Modeling Cognitive Processes in Design from the Designer's Perspective
Towards a computational model for implementing intentional capacities in digital systems

○ Yuval KAHLON [*1] and Haruyuki FUJII[*2]

*1 Assistant Professor, Tokyo Institute of Technology, D.Eng.
*2 Professor, Tokyo Institute of Technology, D.Eng.

Summary: Inquiry into design cognition is important for the progress of artificial intelligence. This research aims to model a well-known cognitive phenomenon often referred to as "seeing as", which plays an important role in designing. In short, seeing as consists of the ability of a human subject to attribute various meanings to the same object. This phenomenon is tightly linked with the cognitive process of interpretation - a major component of human design processes. Accordingly, its elucidation is expected to help implement human-like design capabilities within computational systems. In this study, we collect and analyze empirical data from a design task, developed to enable us to closely observe of this phenomenon. We then present an approach for systematically modeling seeing as, which serves as a first step toward its implementation within computational design systems. Our model integrates state-of-the-art frameworks for design cognition with the highly important notion of intentionality from the philosophy of mind. As such, it serves as an invitation for constructing a bridge between these rather disparate disciplines. By applying our model, we suggest implications for studying design cognition phenomena, towards the construction of artificial agents which can design in a human-like manner.

Keywords: Design science; intelligent systems; intentionality; architectural design.

1. Introduction

Since design can be regarded as a highly intelligent human activity[1], its study is important for the development of artificial intelligence (AI). One field of design science which is relatively well-developed is the study of human interpretation processes. Specifically, much research was dedicated for understanding how architects interpret visual representations, as they engage in various architectural design tasks. As a key example, see the famous work by Schon and Wiggins[2] , in which various kinds of seeing were explored, in the context of designing simple architectural layouts.

Past research has shed light on how designers give meaning to visual objects, mainly by identifying and describing various cognitive phenomena related with this activity. However, to mobilize these insights into AI, the knowledge gained from such studies should be both synthesized and formalized. This research takes a step forward in this direction, by attempting to construct a computational model for design interpretation processes. To do so, we not only draw on past studies, but also on empirical data gathered specifically for our goals.

In this work, we closely observe, document and analyze interpretation activity, in the context of architectural design. A model for this activity is proposed, as a step towards implementation of human-like interpretation capabilities in computational design systems. Our model is presented and discussed. In this, we point out key limitations, as well as outline potential directions for realizing such capacities in digital design systems in the future.

2. Background

2.1. MODELING VISUAL INTERPRETATION IN DESIGN

Interpretation is a fundamental process in design[3]. In this work, we focus on a major aspect of human interpretation processes, which is the phenomenon of "seeing as" (SA)[4]. Simply put, people can look at one thing and (somewhat intuitively) interpret it in various manners (Fig.1).

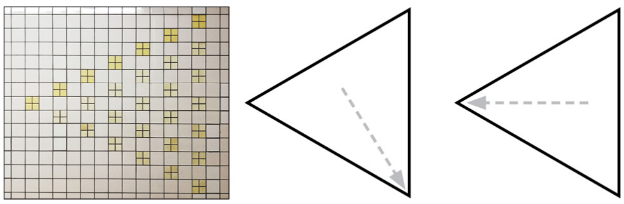

Figure 1. The phenomenon of SA: a set of yellow square-shaped wall tiles can be seen either as a downward pointing arrow or as a left pointing arrow.

One important role of SA in design is to enable designers to escape situations of fixation, by envisioning design alternatives. Consequently, it facilitates high flexibility in terms of thinking and action, which characterizes human design processes. We aim to replicate this valuable human ability in digital design agents, as to facilitate a high degree of adaptivity, which is essential for

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dealing with complex design tasks. To date, research on this topic mainly provided us with qualitative descriptions of SA, via observation of human design processes[2),4)]. However, taking the computational approach to mind, we believe that a deep understanding of SA would require to go beyond observation and into modeling this practice, for its implementation in a computational system. Accordingly, we strive for a computational model of SA, by drawing on state of the art frameworks in design cognition research.

In this work, we utilize Gero and Kannengiesser's situated function-behavior-structure framework (situated FBS)[5)], as a model for systematically describing human design processes. In situated FBS, cognitive activity in design is distributed across three worlds: 1) external world: in which things outside of the designer are noticed; 2) interpreted world: in which objects are assigned with meaning by the designer; 3) expected world: in which the designer imagines the desired state of the world in the future, to be achieved by designing.

