DESIGN THINKING, FAST AND SLOW
A Framework for Kahneman’s Dual-System Theory in Design

Udo Kannengiesser and John S Gero

Abstract. In his book Thinking, Fast and Slow Daniel Kahneman presented a model of human cognition based on two modes or “systems” of thinking: system 1 thinking that is fast and intuitive, and system 2 thinking that is slow and tedious. This paper proposes a framework for applying Kahneman’s model to designing, based on the function-behaviour-structure (FBS) ontology. It casts four instances of designing in this framework: design fixation, case-based design, pattern language-based design, and brainstorming.

1. Introduction
In recent years design researchers have increasingly attempted to establish links between the design domain and the broader area of cognitive science. This aims to foster the development of common models and theories across the two domains, and to remove some of the inconsistencies within design research by relating them to more established notions and terms in cognitive science (Hay et al. 2017). In addition, this can provide design practitioners access to a new range of methods and tools such as creativity tools (Howard et al. 2008).

One well-established model of human thinking from cognitive psychology that is supported by numerous empirical studies is the dual-system theory, or sometimes called dual-process theory (Wason and Evans 1975; Sloman 1996; Stanovich and West 2000; Kahneman and Frederick 2002; Evans and Stanovich 2013). It has been popularised by Daniel Kahneman, in his book Thinking, Fast and Slow (Kahneman 2011). According to this theory, human cognition is governed by two systems: system 1 for fast, intuitive and effortless thinking, and system 2 for slower, analytic thinking that requires greater cognitive effort. System 1 is assumed to govern much of our daily behaviour. It is only when the fast responses generated by system 1 do not produce the results expected that system 2 comes into play. Dual-process theory challenges common beliefs of
ourselves as rational beings that process information and take decisions objectively and analytically.

In this paper we examine the link between dual-system theory and a special area of human cognition: design thinking. Design thinking has a tradition as a scientific study (e.g. Simon (1969)). More recently, it has been understood as a notion covering a set of techniques for stimulating creative solutions to problems in business, education and social domains (Brown 2009, Verganti 2009, Liedtka and Ogilvie 2011). In our present work, we relate dual-system theory and design thinking based on the function-behaviour-structure (FBS) ontology, that is independent of the specific design methods used or the domain of the design. System 1 design thinking is shown as a new process within the FBS ontology.

The paper is organised as follows: Section 2 describes the foundations of dual-system theory mainly based on Kahneman’s (2011) account. Section 3 presents previous research on design thinking and its relation to fast and slow modes of reasoning. Section 4 introduces the FBS ontological model of design thinking. Section 5 represents the two systems in the FBS ontology and explains how they interact. Section 6 casts instances of fast and slow design thinking in this ontology. These cover design fixation, case-based design, pattern-language based design and brainstorming. Section 7 concludes the paper with a summary and discussion of future work.

2. Dual-System Theory
According to dual-system theory, human cognition has two distinct types of thinking: one that is fast, automatic and effortless, and one that is slow, analytic and effortful. This theory originates from the 1970s (e.g. Wason and Evans 1975) and is now well established with a large amount of experimental evidence in cognitive psychology and neuroscience. While the two types of thinking are independent of particular areas in the brain (Evans and Stanovich 2013), Kahneman (2011) refers to them as “system 1” and “system 2”, respectively. He does this to enable his readers to conceptualise them as two different characters with distinct “personalities” rather than as abstract concepts, and thus to facilitate understanding. In this paper, we will also use Kahneman’s terms.

Most of Kahneman’s (2011) book is about system 1. This is because its influence on human reasoning is underestimated by many people, who are commonly convinced about the rationality and objectiveness of their beliefs, decisions and actions. Kahneman shows that system 1 is involved in a large part of human reasoning, which becomes most evident by the many systematic errors of judgement (also called cognitive biases). One of the examples provided by Kahneman (2011, p. 44) is based on the so-called “bat-and-ball problem”: 
“A bat and ball cost $1.10.
The bat costs one dollar more than the ball.
How much does the ball cost?”

