

**ABSTRACT:** Design cognition is a human cognitive ability that is characterized by multi-faceted skills and competencies. This skill requires finding solutions for a vague problem, where the end point is not specified and the transformations from the problem state to the solution state are also flexible. Designers solve such tasks regularly, but the mental processes involved in such a skill are not known completely. Design research has involved empirical studies and theoretical modeling to understand the cognitive processes underlying this skill. In lab-based studies, a sub-class of problem-solving tasks called “ill-structured” tasks has been used to study the design process. However, the use of a cognitive neuroscience perspective has only been nascent. In this review, some defining features of design creativity will be elucidated and a few cognitive neuroscience studies of design creativity that shows the underlying brain networks will be highlighted. Results from these experiments using ill-structured tasks along with functional magnetic resonance imaging (fMRI) show that the brain networks underlying design creativity only partially overlap with brain networks underlying other kinds of creativity. This argues for studying design creativity as a unique subset of creativity using experiments that mimic the real-world design creative processes.

**KEYWORDS:** Design cognition, ill-structured task, creativity, functional magnetic resonance imaging

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## Introduction

Design cognition can culminate in a variety of outcomes—physical artifacts, processes, symbolic systems, scripts, laws, behavior, and so on.<sup>1</sup> It can be defined as a fundamental ability to fabricate outcomes, where intentional execution of plans on variables in the environment (physical object, behavior, rules, etc) is enacted such that it results in favorable outcomes to the executor. This ability has benefited human society in numerous ways and designers are increasingly asked to solve complex social, behavioral, and technical problems in the modern world.<sup>2</sup> Although design encompasses varied specializations and skills like graphic design, product design, engineering design, communication, interaction design, software design, and so on, it is defined by its outcomes. The design process results in an innovative solution, which can be contrasted with art because of the utility value of the outcome. Design can also be differentiated from scientific process as it cannot be deduced by a step-by-step manner by pre-existing rules as in scientific creativity. Thus, design creativity can be considered separate from scientific and artistic creativity and by extension, subserved by different mental processes.<sup>3,4</sup>

Cognitive neuroscience studies the neural correlates underlying cognitive processes. With the increasing availability of non-invasive brain imaging tools that can be used in humans like functional magnetic resonance imaging (fMRI), Magnetoencephalography (MEG), Near-Infrared Spectroscopy (NIRS), and so on, the brain regions and networks behind higher cognitive functions like creativity, problem solving, decision-making, emotional regulation are gaining a deeper understanding. This approach has recently been used to test hypotheses related to biologically relevant theories in neuroeconomics, decision-making, creativity,

neuroaesthetics,<sup>5-11</sup> and so on. However, interdisciplinary research in cognitive neuroscience of design cognition has not flourished. Design cognition could also embrace and benefit from the cognitive neuroscience methodology and perspective.<sup>12-17</sup> In this review, a brief overview of the design process will be given followed by a review of a few promising cognitive neuroscience studies using fMRI.

## Studying Design Cognition—Historical Ideas

Early attempts to study design cognition were to model it as purely problem solving and as something that can be reverse engineered and optimized with algorithms.<sup>18</sup> Herbert Simon, in his influential theories, modeled design activity as an objective, quantifiable, algorithmic, optimization process. He made explicit attempts to describe design as an engineering problem and moved away from the subjective, intuitive, and cultural factors involved in design. Even when he acknowledged that design tasks were too vague and open-ended, like in architectural design of a building, he believed that they could be broken down into smaller problem-solving units.<sup>19</sup> However, his contemporaries like Alexander Christopher cautioned against a purely algorithmic approach claiming that “most of the difficulties in design are not of the computable sort.”<sup>20</sup> Rittel and Webber<sup>21</sup> also proposed an alternate model for problem solving describing the design problems as “wicked problems” which have social, behavioral, and political aspects. Although current theories in design research have moved away from a purely problem-solving perspective, Herbert Simon’s ideas are still influential in design research.<sup>22</sup> It is no surprise that early cognitive science studies of design and creativity were mostly through the lens of problem-solving tasks as Herbert Simon was instrumental in the birth of cognitive science as an academic discipline.<sup>23</sup>



## Is Design Cognition a Unique Cognitive Skill?

Most well-studied problem-solving tasks fall under a class of problems called “well-structured” problems. These tasks are characterized by a well-defined problem, solution and the steps needed to reach the solution are also defined by well-defined rules. A step-by-step incremental and logical approach can help one reach the solution to the problem, like in the Tower of Hanoi problem. In this task, there are three vertical rods that can hold disks of various diameters. At the start stage, one of the rods is loaded with all the disks in ascending order, with the largest disk at the bottom and the smallest at the top. The goal is to move the disks one-by-one to a similar ascending configuration on the third rod. The rule is that, at no stage should a larger disk be placed over a smaller disk.