As the situated FBS framework acknowledges the aspect of interpretation, we find it useful for our purposes. However, the framework can be enriched via the inclusion of a central aspect of human cognition – that of intentionality (taken from the philosophy of mind, see 2.2). This work takes a step in this direction of constructing a bridge between design cognition and intentionality, as a means for providing a systematic account of how we engage in interpretation.

2.2. INTENTIONALITY

Simply put, all thought is directed towards something, be it concrete or abstract. Such directedness towards objects is referred in the philosophy of mind as our "intentional capacity" or simply "intentionality"[6)]. It is critical that any framework for design cognition will include this notion in some form, since it is a fundamental property of the human mind.

As explained by Searle, intentionality theory attempts to provide an account of how the mind relates with the world.[7)] Two concepts proposed by Searle are important here: "intentional content" (what one thinks about) and "direction of fit". The latter was introduced to emphasize the difference between mental states like perceiving, in which we fit our thoughts to what exists in the world outside of us (therefore, we say that perception has the direction of fit of "world-to-mind"; WTM) and desiring, in which we wish to change the state of the world based on the contents of our thoughts (thus having the direction of fit called "mind-to-world"; MTW). The above concepts are used in this study to model interpretation activity, by noting the mental content held at certain moments in time by a human designer, and how it relates with the world at that instant.

3. Methodology

3.1. OVERVIEW

We devised a simple design task that will enable observing interpretation by human designers, as they engage in architectural design (which is the dominant design domain utilized in existing studies of such phenomena, as previously mentioned). The specific context selected for this purpose is that of Japanese rock garden (JRG) design, for several reasons: primarily, JRGs consist of forms (rocks) which are meaningful in the sense that they encourage "Mitate (見立て)", i.e. SA, in design (Fig. 2). Additionally, their minimalistic nature enables deep observation and analysis of this highly complex phenomenon, in a manner which is extremely difficult (in fact, potentially impossible) to achieve in real-world design scenarios. The possibility of such a deep inquiry is further facilitated by their emphasis on a single functional aspect (that of appreciating visual forms), which serves to reduce the immense complexity involved in simultaneous consideration of multiple conflicting aspects and requirements (characteristic of many other types of design contexts and tasks, such as designing residential units etc.).

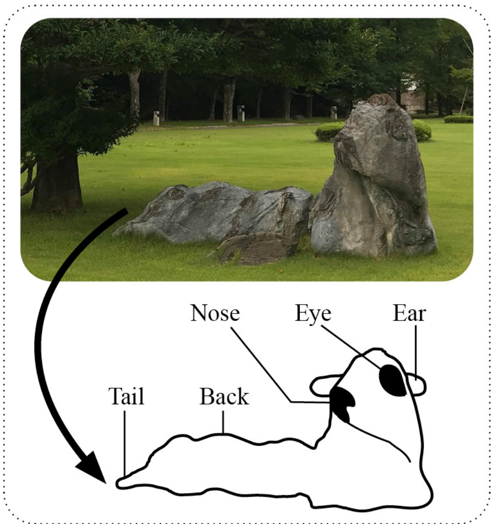

Figure 2. SA in a Japanese garden; large rock representing a cow resting on grass; Nijojo, Kyoto (photo by Jiang Ming; with permission).

3.2. TASK AND DATA COLLECTION

Since the cognitive ability of SA is not limited to design specialists[1], we did not place strong emphasis on collecting data specifically from highly skilled designers, considering the exploratory phase of this work. Ten architectural designers aged 22-30 were recruited for the study (male: 7, female: 3) in varying levels of skill and education. The minimal requirement was that of a Bachelor's in architecture or in a related design discipline.

Each subject was requested to design a miniature rock garden to his/her liking, while verbalizing one's thoughts by designing in a "think aloud" style. Several rocks in various forms were available as design materials, and a small wooden tray with a bed of white sand was provided as the "site" for the design. Each session was capped at one hour, where in several cases the subject wished to continue and work on his/her designs for a short while beyond the allotted time. We captured: 1) audio data of subjects' utterances, and 2) video data of the physical state of the design, as it developed throughout the session.

3.3. DATA PROCESSING AND ANALYSIS

As a basis for analysis, data was processed as follows: 1) full transcriptions of utterances were prepared, including all utterances both by the research subject and by the moderator; 2) the video data was used for extracting images which represent changes to the state of the physical model, as to form sequences of representative frames; 3) utterances which accompanied each step were added next to the corresponding image, resulting in visual protocols.