While the correct answer to this problem is 5 cents, most people’s intuition tells them it is 10 cents. The fast but wrong response generated by system 1 in this case was not challenged by system 2. The reason is on the one hand that system 1 is “overconfident”. On the other hand, system 2 is “lazy”: It directs attention for system 1 and then relies on its automatic response, rather than spending effort in checking the correctness of that response. Errors are detected only when they are obvious or when a likely risk of failure is known in advance.

Despite the various fallacies of fast thinking, system 1 also provides a tool for responding to uncertain or ambiguous situations where the use of analytical reasoning would be impossible or impractical. This is done by what Kahneman calls “substitution”: replacing complex problems by simpler ones. For example, the question “How happy are you with your life these days?”, which may be rather difficult to answer analytically, can be substituted by the simpler question “What is my mood right now?”, which can be answered quite quickly by system 1 (Kahneman 2011, p. 98). Substitution thus provides us with imperfect yet often adequate answers to difficult questions.

The use of system 1 in these situations is not completely under our control. Kahneman illustrates this with a well-known optical illusion of the kind depicted in Figure 1. As printed on the page, the three human figures are of equal size. Yet, the figure on the left appears larger than the one on the right. This is because the cues contained in the image suggest a 3D interpretation, making system 1 automatically substituting the question posed in the caption of Figure 1 with the following: “How tall are the three people?” (Kahneman 2011, p. 101).

The three-men example shows that another characteristic of system 1 is that it performs many computations at once, many of which are contextual and beyond our conscious control. Kahneman (2011, p. 95) calls this the “mental shotgun”:

“[…] we often compute much more than we want or need. I call this excess computation the mental shotgun. It is impossible to aim at a single point with a shotgun because it shoots pellets that scatter, and it seems almost equally difficult for System 1 not to do more than System 2 charges it to do.”
Figure 1. Are the three figures, as printed on the page, of different size?

A summary of characteristics commonly ascribed to system 1 and system 2, respectively, is provided in Table 1. It is based on a list of attributes compiled by Evans and Stanovich (2003).

<table>
<thead>
<tr>
<th>System 1</th>
<th>System 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does not require working memory</td>
<td>Requires working memory</td>
</tr>
<tr>
<td>Autonomous</td>
<td>Cognitive decoupling; mental simulation</td>
</tr>
<tr>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td>High capacity</td>
<td>Capacity limited</td>
</tr>
<tr>
<td>Parallel</td>
<td>Serial</td>
</tr>
<tr>
<td>Nonconscious</td>
<td>Conscious</td>
</tr>
<tr>
<td>Biased responses</td>
<td>Normative responses</td>
</tr>
<tr>
<td>Contextualised</td>
<td>Abstract</td>
</tr>
<tr>
<td>Automatic</td>
<td>Controlled</td>
</tr>
<tr>
<td>Associative</td>
<td>Rule-based</td>
</tr>
<tr>
<td>Experience-based decision making</td>
<td>Consequential decision making</td>
</tr>
<tr>
<td>Independent of cognitive ability</td>
<td>Correlated with cognitive ability</td>
</tr>
</tbody>
</table>

3. Does a Fast Mode of Design Thinking Exist?
Designing is commonly viewed as a complex activity that is not associated with a fast, effortless mode of thinking. Most design processes in industry take place within timeframes of weeks and months, and in some cases...
several years. Even the accomplishment of design exercises in university classrooms takes at least a couple of hours – which is very slow compared to most instances of fast, intuitive thinking provided by system 1. Yet, a number of theoretical and empirical studies show that a fast mode of thinking does play a role in design, at least for parts of the design process.

Fostering fast design thinking has been one of the goals of research in design methods. For example, “design catalogues” (Roth 2000), “selection charts” (Pahl and Beitz 2007) and “design patterns” (Alexander et al. 1977; Gamma et al. 1995) can be viewed as methods for increasing the efficiency with which designers come up with design concepts and solutions. They are based on collections of existing design solutions that are indexed and stored for fast reuse by designers when confronted with similar design problems.

