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THE OCULOMOTOR CORRELATES OF DESIGN COGNITION

Two eye tracking studies in exploratory model making

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BACKGROUND AND MOTIVATION

How do designers use their eyes when they make exploratory models? What does their gaze behavior reveal about this creative practice? In my thesis, I study the eye movements of designers and non-designers in different exploratory model-making tasks. The aim is to deepen our understanding of the design cognition mechanisms and behaviors that are co-constitutive to this and other creative design praxes. This work fits well within current research trends in Architectural Robotics and Design Studies centered on the potential of human-machine creative collaboration in the architectural design process.

The term design cognition embodies the belief that there is a distinct type of cognitive process, or combination thereof, that is inherent to design activity (e.g. Cross 1982). Despite receiving increasing attention the last 40 years, there is no consensus on what the concept precisely means (Kimbell 2011). Here, I use it as an umbrella for the cognitive mechanisms and behaviors that underlie creative design praxes in design-related disciplines. So construed, design cognition is at the core of the generative workflows that designers engage in when they design. Yet, its inner workings remain elusive. Can a better understanding of design cognition inform new computational tools to support these workflows? How can this understanding be attained?

Recently, design scholars have asked the above questions in the context of exploratory model making —i.e. the creative act of improvisation where designers conceive new ideas by physically materializing them (Janke 1978). I follow Smithwick and Kirsh (2016) and take an embodied view of design, a view in which physical models are central to design creativity. An embodied view of design brings forth a methodological breakthrough: it allows us to look at perceptuomotor processes in exploratory model-making as a form of design cognition. In my research, I focus on gaze behavior which can be studied using eye tracking technology.

Eye tracking is the process of measuring an individual's point of gaze to reveal where a person looked, in what order, and for how long (Duchowski 2017). Two eye movements commonly are of most interest: saccades and fixations. The former are rapid eye motions that occur 3-4 times per second to sample different regions of the visual field, and the latter are the brief pauses between saccades to process visual information from said regions (Richardson et al. 2007). Eye movements are driven by bottom-up and top-down factors: gaze is pulled by salient elements in the visual field and pushed to specific locations by cognitive influences (p332). They not only provide a measure of but also exert influence in cognitive processing: as other perceptuomotor processes, they are real-time manipulators of cognition (Spivey et al. 2009). Crucially, because of how fast and metabolically cheap they are, eye movements have an elicitacion threshold significantly lower than other human behavioral responses. This means they hint at cognitive processes that do not trigger any other behavior and that would go otherwise unnoticed (Spivey et al. 2009).

My thesis aims to leverage eye tracking to increase our understanding of the design cognition behaviors that underlie exploratory model making and, in doing so, provide an empirical basis to inform the development of digital tools that empower designers' creative work.

PROBLEM STATEMENT AND RESEARCH QUESTIONS

In order to effectively support exploratory model making, computational design tools need to deploy 'designerly' behaviors opportunely during their synchronous interactions with designers.

Be it an augmented reality head-mounted display or a robotic arm, information about the design cognition processes that occur during the model making activity is needed in real time as it unfolds. The challenge is twofold: the system needs to attain an understanding of the designer's cognitive behaviors, and must do so in a continuous, near real-time fashion. A methodology to do this has not been formalized in Architectural Design nor in Design Studies.

Eye tracking is a good candidate to tackle this challenge. While it is not a commonly used research methodology in architectural design (Goldschmidt 2014), it has long been applied with great success in several other domains (Duchowski 2017). The eye tracking literature suggests gaze behavior highly correlates with motoric action in natural tasks; varies significantly as a function of cognitive demands; and is often modulated by level of expertise. Thus, the following research questions are formulated:

1. What are the gaze behaviors of designers during exploratory model-making?
2. How do these gaze behaviors correlate with motoric action and high-level design strategies?
3. How are they affected by design task and modulated by level of expertise?

METHODS

I will conduct two eye-tracking studies. The first consists of a real model-making activity and aims to capture the oculomotor action that accompanies high-level design behaviors. The second is screen-based and uses two-dimensional stimuli to delve into the specific design cognition mechanisms that underlie these behaviors. The two studies are complementary: they operate at different levels of analysis and are based on different eye-tracking paradigms (Table 1). Taken together, they will contribute to our incipient understanding of the cognitive bases of exploratory model making.