To identify events of SA and extract interpretations assigned by designers to the design materials (rocks, sand etc.), we then reviewed the visual protocols and marked places where SA events occurred. Identification is done either based on explicit utterances, in which similarity between a rock and a referent was pointed out (e.g. "this rock looks like a tree"), or by metaphorical utterances with respect to how the designer views the rock (e.g. "this rock is a mountain"). SA and non-SA events were then organized sequentially within the three worlds of situated FBS (Fig. 3). From these we derived the relevant entities which need to be accounted for in order to replicate this process in a computational design system.

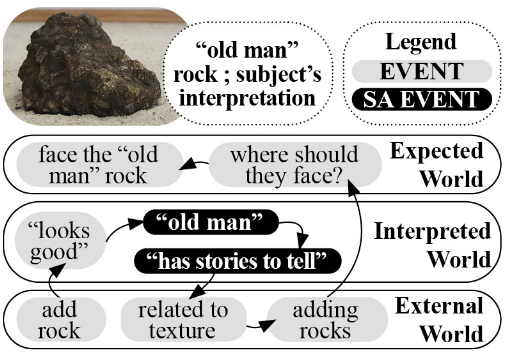

Figure 3. Example for dissection into events using situated FBS.[5)]

The mapping method developed throughout the analysis was used to create visual representations of the designer's perspective at a given time, which enable to derive insights regarding important events characterizing the process of SA. Based on these, we drew insights for modeling the phenomenon under consideration, towards its elucidation and implementation within computational systems.

4. Results

Utterances in a single session amounted to ~2050 words on average. Surprisingly, while subjects were not instructed to employ SA, all sessions included at least one SA occurrence. To explain our proposed modeling approach, we present one such example. A subject formed a composition of a person riding a turtle, which he later associated with the famous Japanese fairy tale of Urashima Taro (Fig. 4). In this fairytale, the protagonist (Urashima Taro) rides a turtle into a hidden kingdom found in the depths of the ocean.

By examining this short segment we can readily identify several consecutive events of SA. Reading the figure from top to bottom, we notice that the designer first sees two similar rocks as "twins" (1). Then he sees another rock as "a turtle" (2), leading him to search for a "head" (3) and see another rock as "a turtle's foot" (4) etc. Breaking such interpretation processes down into series of small steps enables us to gradually trace the chain of events which characterized the formation and elaboration of the SA that was employed in each case. In the following section, we apply our model to this small segment, and demonstrate how close observation can aid in developing a deep and systematic understanding of the processes involved in SA, towards its modeling and implementation in computational systems.

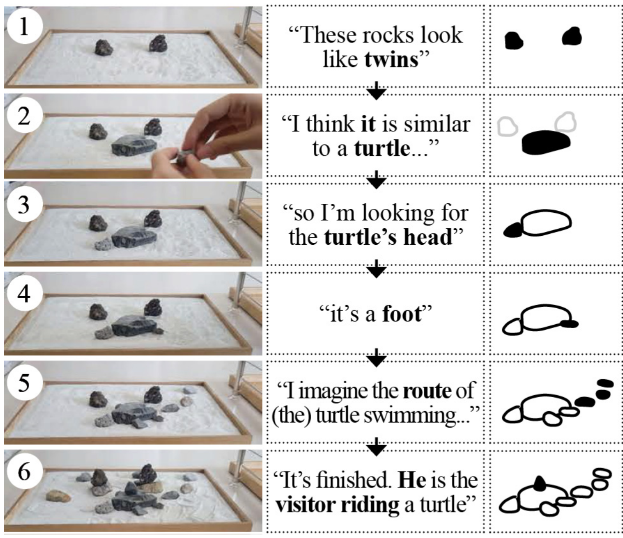

Figure 4. Example for an interpretive process driven by SA, extracted from a design session of a novice research subject.

5. The proposed model

5.1. KEY TERMS AND DEFINITIONS

We outline key terms which serve as the basis for our modeling approach, demonstrated in the following sub-section. First, we distinguish between two main design worlds ("World", "Mind") according to the work by Searle (introduced in 2.2) and relate them with the situated FBS framework (introduced in 2.1). We then introduce key entities which we view as essential for modelling SA processes. Important definitions are given below in Table 1. Note that, in addition to these, the term "direction of fit" is used in accordance with the definition by Searle[7], preserving his basic distinction between "world-to-mind" direction and "mind-to-world" direction (WTM and MTW, accordingly; the reader may refer back to 2.2).

Table 1. Key terms and definitions.

Term	**Definition**
World	External reality, which is accessible to an agent through his senses; generally corresponds with the external world in situated FBS.
Mind	The totality of internal mental content at any moment (containing both the interpreted and expected worlds in situated FBS).
State	A time duration in which change is not observed.
Concept	A linguistic (symbolic) expression which identifies & classifies an object.
Interpretation	Meaning given by an agent to an object, given as a symbolic linguistic expression.
Mental image	Non-symbolic mental content held by an agent at a certain moment in time as means for search.