Recent studies examine the role of intuition or “gut feeling” in design. Badke-Schaub and Eris (2014) characterise design intuition as holistic, fast, multisensory and experience-based. In addition, they see intuition as related to unconscious processes, emotions and creativity. They propose a framework of design thinking that integrates intuitive and rational decision making. Taura and Nagai (2017) examine the role of intuition in creative design, distinguishing two kinds of intuition: experiential and associative intuition. Experiential intuition uses previously grounded patterns of experience, and associative intuition combines sets of different experiences. The notion of grounding refers to the construction of design experiences based on the interaction of designers with their current view of the world that is formed by their previous experiences and interactions (Gero 1999).

Research in design computing has come up with three modes of reasoning (Maher and Gero 2002) – reflexive, reactive and reflective reasoning – in a design agent that imply different speeds with which they are carried out.

**Reflexive** reasoning is a direct response of the design agent to specific sets of stimuli. Reasoning here does not entail any internal processing or decision making; it is merely a mapping of sensory input to actions performed by the design agent’s effectors. Hence, reflexive reasoning can be considered as fast. Examples include “hard-wired”, biological reflexes, and habituated responses to recurring stimuli. One may ascribe a high degree of confidence to reflexive reasoning that the resulting actions will produce desirable outcomes. This confidence is implicit in the actions rather than an explicit, cognitive state of the agent.

**Reactive** reasoning involves a limited form of interaction between various of the design agent’s internal representations. This interaction can be viewed as the process of selecting among several alternatives the most appropriate schema given the stimuli presented. The need for decision making leads to a lower degree of confidence associated with the outcomes of the agent’s
actions. As a result, agents assess their decisions by monitoring the effects of their actions and comparing them against a set of criteria. Reactive reasoning can still be considered rather fast but requiring slightly more time and effort than reflexive reasoning.

Reflective reasoning involves a more significant amount of interaction between a model of the external world and the design agent’s goals and concepts. It is a construction process that uses filtering, emphasising and distorting of certain aspects of the external cues, driven by changes in the agent’s expectations. The outcomes of actions devised by this mode of reasoning produce new expectations that provide new criteria for assessing these actions. Reflective reasoning is usually slow and requires high amounts of cognitive effort by the agent.

The three modes of reasoning have been used for a model of affordances (Kannengiesser and Gero 2012; Gero and Kannengiesser 2012) that shares similarities with some of the examples of fast and slow thinking presented in Kahneman’s (2011) book. The effect of learning on the three modes of reasoning has been shown computationally by Gero and Peng (2009): When experiences become more grounded in an agent’s memory, the corresponding reasoning processes over time transform from being reflective to reactive and then reflexive.

Some evidence for the existence of fast ways of thinking in design comes from empirical studies. Designers are frequently observed to “jump” to concrete design concepts right from the beginning of a design task (Ullman et al. 1988, Lawson 1994, Cross 2001; Kannengiesser and Gero 2017). This may lead to designers getting “stuck” or ignoring alternative concepts – a phenomenon commonly known as design fixation (Jansson and Smith 1991).

The designers’ preference for swift solutions rather than lengthy analyses has also been observed in other empirical studies even though they have different research goals. For example, the low acceptance of functional modelling methods by design practitioners has partially been explained by their tendency “to avoid abstract and solution-neutral thinking, […] instead preferring to work in a goal/solution-oriented fashion that swiftly leads towards a concrete result” (Eisenbart and Kleinsmann 2017). Similar observations were made by Eckert (2013) and Eisenbart et al. (2017).

4. A Framework for Design Thinking
A framework for design thinking is based on the function-behaviour-structure (FBS) ontology (Gero 1990; Gero and Kannengiesser 2014). It has been proposed as a design ontology that describes all designed things, or artefacts, irrespective of the specific discipline of designing. Its three fundamental constructs – function (F), behaviour (B) and structure (S) – are defined as follows:
Function is the teleology of the artefact (“what the artefact is for”). It is ascribed to the artefact by establishing a connection between one’s goals and the artefact’s measurable effects.

Behaviour is defined as the artefact’s attributes that can be derived from its structure (“what the artefact does”). Behaviour provides measurable performance criteria for comparing different artefacts.

Structure is defined as its components and their relationships (“what the artefact consists of”).