Cognitive psychology literature used many of these well-structured tasks like the tower of Hanoi, radiation problem, matchstick problem, triangle problem, and so on to study problem-solving creativity.<sup>24,25</sup> These tasks however do not represent the cognitive demands of a design task as those are more open-ended and vague in nature. Design problems are best represented by another class of problems called “ill-structured” tasks, where the problem is open-ended, not well-defined and the solution is not apparent at the start. The problem and solution also co-evolve as the task progresses.<sup>26</sup> Design cognition requires a certain level of abstraction and modification of the problem statement and in the connections made between the problem and solution, as vividly explained with the example of the Sydney Opera House by Vinod Goel.<sup>25</sup> Also, in design, creativity is not always needed to design an outcome; some designs can be minor modifications of previous designs.<sup>1</sup> There is also a differentiation between “personal” creativity, where a creative solution has occurred for the first time to the individual and “historic” creativity, where it has occurred for the first time in history.<sup>26,27</sup> Sometimes, the designer might also stumble upon the solution through serendipity.<sup>28</sup> Another dimension that design incorporates is the individual preferences, cultural and environmental realities into the end-product, which are not available in a well-structured task.<sup>29</sup>

## Stages of The Design Process

How does a designer create? From the outside, the process of design could appear mysterious or spontaneous, but it can be broken down into a sequence of procedures which are highly skilled. This process, from the initial specification of the problem to the emergence of the final solution, follows a series of steps.<sup>4</sup> Scholars are generally in agreement over the division and sequence of the design process into three or four major stages. Although there is some variation in the terminology and the exact demarcation, they generally follow similar divisions like (1) analysis of problem, conceptual design, embodiment of schemes and detailing<sup>30</sup>; (2) exploration, generation, evaluation, and communication<sup>4</sup>; (3) problem structuring, preliminary design, refinement, and details specification<sup>31</sup>; and (4)

generation of representational diversity, manipulation of representational diversity, and recognition of novel representation.<sup>32</sup> A brief overview of each stage is provided below.

### *Problem-defining stage*

The design process begins at the problem formulation stage, where the designer defines the problem he or she must address. Here, the designer must survey the problem, understand the constraints, and try to construct a conceptual understanding of the problem. For example, a designer might get instructions to design a better waste management system. The problem can be formulated at the level of waste production or waste disposal or waste segregation or waste degradation and so on. So, here the designer has the freedom to define the problem, frame a context in which to place it before they can work on it. This step is called “problem setting” or “problem framing.”<sup>33</sup> This is one of the unique features of design problems, which is not reflected in “well-structured” tasks.

The problem framing occurred not just in the beginning of the task but throughout the design task. This is referred to as the co-evolution of the problem and the solution.<sup>26,34</sup> This is another unique aspect to design problems. The act of problem structuring is idiosyncratic and can be influenced by the designer’s biases and interpretations of the problem. This stage is vital to the success of the design task. It has been shown that designers who spend a lot of time on problem structuring were able to make better creative solutions later.<sup>35</sup> Skipping through the problem setting stage or spending too much time on it can be detrimental to the creativity of designs.<sup>36</sup> Although a vague problem definition might sound disadvantageous, the vague problem formulation is a hallmark of design and a spark for creativity. It has also been observed that designers sometimes treat a well-defined problem as an ill-defined problem by changing the goals and constraints.<sup>37</sup> In some cases, it has been shown that concentrating on defining the problem too rigidly can be detrimental to the outcome of the design process.<sup>35</sup> It seems like the ambiguous definition of the problem in the ill-structured problem-framing stage drives the creativity in design.<sup>38</sup>