5.2. APPLYING OUR MODEL

We apply our model on the short segment previously presented in Fig. 4. Specifically, we focus on the second and third steps, in which the designer notices that a rock can be seen as a turtle, and then finds another rock to represent the turtle's head. This process is visualized in Figure 5, which should be read from top to bottom. Table 2 serves as complementary to this figure, and summarizes the values associated with each entity in the selected segment.

As a first step (state 1) an object (ob1) in the World is noticed (or1) and recognized as a rock (c1). Next (state 2) the rock is said to be seen as a "turtle" (I1). However, later we discover that the intended meaning was that it looks like a turtle's body or its shell. Therefore, the actual interpretation is such that the rock is seen as a "turtle's body" (i1; an interpretation which remains implicit yet can be safely inferred). This interpretation is projected onto the real rock (f2). Following this the subject is "looking for the turtle's head" (state 3). In this case, we see that a mental image (m1) appears in the Mind. This mental image serves as a means for finding a rock that can serve as the "head"[2]. This brief search episode is characterized by a two-sided direction of fit (f3, f4), i.e. both WTM and MTW (more in 6). Finally, a candidate rock for the head of the turtle is found (ob2), and consequently the mental image of the imagined "head" fades away, as it is no longer of use to the designer, at least for the time being.

This application of our model enables us to closely examine the components and processes involved in visual interpretation and ask essential questions regarding the nature of SA as a cognitive process. In the next section, we raise several such questions, and hypothesize regarding potential answers for these, based on our insights from this study thus far.

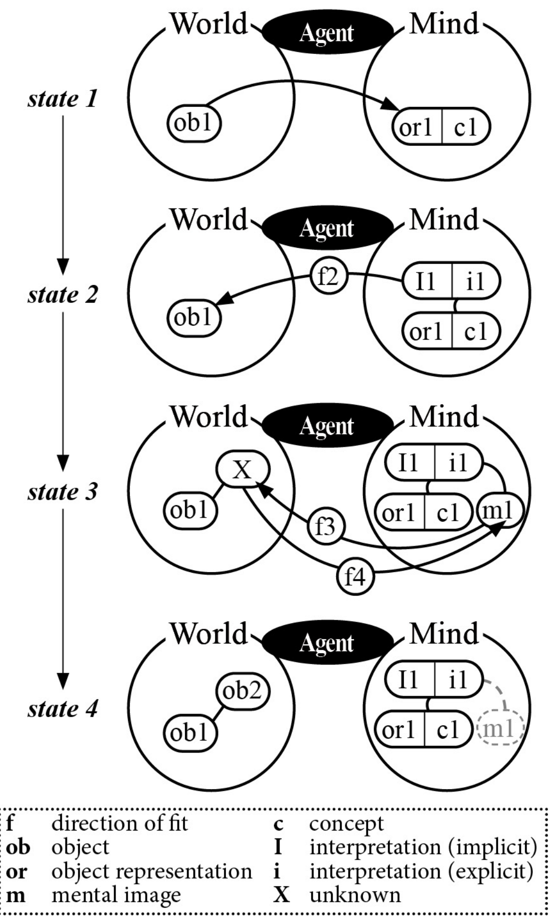

Figure 5. Close examination of events in SA using our model.

Table 2. Values associated with the entities in Figure 5.

Entity	**Associated value**
c1	"rock"
I1	"like a turtle"
i1	turtle's body
f1	perception
f2	projection (MTW)
X	future "turtle's head"

m1	search image; "turtle's head"
f3	evaluation in search (MTW)
f4	perception in search (WTM)

6. Discussion

6.1 IMPLICATIONS FOR MODELING SA

When examining the above visualization, the following fact is striking – there seems to be no necessary connection[3] between states 1 and 2. In state 1 the designer picked up a rock, and in state 2 he declared it looked "like a turtle". The key question that we should raise here is this: why did the designer engage in SA in state 2? Did he consciously decide to do so, or was driven to this by a trigger of some sort (visual/haptic/other)? These questions are highly important, since we cannot construct a computational design agent which interprets objects in a human-like manner if we do not know how behavior is regulated when designing. In other words, we need to know how (or when) do designers decide to utilize one cognitive strategy (SA) rather than another one (for instance, focusing on the aesthetic dimension without interpreting the rock using any referent).