Humans construct connections between function, behaviour and structure through experience and through the development of causal models based on interactions with the artefact. Specifically, function is ascribed to behaviour by establishing a teleological connection between the human’s goals and the observable or measurable performance of the artefact. Behaviour is causally connected to structure, i.e. it can be derived from structure using physical or other causal-type laws or heuristics. There is no direct connection between function and structure.

The FBS ontology defines the processes of designing and design thinking as transformations between function, behaviour and structure (Gero 1990; Gero and Kannengiesser 2014). The most basic view of designing consists of transformations from function to behaviour, and from behaviour to structure:

1. \(F \rightarrow B\), and
2. \(B \rightarrow S\)

In this view, behaviour is interpreted as the performance expected to achieve desired function. Yet, once a structure is produced, it must be checked whether the artefact’s “actual” performance, based on the structure produced and the operating environment, matches the “expected” behaviour. Therefore, the FBS ontology distinguishes two classes of behaviour: expected behaviour (Be) and behaviour derived from structure (Bs). This extends the set of transformations with which we can describe designing to include:

1. \(F \rightarrow Be\),
2. \(Be \rightarrow S\),
3. \(S \rightarrow Bs\), and
4. \(Be \leftrightarrow Bs\) (comparison of the two types of behaviour).

The observable input and output of any design activity is a set of requirements (R) that come from outside the designer and a description (D) of the artefact, respectively. The FBS ontology subsumes R in the notion of function and defines D as the external representation of a design solution:

5. \(S \rightarrow D\)

Based on the common observation that designing is not only a process of iterative, incremental development but frequently involves focus shifts,
lateral thinking and emergent ideas, the FBS ontology defines the following additional transformations:

(6) \( S \rightarrow S' \),
(7) \( S \rightarrow Be' \), and
(8) \( S \rightarrow F \)

The eight fundamental transformations or processes in the FBS ontology are shown and labelled in Figure 2:

1. Formulation (\( R \rightarrow F \), and \( F \rightarrow Be \))
2. Synthesis (\( Be \rightarrow S \))
3. Analysis (\( S \rightarrow Bs \))
4. Evaluation (\( Be \leftrightarrow Bs \))
5. Documentation (\( S \rightarrow D \))
6. Reformulation type 1 (\( S \rightarrow S' \))
7. Reformulation type 2 (\( S \rightarrow Be \))
8. Reformulation type 3 (\( S \rightarrow F \))

Figure 2. The FBS ontology defining eight fundamental processes in designing

5. Locating the Two Systems in the FBS Ontology
For locating the two systems in dual-system theory in the FBS ontology, it is useful to begin with a simplified view of design thinking: as an input-output transformation, where the designer takes requirements as input and produces a design description as output. This is shown in Figure 3.
Figure 3. An input-output view of design thinking: A designer transforming requirements (R) into a design description (D)

The details of the transformation of R into D are hidden inside the designer that is viewed as a “black box” (indicated by the “+” symbol in Figure 3). In Figure 4 this black box is expanded to show possible pathways from R to D, using the processes defined in the FBS ontology. The entry and exit paths of this process system are the transformations of R into F (part of formulation, process 1) and of S into D (documentation, process 5), respectively. They correspond to activities of interpretation and action that are executed by the designer.

Figure 4. Expanding the transformation of R into D, based on the FBS ontology

In addition to the eight fundamental processes in the FBS ontology, a ninth process (2’) is depicted that transforms F into S. This additional process allows distinguishing two basic pathways between the interpretation of R and the action producing D: (1) a direct pathway provided by process 2’, and (2) an indirect pathway that involves at least four processes: 1b, 2, 3 and 4.
Since 2’ establishes a direct link between interpretation and action, it can be seen as a reflex – an immediate response to a stimulus without involving any form of reasoning. This corresponds to system 1. The reflex represented by process 2’ is based on learning a connection between stimulus and response through previous experiences of the designer. Whenever a pattern in the environment is interpreted that matches a previous stimulus, the associated response is executed as an instant reflex. Examples of pattern matching in architectural design include designing using precedents (Clark and Pause 2005).

