A Quantitative Method to Compare the Impact of Design Media on the Architectural Ideation Process

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Abstract. Although we may know a lot about architectural design in terms of the inputs (e.g., early design decisions, programming, collaborative design) and outputs (e.g., project representations and building constructions), little is known about the actual design process itself. Currently, few studies have attempted to identify which cognitive functions are involved in the design process, how they operate, and to what extent they complement each other. From an extensive literature review, we have identified two cognitive functions, which are thought to underlie some of the complex activities involved in the design process, namely mental workload management and imagery. These two functions are quantitatively measured in the context of real design tasks using Bakan's task for workload management, and eye tracking for imagery.

To our knowledge, this paper presents the first attempt to address the complex design process in a quantitative and online manner. Preliminary results are reported testing the impact of three design media, namely: physical modeling, hand drawings, and CAD software. An interpretation of fractal structures is also given and proposed to account for the impact of different media on mental imagery.

1. Research Objectives

The research aims to propose, develop and validate a quantitative method for assessing the impact of medium – both analog and digital – on the design process, specifically during the phase of ideation, which we define as the internal and external representation, and back and forth formulation of the earliest design ideas. This assessment stems from the observation that whatever medium, system
or technology is used to "assist" the design process, it comes with a cost in terms of a reduction in creative possibilities. Any medium limits the process of ideation in one way or another whether it is the learning curve required to master the technique or the interface (e.g., drawing, modeling software, etc.), the time necessary to obtain the result (the artifact), or the characteristics and properties that are required for the medium used (e.g., specific user skills). Thus, there is always a tradeoff for the designer in choosing a medium to reach a goal, from the idea to the artifact (or its representation), from the intangible to the tangible idea. The question then is which medium is the most effective for the process of ideation and which incurs the least cognitive cost? We propose a measure to evaluate this quantitatively.

The originality of the research stems from its proposed method. Previous comparisons of design media have essentially been qualitative in nature, often relying on subject verbalization for data acquisition, all depending at one point or the other upon the subjective interpretations of the experimenter, the participant, or both. However, verbal reports have been shown to be quite limiting in knowledge acquisition by many authors, namely Ericsson and Simon [1]. The proposed quantitative method eliminates this bias by using an objective measure of the impact of each medium on the designer's cognitive processes [1].

2. Background

Currently, all assessment methods for design media and design process analysis are essentially qualitative and subjective, based upon participant answers or experimenter interpretation. In the current paper we evaluate and compare three different design media for three design situations. The first medium, the physical model, is analogue and is used as the control situation. It is currently taught extensively in our schools of architecture, and is one of the best-known and well-documented media [2]. Its 3D nature provides an unbiased point of view to compare with the second medium, which is 3D CAD software [3] (here SketchUp). Finally, the third medium, freehand drawings, is also studied widely and is very well documented [4].

For the development of spatial representations [5], mental imagery and cognitive control of resources and actions [6] are important factors in the design process. Thus, the incidence of the three media is evaluated and compared using two cognitive functions used in the process of ideation, namely mental workload management (measured by the Bakan task) and mental imagery (measured by the monitoring of eye movements). The Bakan vigilance task, performed concurrently with the main design task, requires the participant to detect a particular sequence of digits amongst random numbers presented in an auditory stream. The use of an auditory version of the Bakan task served to increase
mental workload (the same higher-order cognitive management resources are used for both the primary and secondary tasks), whilst eliminating any more specific, direct competition with the design tasks in the visual modality.

2.1. Scale model

A physical model was used as an example of a 3D tool traditionally used in architecture teaching and practice, that could be compared to a 3D digital medium. Indeed, the scale model is a very effective tool for experimenting with potential structures, and means that decision-making and the validation of forms regarding details and textures are made directly with the design object. Moreover, it is a 3D shape that is manipulated and studied in the real world, thus controlling the formal research and proportions without intermediate images on the computer screen or drawn on paper. The model contains the thoughts and deliberations of a designer in the early stages of the process [7]. Also, the model, like the sketch, is a tool for visualization and simulation, which is quick, intuitive and widely used. In ideation, an imprecise and ambiguous model is sometimes more efficient for the designer than one with a more precise and finite form [4]. Changes are easily made and precision is not necessary for the expression of an idea [8]. Moreover, designing a model allows our brain to see the information, understand and respond to it. Like architects’ sketches, Schön believes that models are a reflection of thoughts in action [9].

