09 (σ=.71)
Originality	1.77 (σ=.86)	1.90 (σ=.76)	1.83 (σ=.76)
Functionality	2.52 (σ=.67)	2.44 (σ=.67)	2.37 (σ=.62)

To look for statistically significant differences between the assessments, four one-way repeated-measures ANOVAs were run on each assessment criterion: overall, aesthetics, originality and functionality. The assumptions of normality, homogeneity of variance, and sphericity were met.

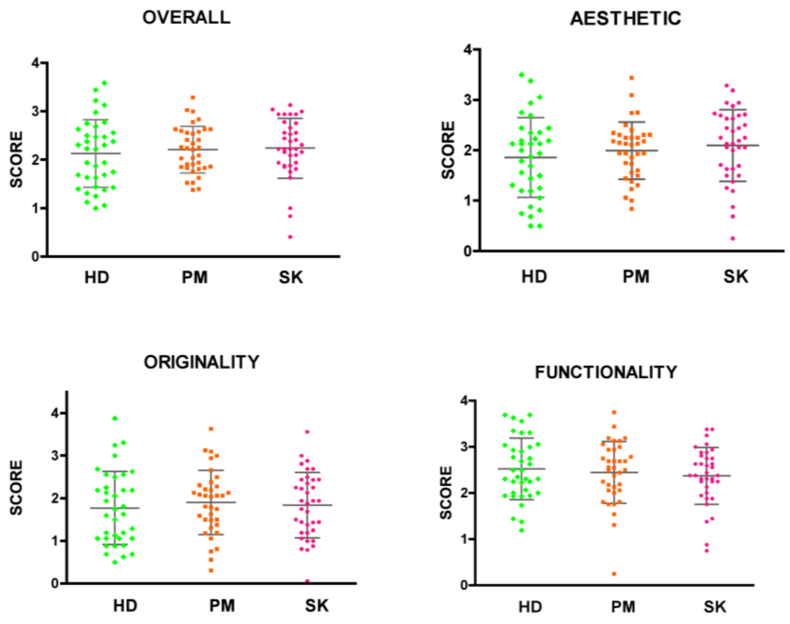

Figure 3. Scatterplots of project evaluations (%)

The results for the overall assessment showed that there was no significant difference between the three media, $F(2, 65)= 1.34$; $p = .607$ (Fig. 3). Concerning aesthetics, originality and functionality, there was again no significant difference between the three media, $F(2, 64) = 0.57$, $p = .231$), $F(2, 69) = 1.56$, $p = .707$, and $F(1, 35) = 0.145$, $p = .494$.

4.3. Correlation between cognitive load and design assessments

Correlation analyses were performed between the two measures of cognitive load (CR and RT) and the four assessment criteria (Overall, Aesthetics, Functionality and Originality) for each of the design media. Results did not indicate any significant relationship between these variables, regardless of the medium used (see Table 2). This means that the quality of the participants' designs was not related to reductions or increases in cognitive load.

Table 2. Correlations between cognitive load measures and design assessments

		Hand Sketch				Physical Model				SketchUp			
		Over.	Aesth.	Origi.	Funct.	Over.	Aesth.	Origi.	Funct.	Over.	Aesth.	Origi.	Funct.
Corrrect responses	Pearson cor.	*.265*	*.202*	*.201*	*.107*	*.182*	*.096*	*.209*	*.102*	*-.138*	*-.182*	*-.159*	*.031*
	sig.	*.119*	*.238*	*.239*	*.536*	*.289*	*.578*	*.222*	*.553*	*.423*	*.288*	*.356*	*.858*

Response times	Pearson cor .	*.091*	*.100*	*.090*	*.159*	*-.045*	*.068*	*-.021*	*-.112*	*.246*	*.228*	*.314*	*.067*
	sig.	*.599*	*.562*	*.600*	*.353*	*.798*	*.698*	*.905*	*.521*	*.149*	*.181*	*.062*	*.696*

5. Discussion and conclusion

The major goal of this exploratory research was to analyse certain aspects of the cognitive activities of novice architects during conceptual phase as well as to illustrate the impact of design media on their performances. Borrowed from experimental psychology and human factor studies, a mixed methodology was proposed to document the link between the use of design media, the design process and the results of creative design process.

The present study yielded three findings: (1) none of the design media has imposed an additional cognitive load on the designer, in contrast to the literature, which suggests that the hand sketch is the ideal tool for the design process; (2) the quality of the design did not depend on the medium used; and finally, (3) there was no relation between cognitive load and design quality. These different kinds of observations can be commented more precisely.

Firstly, historically, hand sketch seemed to be the designated medium for the architectural design. Indeed, the studies comparing traditional (hand sketch) and digital media criticize the fact that modeling software slowed down the externalization of the designer's mental imagery (Bilda, 2006). In contrast, our results show that these digital media do not impose additional load compared to other media. Furthermore, the current widespread use of digital media, offers multitude potentials, which can become a strong complement to other media at all stages of the design process. Thus, usages of complementary media could be investigated with regard to the stages of the design activities.

Secondly, the overall quality of generated projects was not influenced by the medium used. Thus, our results suggest that each tool may provide the same potential for representing and externalizating the designer's mental imagery. Future works will aim to detail these potentials.

To conclude, the results of this research suggest that each design media offers opportunities for design. The dialogue that ensues between the designers and their representations, contibute to the emergence of opportunities specific to each medium. For example, using primitives (cube, cylinder, pyramid, etc..), applying geometric transformations, manipulating them with a software (such as Sketch-Up) and obtaining complex volumes or spaces, definitely creates opportunities and promotes ideas that the designer probably would not have developed as easily with a drawing or model. As highlighted by Keehner et al. (2008), the properties of external representations influence how we interact with them, they structure and anchor the cognitive and metacognitive strategies used to develop mental images. Therefore, depending on the context and the stage of the design process, each designer should be able to choose the tool(s) that are appropriated with regard to his or her knowledge and metacognitive strategies, in order to facilitate as much as possible his or her creative activity.

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