Process 2’ can be thought of as subsuming the set of processes 1b, 2, 3 and 4, as is shown in Figure 5:

\[ 2' \theta = \{1b, 2, 3, 4\} \quad (1) \]

where \( \theta \) is a substitution\(^1\).

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\(^1\) \( g \) subsumes \( s \) if and only if there is a substitution \( \theta \) such that \( g \theta = s \)
order on an indeterminate past” (Weick 1995). This distinction corresponds to Conklin and Yakemovic’s (1991) notions of “structure-oriented” and “process-oriented” design rationale, respectively. The compilation of a design process into a single step, from F to S, can be seen as an extreme form of structure-oriented design rationale.

Designing often involves a great deal of incompleteness and uncertainty: the requirements may be unclear, conflicting or incomplete, and the environment and its possible interactions with the artefact may be unknown. Process 2’ can be a useful tool for commencing designing in these conditions, by providing heuristics (Gigerenzer and Goldstein 1996) to come up with design structures. The use of heuristics has been linked to creative concept generation (Yilmaz et al. 2015). However, designers should be wary of the fallacies of system 1 executing these heuristics (Bulleit 2013), as heuristic knowledge may be too simplified or based on insufficient information about the ranges of applicability. As system 1 is concerned only about the coherence but not the quality or robustness of the responses it generates, system 2 should become involved to avoid potentially serious design errors. It does so by monitoring the results of system 1. In the FBS ontology, this corresponds to processes 1b (setting expectations about the behaviour), 3 (analysing the structure) and 4 (comparing expected and actual behaviour). In case of failure of the generated structure (S) to meet the expectations, a new structure needs to be generated. This can be done in one of two ways: (1) by selecting the second most grounded pattern, or (2) by reformulating structure based on reflection (Schön and Wiggins 1992).

The first of the two ways of generating new structure is executed by system 1, because it is still based on pattern matching even though the most grounded pattern (which produced the failed S) is now “blocked”. In the FBS ontology, this process is captured by applying process 2’ again. It can be viewed as a new attempt of system 1 to propose an S that is part of a pattern linked to F.

The second way of producing new S is by reformulation, which in the FBS ontology is represented by process 6. As it is a reflective process, it is executed by system 2. The relationship between processes 2’ and 6 is again one of subsumption, with the necessary condition that there already pre-exists a structure, as highlighted in Figure 6:

\[(2’ \ 0 = 6) \rightarrow \exists \ S^{prev} \]

where \(S^{prev}\) is a previous structure.
Process 2’ can be executed several times, each time proposing a new structure that is first monitored and evaluated and then eventually replaced by another structure proposal. This corresponds to a process of search, in which a given (i.e. grounded) set of structure candidates is examined one by one, until a satisfactory candidate is found.

6. Instances of Fast and Slow Design Thinking

6.1. DESIGN FIXATION
Design fixation is the premature commitment on a design concept early in the process of designing (Jansson and Smith 1991). This is often perceived as an obstacle for design creativity. Fixation has been attributed to an “overactive” system 2 (Moore et al. 2014) that aims to transform initial ideas in an analytic manner (Sowden et al. 2015) without considering alternative options. We can use the FBS ontology to describe the role of the two systems in design fixation in more detail.

Fixation starts with the generation of structure (S) (or its presentation to the designer by an external source; for example, as a precedent) as a potential solution to a design problem. For fixation to occur, it is assumed that the structure causing that fixation is highly grounded and there is a strong connection between F and S. In the FBS ontology, this corresponds to process 2’.

Figure 6. After failure of the initial S, process 2’ (executed by system 1) can be used again by selecting the second most grounded pattern to be matched. Process 2’ (bold, solid arrow) subsumes process 6 (bold, dotted arrow).
Once S has been produced, it is used as the basis for generating further structures that can be viewed as elaborations of the initial S (e.g. decompositions). This is represented by process 6. It includes analytic forms of reasoning executed by system 2.

The processes involved in design fixation are summarised in Table 2.