2.2. CAD software

Research on the study of external representations has mainly concentrated on "freehand" sketches in the conceptual phase. Some empirical research has investigated drawings or ideation through digital tools. Decortis et al. [10] pointed out that despite the abundance of architectural digital tools on the market, designs typically begin with a pencil and paper. Designers tend to transfer their designs to a computer at the end of their design process, by using it as a presentation tool. According to these authors, digital tools require a high level of precision and no ambiguity while the factors of unconstraint and abstraction seem to be necessary in the first phases of design. However, other studies [11, 12] suggest that visual representations from digital tools provide a better understanding of forms and thus provide better support for visual thinking. Tang and Gero [13] argue that higher-level cognitive activities are not affected by the change of medium (traditional, vs. digital). To our knowledge, based on a protocol analysis [14], Bilda and Demirkan’s research [11] is the first experimental study to explore cognitive activities during analog ideation (freehand sketches) versus digital ideation. The results showed that traditional media have advantages over digital media, in terms of perception of visual-spatial properties and production of alternatives. This conclusion is supported by the literature [4, 15] and the fact that
designers are used to sketches as tools for representation throughout their education, which could limit their interaction with digital tools. In addition, the authors showed that the total number of cognitive actions was also higher with traditional media, which means that the designer’s cognitive activity was more intense when they sketched. Moreover, the interest in 3D CAD in architectural design is fairly recent and studies about this medium are only qualitative, based on observations and protocol analysis [16, 17, 18].

2.3. Freehand drawings

Freehand sketches are often seen as abstract, ambiguous and imprecise [19]. The drawing is a graphical simulation system [16]. It allows for the representation of ideas with graphical objects through an interactive psychomotor process. The visual image becomes stronger when the results of this psychomotor activity are integrated with visual observations [20]. The connection of the mental image with psychomotor performance produces a physical image: a drawing. This is possible through a closed network consisting of graphical representations, vision, mental imagery and hand movement [21]. According to Furness, the creative process is enhanced when all three processes (visual, mental and psychomotor) are active. Furthermore, compared with detailed plans, sketching contains the thoughts and deliberations of the designer in the early stages of the process [7]. Lockard [22] argues that freehand drawing allows our cognitive system to see the information, understand and respond to it. By analyzing the drawings of architects, Schön [9] claims that they are thoughts in action.

In the 1990s, a great deal of research was concerned with the use of visual representations in the design process. These studies were mainly interested in sketches as tools for externalizing the mind of architects and the mental images that they held about a given problem. To Ullman and al. [23]: "[…] without the external media, there can be no resolution of problems". To summarize, studies of sketches argue that external representations are part of the design process [24]. They allow: 1) access to extended memory for mental images, 2) rapid manipulation of ideas because they can be rapidly produced, 3) a representation of information in various forms (different views and levels of abstraction), 4) store design solutions, 5) refine ideas, and 6) produce concepts and facilitate the resolution of problems.

3. Methodology

The proposed methodology provides a quantitative and objective measure of how cognitive functions might be supported by a design medium aide. Each cognitive function is associated with a quantitative measure. Before measuring any
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cognitive function, all participants had to attain a minimum level of competence across all three media.

The ecological validity of the experiment is an important issue. The experimental situation must be complex and dynamic, assessed at a global level without being segmented, and it cannot be intrusively managed. Therefore, a full design task is proposed (although limited in time), which captures the complexity of the design context. The design tasks are: a bus station, a recycling station, and a public restroom. Finally, only non-intrusive measures are applied during the experiments while intrusive ones were given only before or after the design task.

3.1. Mental imagery and workload management

Mental imagery and mental workload management are crucial cognitive functions with regard to the design process. From a cognitive standpoint, the design process (e.g., an architectural one) is defined as an unstructured, undefined, and open creative process (of problem solving, for some authors) where the need for internal representations (by cognitive functions) and external ones (by design media) is the same for all acts of design.

Research on the cognition of design is about the designer; trying to understand how he or she deals with their complex design task, and in particular with the medium they choose to perform the task of design. This design task is "composed of several problems, multifaceted and multi-domain rather than a single problem" [16]. In this iterative process of internal and external representations, the medium should be playing a central role. To understand the impact of a design tool on a designer's work, one must understand the relation between the designer and his/her medium, and thereafter the cognitive functions that are involved when using it.