### *Prototype generation stage*

The next stage of the design process is to produce multiple prototypes of potential solutions. Since the nature of design problems does not afford much clarification, the designer moves on to generate potential solutions. These prototypes are rough ideas which could later be polished into a finished product. These prototypes are derived from a few kernel ideas. Variations of these kernels are generated by slight modifications called lateral transformations.<sup>25</sup> The initial drawings are conceptual sketches, which are symbolic representations and abstract in nature. Using these diagrams, the designer represents the problem with a symbolic language, which can be

manipulated and expanded such that these prototypes can be used as tools to understand the problem and advance toward a solution.<sup>25,39</sup>

The predominant cognitive strategy used by the designer to generate multiple prototypes is called divergent thinking. It is characterized by thinking that moves away in divergent directions and makes associations with ideas that are seldom directly connected. This process is also called “generative” or “associative” reasoning. Divergent thinking has been a popular theory in creativity studies and has been studied extensively and is often synonymously considered with creativity itself. This is exemplified by Alternative Uses Task (AUT), where an object is showed and as many uses of the object are to be reported and later the Torrance Test of Creative Thinking (TTCT).<sup>40,41</sup> If a prototype is diverse or indirectly connected to the problem, then the solution is rated as more creative. This step of creating multiple creative prototypes is vital in the creative process of design as it has been shown that not generating multiple kernel ideas or getting fixated on one initial solution will lead to a block to creative solutions.<sup>42</sup> Divergent thinking has been correlated with a de-focusing of attention<sup>43,44</sup> and better memory retrieval,<sup>45</sup> which aids in generation of several novel ideas.

How do designers create new ideas? One way is to rely on making a connection with another idea. Many studies have shown that when faced with a problem to solve in the present (target), a designer may look to similar problems in the past (source) and establish a relationship between the target and the source.<sup>46</sup> Analogical reasoning has been attributed to the underlying cognitive strategy by which designers make this connection and is well studied.<sup>47</sup> The nature of mapping between the source and target dictates how creative the solution is, where mapping at a superficial level or at a complex level dictates the quality of the solution. The greater the creativity, the larger the “distance” between the source and the target. Creative solutions as a result of analogies from “nearby” sources are called as “mental hops” and creative results from analogies from “far” sources as “mental leaps.”<sup>48</sup> Many designers have also shown that more “original” and “creative” results come from analogical reasoning from a distant source.<sup>49</sup> For a good design, the designer must inhibit the salience or the attention to the “surface” characteristics and look for deeper structural, abstract connections.

#### *Evaluating outcome stage*

After the designer has created many possible solutions in the divergent thinking stage, the next stage is to choose the best possible solution that meets the solution criteria. This process utilizes convergent thinking, which involves analytical thinking and focused attention. The preceding stage of divergent thinking produces many ideas, but all of them are not a good fit to the end goal, even if they are novel and non-conformist. Such ideas are called “quasicreativity.”<sup>50</sup> In the stage of convergent thinking, these designs are weeded out or modified so they can

be transformed into an appropriate final solution.<sup>51</sup> Without convergent thinking, the novelty generated in the divergent thinking phase might become ineffective if it does not meet the task requirements. It must be noted that convergent thinking can also produce ideas on its own; however, they are “orthodox” and devoid of variations.<sup>50</sup>

Historically, these kinds of thinking were thought of as opposing forces, with divergent thinking being equated with creativity and convergent thinking with analytical thinking. But recent research shows that creativity is a dual-process theory involving both divergent and convergent thinking. So, creativity can be defined by mode-shifting between divergent and convergent thinking. It has also been shown that these two processes occur simultaneously, with initial stages (prototype generation) having more divergent thinking and the rest of the stages having both divergent and convergent thinking.<sup>52</sup>

#### *Final outcome phase*

In this phase, the designer must assess which of the prototypes can be advanced to a potential solution. The evaluation is based on assessing the prototypes based on multiple parameters like novelty, typicality, popularity, workability, impact, and so on.<sup>53</sup> Evaluation of ideas involves many complex cognitive skills like assessment of the idea, future forecasting, solution recognition, understanding needs of the environment, and so on. At this stage, the “gut feeling” of the designer might influence his or her assessment of the options. The evaluation is not done based on only the utility value of the prototype but is also affected by the biases and preferences of the designer. Modern theories in decision making have allowed for a major role of emotions<sup>54,55</sup> and inherent biases in decision making.<sup>56,57</sup> The role of emotions in design has been explicitly advocated and many products and processes are designed to elicit a positive affect and favorable behavior toward it.<sup>58</sup> Once a prototype is selected, it goes through a stage of detailing and specification, where features are added or subtracted such that it can be made the solution. This step is called “vertical transformation” by Vinod Goel, where a vague representation of a solution is transformed to a detailed version of the same solution. The indeterminacy and abstractness of the solution reduces and incorporates realistic aspects.<sup>25</sup>