STUDY 1
GAZE BEHAVIOR OF EXPERT DESIGNERS DURING EXPLORATORY MODEL MAKING

Description: Study 1 will look for correlations between gaze behavior, motoric action, and design cognition during a model making task. In a pilot of this study run in early 2020 (Harvard IRB20-0001), I preliminarily found that while most fixations relate to motoric action, others are elicited by high-level, analytical design scrutiny of the model and do not correlate with any discernible action. The study consists of three model-making tasks involving the manipulation of intricate wooden blocks to produce larger aggregations. The tasks vary in level of abstraction and design complexity to elicit a wide range of design and gaze behaviors (Table 2). Participants wear a portable eye tracker while conducting the tasks (Figures 3 & 4).

Rationale: The study draws from eye tracking research on natural tasks involving dexterous object manipulation (e.g. Land et al. 1999, Pelz and Canosa 2001). Evidence shows that in these activities, eye movements are predominantly driven by top-down task demands and are tightly coupled with motoric action. The low-level contributions to eye movement control commonly observed in laboratory-based experiments (e.g. Itti and Koch 2000) are overwhelmed by the need to direct attention towards information-rich, task-relevant locations in the visual field. Study 1 explores if and how these findings generalize to a creative model-making scenario, and what oculomotor behaviors are specifically elicited by the creative nature of this design praxis.

Hypotheses: (i) Task unrelated fixations will be minimal; (ii) most fixations will anticipate or accompany block picking and manipulation and will be classified as either l*ocating, look-ahead, guiding* or *checking* (Land and Tatler 2009); (iii) some fixations will not anticipate or accompany any discernible action; (iv) fixations' spatial and temporal characteristics will be modulated by design behavior.

STUDY 2

EYE MOVEMENTS IN VISUAL DESIGN COGNITION TASKS WITH EXPLORATORY MODELS AS STIMULI

Description: Study 2 will explore how designers and non-designers' eye movements during visual inspection are affected by high-level design tasks. The stimuli will be computer-generated images of three-dimensional exploratory models. The design tasks will be designed to make participants engage in two cognitive processes that I hypothesize participate in exploratory model making: *mental imagery* and *semantic signification.* I expect the correlations between task and oculomotor behavior to be significant enough to decode task and stimulus using gaze data. Furthermore, I anticipate the correlations will be modulated by participants' level of design expertise.

Rationale: Pioneering work by Buswell (1935) and Yarbus (1967) showed the top-down effect of task on oculomotor behavior. In absence of an explicit visual task, fixations are controlled by the visual stimulus' low-level saliency and semantic features (Tatler 2014). However, high-level cognitive tasks dramatically affect eye movement patterns, even for the same stimulus. Statistical and probabilistic methods have proven this effect to be so marked that eye movement patterns decode task (e.g. Borji and Itti 2014, Haji-Abolhassani and Clark 2014). Borji and Itti (2014) concluded that successful task decoding is achievable but depends on how inherently different the tasks are, how much information each stimulus contains, and how knowledgeable the observers are.

Hypotheses: This study is still under design. The following hypotheses are very general and referential only:
(i) Fixation patterns will decode design task and stimuli above chance level; (ii) oculomotor metrics will predict level of expertise; (iii) Fixation patterns of designers will reveal *semantically rich areas* in exploratory models (Wang et al. 2018).

EXPECTED CONTRIBUTIONS

1. Validate portable eye-tracking as a research method to study architectural model-making. I aim to achieve this by replicating results from validated research conducted in other fields of study.

2. Demonstrate the correlations between eye movements and high-level design behaviors in a real model making task.

3. Demonstrate that gaze data can be used to decode design task above chance level in controlled, laboratory settings.

4. Develop a preliminary framework of the cognitive bases of model-making, based on the results of my studies.

FIGURES AND TABLES

STUDY	SETTING	TYPE OF EYE TRACKER	PARADIGM	STIMULI	SAMPLE SIZE	ANALYSIS METHOD
01	Real-world	Head-mounted (Pupil Core)	Behavioral	Wooden blocks	8 - 10	Protocol analysis
02	Laboratory	Table-mounted (Eye Link 1000)	Computational	2D renderings	30 - 50	Statistical analysis

TABLE 1 - Summary of differences between studies 1 and 2.

TASK	DESCRIPTION	SUBTASKS	LENGTH	DIFFICULTY	DESIGN SCOPE	DESIGN STRATEGY	ABSTRACTION
01	Copy blocks from image	5	6:00	Low to med.	Non-design	Mimetic	Iconic
02	Do aggregations that meet condition	4	8:00	Med. to high	Proto-design	Convergent	Indexical
03	Design high-rise building	n/a	No limit	High	Design	Divergent	Symbolic

TABLE 2 - Summary of study 1 experimental tasks.