However, the creative process of ideation includes several cognitive mechanisms that are either not formalized or difficult to identify [25]. Nevertheless, researchers have identified a cognitive function essential to the design process, namely mental imagery

3.1.1. Mental Imagery

This idea that architects use mental imagery in design is corroborated by independent observations [17, 19]. According to Kosslyn's theory [26], mental images are associated with working memory (WM) and are formed in the "visuospatial sketchpad", a part of Baddeley's WM model [27]. According to Baddeley's model, it is within the sketchpad that mental images are generated and that visual and spatial stimuli are processed.

Studying imagery could be quite difficult for obvious reasons, namely that it is difficult "to read or look at" contents of one's mind. Usually, researchers will rely on participants' verbalizations [4, 18]. In terms of quantitative methods, to our
knowledge, no study in the field of architectural design has been conducted. However, studies of eye movements applied in the field of experimental psychology suggest that there is a link between eye movements and mental imagery [28, 29, 30]. Eye movements would act as a spatial index, which is stored and reused when forming a mental image, allowing for the proper arrangement of components [29].

Results from qualitative studies dealing with mental imagery in the field of design also highlight the role played by other cognitive functions, such as the management of cognitive workload. Studies on working memory show that cognitive workload capacity is limited if the tasks performed require the use of mental imagery. The externalization of ideas is therefore necessary to reduce the burden on cognitive workload management.

### 3.2. Management of Cognitive Workload

According to Bonnardel [31], the complexity of the design task (e.g. ill-defined problems, imprecise and changing representations, and numerous constraints) implies that the designers' activity requires a considerable amount of cognitive resources. Several authors [16, 17, 31] argue that mental representations must be externalized in order to reduce the need for maintaining visual-spatial information in so-called Working memory. The concept of cognitive workload management has been widely used in psychology research over the past forty years [32]. It often refers to the amount of mental resources utilized by a participant to perform a task. There are several types of qualitative and quantitative measures that assess mental workload management (see [33]).

Our proposed theoretical model assumes an interrelation between mental imagery from which a decision emerges and the management of the cognitive workload. When designing, it is in working memory that the both cognitive functions interact from input media, and in the process, the knowledge and mental representations are stored in long-term memory (Figure 1).
Several researchers have highlighted the functional role of eye movement for mental imagery [28, 29]. Eye movements would act as spatial information store index that is reused when forming a mental image, thus allowing for the proper arrangement of components [30]. Mental imagery assessed by eye movement tracking, used a light handheld device (glasses) that is not detrimental to participant mobility and visual perception, and can be easily applied during the design exercise.

### 3.3. Participants

Participants were 19 students from one school of architecture who, to ensure their competence in design and media manipulation, were in the last three years of a five year course. Each participant completed three sessions using one of each of the three media: modeling (Mo), freehand drawing (Hd), and the CAD software (Cad). Participants were trained for a short period to become used to the experimental apparatus (namely glasses, headphones and a pedal). For each medium, they performed a twenty-two minute task to design either a bus station (BUS), a recycling station (RS) or a public restroom (WC). Table 1 summarizes the sessions to which participants were randomly assigned.
Table 1. Session Management: Latin square design.

<table>
<thead>
<tr>
<th>Subject</th>
<th>SESSION 1</th>
<th>SESSION 2</th>
<th>SESSION 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>BUS / Mo</td>
<td>WC / Cad</td>
<td>RS / Hd</td>
</tr>
<tr>
<td>Subject 2</td>
<td>RS / Mo</td>
<td>WC / Hd</td>
<td>BUS / Cad</td>
</tr>
<tr>
<td>Subject 3</td>
<td>BUS / Hd</td>
<td>RS / Cad</td>
<td>WC / Mo</td>
</tr>
<tr>
<td>Subject 4</td>
<td>RS / Cad</td>
<td>BUS / Mo</td>
<td>WC / Hd</td>
</tr>
<tr>
<td>Subject 5</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

3.4. Material

The eye tracker equipment used in the current protocol is an ASL Mobile Eye System. This head-mounted video-based eye tracker records pupil-corneal reflection and does not interfere with the mobility or the visual perception of the participant during the design task.

A Bakan’s task that was adapted to the design tasks, measured the mental workload management. It is a dual task whereby the participant has to perform two tasks in parallel in order to increase the workload [34].

The Bakan’s task was conducted as follows. Throughout the 22-minute design task, the numbers from one to five were played randomly over headphones at a rate of one every five seconds. The participant’s task was to press on a foot pedal as quickly as possible whenever two ascending digits are repeated. The use of a foot pedal minimized interference with the main design task that required the use of hands. Before each experimental session, participants received a list of written instructions that clearly indicated that the design project was the main priority.