Another important observation which can be made by examining our visualization, is the following - state 2 has led to the production of a mental image which directed (if not governed) the action in state 3. This mental image, which specified how a "turtle's head" should be represented is unique to the subject in several ways: first, it depends on his past knowledge, which is in-turn derived from his personal background etc. Second, and more obviously, it cannot be experienced by anyone else, i.e. it is purely subjective. The fact that such subjective mental images (which are inaccessible to direct scientific inquiry to date) drive action means that we can never realistically model human designing without providing an explanatory model for subjectivity, and the ways in which it shapes thinking and action. Therefore, we must develop methods for externalizing such mental images so that they can be studied and modeled as computational processes as well.

Finally, extending the previous point, notice that the activity of finding the desired rock using the mental image can neither be characterized solely as a WTM or MTW process. Instead, we see a mind-to-world-to-mind loop, as the designer not only imposes the mental image on the world when looking for a rock which fits it (f3), but also considers potential candidates in the world which are not initially included in the mental image (f4). By jumping back and forth between the desired object and the available ones, the designer can locate a successful candidate to fill the design requirement and make progress in the design process. This exemplifies the potential of our model as a tool for making sense of complex processes involved with SA, via their description in terms of simpler processes, which can be inquired into via intentionality theory.

6.2. LIMITATIONS AND FUTURE WORK

First, the current model deals with organizing and representing the mental content of designers and its relation to external reality. However, in practice, mental content is almost always associated with a certain type of mental state. Therefore, our account must also include the aspect of types of mental states, and the way in which they relate with mental content. One potential direction is to employ well-established models from AI, such as the belief-desire-intention architecture, or simply BDI[8)].

Second, while currently we model SA by capturing key components within symbolic terms, human cognition has a sub-symbolic aspect as well[9)]. For example, when our subject uttered the word "turtle" in SA, the word was further associated with mental images which cannot be reduced to any single linguistic or symbolic term. Such aspects may be integrated into the model by adding a computational layer to serve as grounding for symbolic terms, facilitating their assignment and manipulation. To make progress in this direction, we may employ recent methods in AI, which enable us to capture patterns without explicit representation, and associate them with single symbolic terms in the memory (e.g., by using supervised learning methods).

Further, note that in Searle's theory we do not only have mental states with a type and content, but also a "background" which they operate against. The difficulty with integrating this idea into the work lies in the fact that, for Searle, the background is "non-representational". However, recently it was proposed by Schmitz that, rather than non-representational, it may be better to regard it as non-conceptual[10)]. In this manner, and by drawing on the idea of including a sub-symbolic layer mentioned above, the background may be subsumed into future models for computational design agents. We believe that striving in this direction would require modeling not only mental content but also additional aspects of the agent, such as embodiment, social environment, etc.

Lastly, it should be made explicit that the current model does not consider the aspect of functionality, which is central to designing. As previously noted, we have resolved to use JRGs for this study in order to simplify the highly complex process of interpretation. JRGs enabled to achieve this, at the cost of oversimplifying the aspect of functionality (as one of their primary functions is a representational one; i.e. function is almost identical with interpretation). To further develop the model and integrate this important aspect, we intend to examine such design activity in the context of Chinese traditional gardens, as these not only include rocks, but also enable the visitor to interact with them (by touching, climbing etc.).

6. Conclusion

An approach for modeling SA, which is a key cognitive ability in design, was proposed and demonstrated. Our findings' importance is twofold: 1) it was demonstrated that certain aspects of SA can be described using symbolic terms, which may serve as a basis for future computational implementations; 2) the analysis conducted using our method also points to the necessity of developing methods for studying subjective aspects of cognitive phenomena in design, as an essential step towards modeling for human design processes. In the absence of such methods, any model which attempts to explain human behavior in design, and specifically the important ability to engage in SA, will remain partial at best. The proposed model serves as a starting point in this journey, in two key-aspects: in identifying and elaborating the components of SA processes, and in aiding to expose gaps in our current understanding. As such, it can be used to construct a road map for achieving human-level interpretation capabilities in AI systems which target design tasks, and direct our inquiry as we move into this uncharted territory.

Acknowledgements

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Endnotes

1. In fact, in a previous experiment we have witnessed children as young as eight naturally engage in SA, when presenting them with a set of rocks in various forms. These children did not have any educational background in design.
2. This image can be considered as a "search image" – a term proposed in the thought-provoking work by Jakob von Uexküll, as an explanation of how animals retrieve desired objects[11].
3. The idea of necessary connection has long been a challenging topic for philosophical debate. Hume has even argued that it is merely an illusion, which stems for the frequent observation of seeming regularity in the world[12]. For all practical purposes however, we can establish that a necessary connection exists when causal relations can be assumed with a high degree of confidence. For example, between the sun rising and the fact that there is light.

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