### TABLE 2. Processes involved in design fixation

<table>
<thead>
<tr>
<th>System 1</th>
<th>System 2</th>
<th>FBS representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Generating an initial idea or concept</td>
<td></td>
<td><img src="process_2" alt="Diagram" /></td>
</tr>
<tr>
<td>2. Elaborating the initial structure</td>
<td></td>
<td><img src="process_6" alt="Diagram" /></td>
</tr>
</tbody>
</table>

#### 6.2. CASE-BASED DESIGN

Case-based design is an application of the Artificial Intelligence (AI) technique of case-based reasoning in the design domain (Kolodner 1987; Maher et al. 1995). It is based on retrieving and adapting design cases stored in memory (also called “case base”). A design case is a specific past design episode including the problem, the solution and the process for arriving at the solution (Rosenman et al. 1991). Case-based design involves the following phases: problem anticipation, search, match, retrieve, select, modify and repair (Maher et al. 1995).

*Problem anticipation:* enriches the given information about the design problem (i.e. the requirements, R) with as much implicit information as possible. This is captured by process 1a in Figure 4.

*Search, match and retrieve:* This phase aims to find an appropriate design case, based on the problem description (in terms of F) and information associated with it within the design cases. This corresponds to process 2’ that is executed by system 1.

*Select:* determines the “best” matching design case among the retrieved ones. This can be represented using processes 3 and 4, as they are concerned with analysing and evaluating alternative designs.
Modify: involves some adaptations of S to enhance the fit with the specific design situation at hand. This can be represented using process 2, where the new S is subsumed by the previous S.

Repair: is used after some performance failure of the design. This is done either by retrieving and selecting a different design case, or by modifying the existing design case. The former is captured by process 2', the latter by process 6. The new S produced by process 6 is subsumed by the previous S.

The processes involved in case-based design are summarised in Table 3.

<table>
<thead>
<tr>
<th>System 1</th>
<th>System 2</th>
<th>FBS representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Problem anticipation: formulating implicit requirements</td>
<td>Process 1a</td>
<td></td>
</tr>
<tr>
<td>2. Search, match and retrieve from existing case base</td>
<td>Process 2'</td>
<td></td>
</tr>
<tr>
<td>3. Select the best matching design case</td>
<td>Process 3</td>
<td></td>
</tr>
<tr>
<td>4. Modify S to establish a better fit with the design situation at hand</td>
<td>Process 2</td>
<td></td>
</tr>
</tbody>
</table>
5a. Repair by retrieving and selecting S of a different design case

5b. Repair by generating new S based on the existing S

6.3. PATTERN LANGUAGE-BASED DESIGN

The concept of a pattern language was introduced by Alexander et al. (1977) in the architectural design domain and has since been applied in various other domains including software design (Gamma et al. 1995), process design (Lerner et al. 2010) and educational design (Goodyear 2005; Dehbozorgi et al. 2018). Patterns are descriptions of solutions to recurring problems, including information about context and rationale. A pattern language is a representation of the interconnections between a collection of patterns.

Designing using a pattern language commences a search for potentially applicable patterns based on the problem represented as function (F). This search yields a pattern that contains a solution in terms of structure (S), leading to a direct transformation of F into S according to process 2’ (which therefore is system 1 thinking). Considering the rationale included in the pattern, corresponds to processes 3 and 4 that are executed by system 1. In case a potential pitfall is identified, a new search is carried out to identify a pattern that addresses the pitfall as a problem. This can be viewed as a reformulation of structure by means of a new instance of process 2’.

The processes involved in pattern language-based design are summarised in Table 4.
6.4. BRAINSTORMING

Brainstorming is one of the most known creative design techniques (Cross 2000). It is based on bringing together a diverse group of people with a wide range of expertise and capturing their spontaneous ideas about a problem without assessing them.

A brainstorming session commences with the group leader formulating the problem statement. This can be represented as process 1a.

The group members then write down the first ideas that come to their minds. Every idea needs to be articulated succinctly so it fits on a small card. This corresponds to multiple instantiations of process 2’.

The next stage is the presentation of every idea to the group. No criticism or evaluation is allowed yet. The group rather reflects on the ideas, trying to develop them further or combining them. This can be viewed as process 6.