3.5. Procedures

The quantitative experimental session took about 30 minutes. After calibrating the glasses for eye movement, the participant had to practice freely for 3 minutes while wearing the glasses and headphones (necessary for Bakan’s task) to become accustomed to wearing the hardware. Then, after reading the guidelines and criteria for the design project (± 5 minutes), participants had 22 minutes to execute the design task on a table allowing an upright posture.

The Figure 2 below shows the results of these experimental design sessions.
4. Results and analysis

4.1. Participant profiles

The preliminary results are from a group of 19 students (12 male) who participated during the Fall Semester 2010 and Winter Semester 2011. Nine students were in the 3rd grade, four 4th grade, and six in 5th grade. Before starting the experiment, participants completed a questionnaire that evaluated their ability on a 5-point Lickert scale (1 = no ability, and 5 = excellent ability) to use each of three design media. All participants considered themselves competent to use the media, with the highest score for the CAD medium (Responses Mean: Mo = 3.87; Hd = 3.39; and Cad = 4.17; N = 19).
4.2. Statistical analysis

4.2.1. Bakan’s task analysis

The capacity of working memory is limited but it is possible to perform competing tasks. Reaction time on the secondary task indicates the level of cognitive load induced by the main task [33], both of which involve similar cognitive management processes [32]. Table 2 shows the number of correct responses and reaction times.

Table 2. Reaction time (ms) and correct responses (%) of Bakan’s task.

<table>
<thead>
<tr>
<th></th>
<th>MO REACTION TIME (MS)</th>
<th>HD REACTION TIME (MS)</th>
<th>CAD REACTION TIME (MS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1734</td>
<td>1980</td>
<td>2051</td>
</tr>
<tr>
<td>Deviation</td>
<td>260,9</td>
<td>498,1</td>
<td>684,3</td>
</tr>
<tr>
<td>Median</td>
<td>1737</td>
<td>1910</td>
<td>1936</td>
</tr>
<tr>
<td>Mo Correct Response (%)</td>
<td></td>
<td>Hd Correct Response (%)</td>
<td>Cad Correct Response (%)</td>
</tr>
<tr>
<td>Mean</td>
<td>60,03</td>
<td>53,45</td>
<td>47,65</td>
</tr>
<tr>
<td>Deviation</td>
<td>23,74</td>
<td>26,76</td>
<td>26,77</td>
</tr>
<tr>
<td>Median</td>
<td>56</td>
<td>48</td>
<td>56</td>
</tr>
</tbody>
</table>

Two metrics were used to analyze the Bakan’s task results: the number of correct responses given by participants and reaction time. It should be noted that some subjects completed the design task in less than 22 minutes. In order to compare their results with the other participants (and given that a maximum of 25 correct responses were possible), the following ratio was computed (% of correct responses (for x minutes) = (# good responses / (25 - # of missing responses)) x 100). Table 2 presents the results from which the box plots were generated (Figure 3). The box plots graphically depict data clustering based on five statistics: lowest observation, lower quartile, mean, upper quartile, and highest observation.

These descriptive statistics show that subjects who used modeling (Mo) to conceptualize their project performed better on Bakan’s task (greater number of correct responses and shorter reaction time).

One-way Anovas were computed for reaction time and correct responses. The results show that there is no significant difference between the three media for the two measured metrics (p > .05, N = 19). Only one significant difference was observed between Mo and Cad, for correct responses with p = .049, where
modeling has a positive effect on correct responses over the CAD medium (Figure 3).

Fig. 3. Bakan's secondary task; left: Box Plots of reaction time (ms); right: Box plots of correct responses (%).

Given that this research is exploratory and descriptive, it is challenging to compare our quantitative results but we can build on the observations in the literature. The main issue about mental workload management is whether the externalization of cognitive activities is facilitated by one of the three design media. From the Bakan’s task results we can see that there is no significant difference between the three media with regard to the required mental workload management. However, there seems to be a tendency for the CAD to be more demanding in terms of workload management for both reaction time (Mo < Hd < Cad) and correct responses (Mo > Hd > Cad).

One explanation could be that with modeling, unlike with the two other design media, the relatively slow pace of actions, which is intrinsic to the medium task (such as, taking a craft knife, cutting cardboard, using glue and waiting until it sets, etc.) could give more time to react properly to the secondary task. With sketches, subjects perform more actions (drawings) on the same laps of time. And for CAD, one must concentrate on multiple devices, such as the screen (and its multiples zones within), the keyboard, and the mouse, etc.