### **Cognitive Neuroscience Imaging Studies of Design Creativity**

There have been studies in cognitive science that looks at the various underlying cognitive modules behind each stage of design cognition, like working memory, attention, divergent and convergent thinking, mental imagery, hypothesis generation, and so on. However, there are only a few cognitive neuroscience studies that have used a realistic design task. In this section, a few studies that have used tasks that portray real-life design problem with adequate controls will be reviewed. These studies have also unearthed the salient brain areas and networks in the brain which underly design cognition.

### *Ill-structured tasks and prefrontal cortex*

The ill-structured tasks were first used in the laboratory to study the effects of prefrontal cortex damage in humans. Many of these patients have normal intelligence, language ability and perform well in tasks like the Wisconsin card sorting task and Tower of London task, which are traditionally used for testing prefrontal functions, but it was observed that they were not able to function in everyday life. To investigate further, Shallice and Burgess developed open-ended tasks mimicking the problems these patients had in real life.<sup>59</sup> In the Multiple Errands Task, the subject must complete real-life tasks like buying items from a neighborhood grocery, get some information (exchange rate of a dollar), complying to certain rules (cannot go to certain places twice). These tasks demanded that the subjects make plans, schedule sub-tasks, and keep track of time and follow the rules. They found that patients with prefrontal lesions were not able to perform as well as normal controls. Following this, the prefrontal cortex has been regularly implicated in tasks that involved problem solving in open-ended, real-world design-like tasks.<sup>59-61</sup>

One of the first studies to look at the role of prefrontal cortex in design cognition explicitly was a study of an architect with damage to his right prefrontal cortex caused by a seizure.<sup>36</sup> He was given a task to redesign a laboratory space to make it more efficient and comfortable within 2h. Protocol analysis methodology was used, where the subjects talk aloud while completing the task, which is later transcribed and analyzed. The design outcome of the patient was poor compared with the control subject. Because of the design of the task, it was possible to narrow down the stages of design where the patient had faltered. The subject spent significantly higher amount of time in problem structuring when compared with the control and did not progress from the first stage of problem structuring. When the drawings of the subjects were analyzed, it was found that his preliminary drawings were fragmented, unrelated, and no abstract information represented in the latter stages. This shows that the right prefrontal cortex is vital in the generative phase. It was later shown using a novel word generation task that right Prefrontal Cortex (PFC) was implicated in generation of new hypothesis,<sup>62</sup> for open-ended tasks that do not have an objective right or wrong answer.<sup>63-65</sup>

The involvement of right PFC was cemented by probably the first study to use fMRI, using an ill-structured task, where subjects were asked to design the interior of the room by placing multiple pieces of furniture. They were scanned in the fMRI while they manipulated the location of pieces of furniture on a schematic representation of a room.<sup>66</sup> This task was to mimic a real-world interior design task, where there are no restrictions on how the task can proceed except by the solution the designer wants. This control condition was a problem-solving task, where the furniture had to be moved according to strict rules that govern how the furniture must be placed in the room. For example, one of the rules is that the

two tables must face each other. Thus, this task provided a direct comparison between the activations for a well-structured and ill-structured task.

The brain activation in the design task subtracted from the problem-solving task was found to be localized in the right dorsolateral prefrontal cortex (DLPFC), especially in the initial planning phase. They also found that right DLPFC connectivity modulated in correlation with precuneus, which is part of the default network (see below for details) and left frontal pole, which are implicated in mental imagery and self-generated internal representation of information, respectively. It emerges from these studies that the right DLPFC is heavily involved in the generative phase of design cognition.