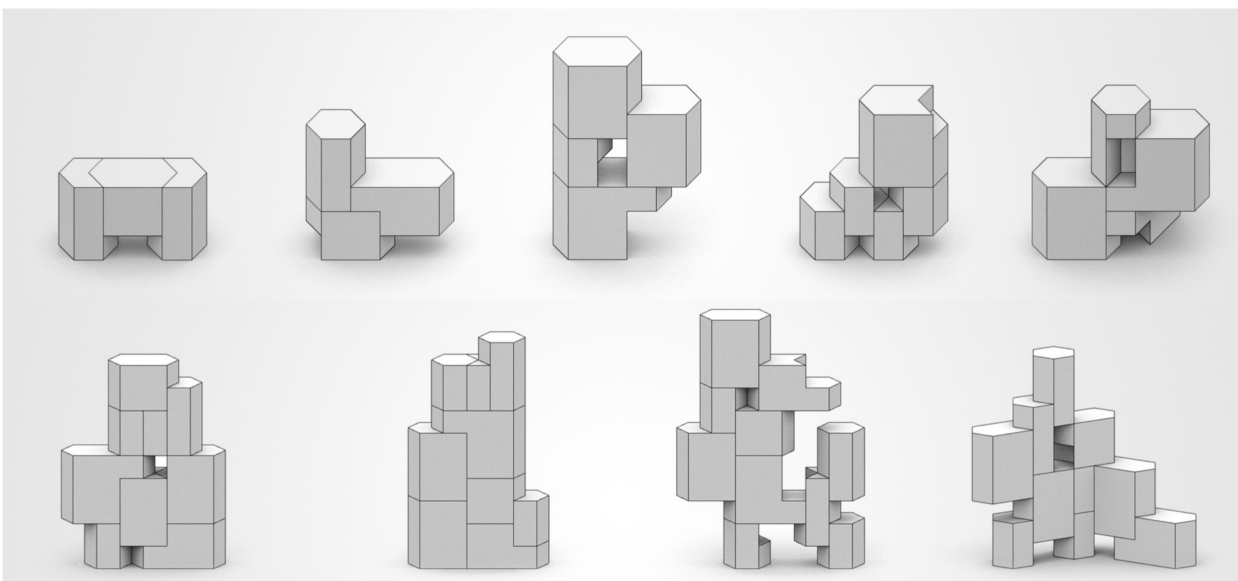

FIG. 1 - Stimuli for study 1 subtask 1 (top row) and subtask 2 (bottom row).

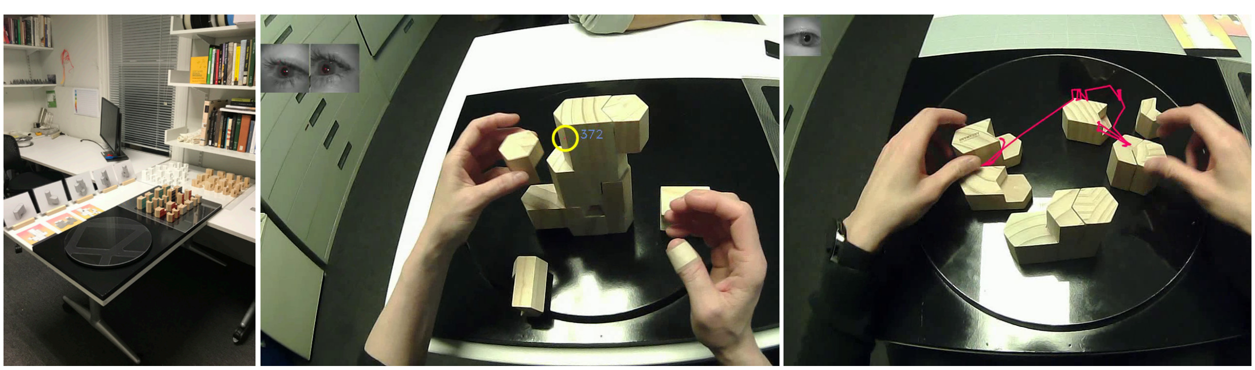

FIG. 2 - Screen captures of the eye-tracker footage during study 1 pilot.

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