Regarding reaction time (i.e., (Mo < Hd < Cad), the results are consistent with the correct response data (Mo > Hd > Cad). One explanation (hypothesis) could be that the actions pace proper to each medium affects inversely the reaction time.

4.2.2. Scanpaths analysis

Scanpath analysis was performed looking at participants' scanpath fractal structure. Fractal use is not new to characterize eye movements [35, 36]. Here, the fractal dimension is the metric used. The interest in fractals and fractal dimension
is twofold: practicality, since it allows one to look at a large amount of data at once in order to characterize and then compare sets (the average scanpath results in more than 30,000 points). The other is more fundamental. Fractals account for spatial structure and thereby could help understand how the scanpath pattern is geometrically built, structured, and generated [37]. To our knowledge, this report is the first account of the fractal dimension interpretation of scanpath patterns. Figure 4 illustrates an example eye movement scanpath in the XY plan.

The XYT space in which fractals are projected should be interpreted as follows. The XY plan coincides with the scene image, which is orthogonal to the vector view towards which the subject looks, and the YT (or XT) plan is in the "Z direction", with T as the time axe.

For illustration purposes, Figures 4 and 6 are reported in the XY plan, while Figure 5 is in the YT plan. Each pattern is reported with its estimated fractal dimension (f.d.), which was computed using the "box-counting" algorithm [38]. Figure 4, in the XY plan, accounts for all the points of subject 13's session using CAD to design a recycling station (40,326 points used, 1,901 rejected for 4.50%), while Figure 5 presents the first of ten segments (3,885 out of 38,853 points) of subject 1's session, this time using hand drawing to design a recycling station, but in the YT plan.
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\[ f.d. = 1.276 \]

*Fig. 5. TY scanpath plan, subject 1, green station, hand drawing, first segment of ten (3 989 points).*

Ten segments of a scanpath are fully illustrated in Figure 6 for the XY plan of subject 7’s session with CAD (3 801 points / segment).

\[ f.d = 1.622 \]

\[ 1.546 \]

\[ 1.519 \]

\[ 1.644 \]

\[ 1.593 \]

\[ 1.642 \]

\[ 1.482 \]

\[ 1.522 \]

\[ 1.637 \]

\[ 1.565 \]

*Fig. 6. Fractal dimensions and XY plan of scanpath segments (10), subject 7, bus station, Cad.*

For each medium, results obtained from the nineteen subjects are reported in Figure 7. The specific design task was randomly assigned as described in the previous section. Few observations can be made about this graphic. The modeling medium (Mo) tends to have higher fractal dimension values, followed by the hand drawing (Hd), and the CAD medium the lowest. Moreover, we can observe that CAD and hand drawing (Hd) media values are more alike. As for the Bakan’s task, there is no significant difference between the three media (p > .05, N = 19) The observed trend in the data (Mo > Hd > Cad), is reinforced for all subjects. Based on the definition of fractals [37] and our current results, one interpretation of a higher fractal dimension value is a greater and more thorough (denser) scanning of one's visual field.
Fractal Dimension in the XY Plan

![Fractal Dimension in the XY Plan](image)

Fig. 7. Fractal dimension in the XY plan for each medium, Mo: Modeling, Hd: Hand drawing and Cad: CAD, (N = 19); Repeated measures anova not significant (p > 0.5, N = 19).

5. Conclusion

This paper is concerned with quantitatively measuring the impact of design media on designers’ cognitive processes. Two cognitive functions are investigated, namely, the management of mental workload and mental imagery measured, respectively, with Bakan’s task and eye tracking in the context of real architectural design tasks.

The 22-minute design session generated a large amount of data that are only partially reported and analyzed in this paper. However, preliminary results on workload management show that there is no significant difference between the three media, with a tendency for CAD to be the more demanding medium. A closer look at workload management would be interesting, for example, during
the design process a particular tool could require fewer cognitive resources at one stage or another.

Scanpath analyses reported are preliminary results. In particular, scanpath segmentation (Figure 6) should be performed for both plans XY and YT, in order to better compare the design media and to identify potential sequences in the process of design. However, fractal dimension measures do not show any significant difference between the media. Moreover, based on the fractal definition, results show that modeling – followed by hand drawing and CAD – tends to induce a denser field of view.

References

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