### *Differential brain network activation for experts and novices*

There has been considerable research effort in design to understand the difference between design cognition in expert and novice designers.<sup>67</sup> There have been various studies that explore these issues: whether design cognition is part of natural intelligence<sup>68</sup> and what are the best ways to educate designers.<sup>69</sup> To explore these issues further, the brain activation patterns for design students and non-design students were compared in a study where participants designed a pen while being scanned in the fMRI.<sup>70</sup>

The results showed that experts generated more creative solutions than beginners and their pattern of brain activation was also different from the novices. Expert designers had more activation in right PFC compared with left PFC and parietal cortex (PC). The novices used bilateral PFC, PC, and the anterior cingulate cortex (ACC). The objective measures of creativity calculated for the expert's designs also correlated to activation relatively in both right and left PFC activation and not separately to left or right PFC. In addition to these parts, the medial temporal lobe (MTL) including hippocampus has been activated during generation of ideas. The areas in MTL, apart from their role in semantic and episodic memory, also have a role in mental imagery, analogical processing, and generation of novel ideas.<sup>71-73</sup> This study shows that design creativity involves interaction between the hemispheres but involves a network of multiple areas in the brain.

### *Emotion networks in design process*

Finally, in another design task, the subjects were asked to either generate ideas or evaluate them in alternate time blocks of the experiment while they were scanned in a fMRI.<sup>74</sup> The subjects were asked to design a cover for a book at one time block and then in another they were asked to evaluate their ideas. They found that during the idea generation stages, MTL (hippocampus and parahippocampus) regions were active and during the evaluative phase, the prefrontal areas which underlie cognitive control and the default network were co-activated.

Thus, for the two stages of design, different brain networks are activated.

The default network is a combination of brain areas like medial prefrontal cortex (MPFC), posterior cingulate cortex (PCC), precuneus, and temporoparietal junction (TPJ). It is important for integrating sensory input with the visceral autonomic and hedonic information. It is also responsible for processing self-generated emotions and processing visceral, autonomic, and hedonic information. During the evaluative period, it is activated along with the brain areas in the PFC which are responsible for executive control. Activation in this area could underlie the emotional evaluation in the design process, the “gut feeling” on which designers rely to make decisions. This activation, along with a more analytical assessment from the executive areas in PFC, could be involved in evaluating the outcomes.<sup>75</sup> The default network does activate for many creativity tasks, especially when they are open-ended. In a study of jazz musicians, where they were asked to improvise their performance, the default network was prominently activated.<sup>76</sup>

## Conclusions

The above studies suggest that design cognition is localized in brain networks that are only partially overlapping with regions implicated in other kinds of creativity like visuospatial creativity,<sup>77,78</sup> musical creativity, verbal creativity, and so on.<sup>9,10</sup> These studies have used a wide variety of tasks and methods.<sup>8</sup> For a meta-analysis of brain areas involved in various kinds of creativity, see Pidgeon et al and Boccia et al. However, there are many aspects of design cognition are not yet addressed in these studies, like, the co-evolution of problem and solution, the interplay between executive control and emotional regulation during evaluation, the influence of environment on design outcome etc. Studying design cognition using real-life design tasks with appropriate controls could shed light on these previously unresearched parts of creativity.

## Future Directions

The ability to manufacture artifacts and processes to influence the outcome of interaction with the environment has been an evolutionarily important step for the cultural and social evolution of humans. This has been made possible by both physical modifications to the body and the changes in the brain architecture.<sup>79</sup> The evolution of the opposable thumb and a large neocortex has allowed manipulation of objects and tool manufacture.<sup>80</sup> One could argue that the capacity for design cognition evolved when early humans were able to make tools. And the earliest form of intelligence has been attributed to manufacture of stone tools and symbolic systems.<sup>81</sup>

Design research has traditionally employed techniques like protocol analysis, interviews, etc, and which have provided very important information<sup>4</sup>; however, self-reports and interviews are not reliable and could be subject to biases. This is exemplified by David Schön who said that “I begin

with the assumption that competent practitioners usually know more than they can say. They exhibit a kind of knowing in practice, most of which is tacit.”<sup>33</sup> The allure of using cognitive neuroscientific methods is that controlled lab-based tasks and brain imaging tools could minimize this bias and give a window into mental processes that cannot be verbalized or detected in behavioral measures. Also, with the increasing influence of ideas from emotional decision-making, embodied cognition, and situated cognition, cognitive neuroscience is equipped to study higher-order processes that are subjective, environmentally situated, and culturally biased, like design cognition.<sup>82</sup> Judicious use of methodologies and tools of cognitive neuroscience in conjunction with design research methods can give a lot of insight on the neural correlates of design cognition. This can benefit cognitive scientist to understand a unique higher cognitive skill and designer researchers to design better training programs.

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