Only later does the group leader assess the ideas, which corresponds to processes 3 and 4.

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**TABLE 4. Processes involved in pattern language-based design**

<table>
<thead>
<tr>
<th>System 1</th>
<th>System 2</th>
<th>FBS representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Selecting S using a search for applicable design patterns</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 2’</td>
</tr>
<tr>
<td>2. Assess S based on the rationale included in the pattern</td>
<td></td>
<td>Process 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 4</td>
</tr>
<tr>
<td>3. Select a new pattern that addresses any pitfalls detected</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 2’</td>
</tr>
</tbody>
</table>
The processes involved in brainstorming are summarised in Table 5.

**TABLE 5. Processes involved in brainstorming**

<table>
<thead>
<tr>
<th>System 1</th>
<th>System 2</th>
<th>FBS representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Formulating a problem statement</td>
<td></td>
<td>Process 1a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Write down spontaneous ideas</td>
<td></td>
<td>Process 2*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Reflecting on the ideas, without criticising or evaluating</td>
<td></td>
<td>Process 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Assessing the ideas</td>
<td></td>
<td>Process 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 4</td>
</tr>
</tbody>
</table>
7. Conclusion

Connecting dual-system theory with the FBS ontology of design contributes to the increasing body of research in aligning models of cognitive science and design science. The paper has shown that system 1 and system 2 thinking can be represented ontologically and mapped onto various instances of design thinking. Dual-system theory can be viewed as a meta-cognitive model of human thinking (Barr 2018), similar to the FBS ontology that is a meta-cognitive model of design thinking. They are generic and therefore independent of the specific domains or the specific instances of thinking and design thinking. This has the advantage that the specifics can be analysed, compared and discussed using a common terminology and common methods. Cross-domain and cross-instance insights can potentially be gained from such a uniform framework.

One insight resulting from this research can be derived from analysing the four instances of design processes presented in Section 6. Three of them – design fixation, case-based design, and pattern language-based design – are instances of routine designing, and one of them – brainstorming – is an instance of non-routine (or creative) designing. Yet, in all of them system 1 plays a distinguishing role. In routine designing system 1 merely reproduces existing design structures, while in non-routine designing it generates new design structures. This is consistent with Taura and Nagai’s (2017) distinction between “experiential” and “associative” intuition and their respective effects on the creativity of the designs produced using these forms of intuition. It is also consistent with Kahneman’s (2011) presentation of system 1, on the one hand, as a source of bias toward known experiences, and, on the other hand, as a “mental shotgun” that produces more (associative) concepts than it is asked for.

The combination of dual-system theory and the FBS ontology required an extension of the original FBS ontology, by adding a direct transformation of F into S. This does not represent a violation of the “no-function-in-structure” principle (De Kleer and Brown 1984). The new process (2’) it is defined in this paper as a substitution of other processes in the ontology for reasons of cognitive efficiency. Yet, it originates from previous design experiences that originally proceeded from function to expected behaviour and then to structure.

Embedding process 2’ in the existing FBS ontology has the benefit that empirical findings can now be better accounted for, especially the frequently observed direct transformation of F into S. For example, Yu and Gero (2016), using a Markov model analysis of design protocols in the context of parametric design, observed a high frequency of F-to-S transformations based on the use of design patterns. Having an explicit process representing this transformation opens up the possibility of revisiting other design
protocols and analysing them for the occurrence of system 1 design thinking. This may also empirically validate the ontological model of fast and slow design thinking presented in this paper.

Future design research may use this work for developing new methods and tools for performing and teaching design. This is because it provides access to well-established findings in the various sub-disciplines of cognitive psychology. For example, methods for analysis and evaluation in design may benefit from cognitive approaches that help overcome the laziness of system 2 to avoid biased judgements due to system 1.

Another possible extension of this work is to investigate the usefulness of Stanovich’s (2009) “tri-process theory” for design thinking. This theory splits system 2 into two modes or processes: an algorithmic and a reflective process. The resulting set of three processes may be mapped onto Maher and Gero’s (2002) reflexive, reactive and reflective modes of reasoning for situated design agents.

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