Design Science

Using fMRI to deepen our understanding of design fixation

Katherine K. Fu[1], Brian Sylcott[2] and Kaustav Das[3]

1 *School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA*
2 *Department of Engineering, East Carolina University, Greenville, NC 27858, USA*
3 *School of Mechanical Engineering, Georgia Institute of Technology Atlanta, GA 30332, USA*

Abstract

Design fixation refers to blind adherence to a set of ideas, which can limit the output of conceptual design. Engineering designers tend to fixate on features of pre-existing solutions and consequently generate designs with similar features. The objective of this study is to leverage functional magnetic resonance imaging (fMRI) to study the brain activity of engineering designers during conceptual design in order to understand whether/where design fixation can be detected in a person's brain when solving design problems. Design solutions indicated that fixation effects were detectable at a statistically significant level. fMRI results show increased activation in areas associated with visuospatial processing when comparing ideation activities using an Example solution to No Example solution. Activation was found in the right inferior temporal gyrus, left middle occipital gyrus, and right superior parietal lobule regions. The left lingual and superior frontal gyri were found to be less active in the example condition; these gyri are close in proximity to the prefrontal cortex, associated with creative output. The spatial patterns of activation provide evidence that a shift in mental resources can occur when a designer becomes fixated. For designers, the timing of ideation relative to the timing of benchmarking existing solutions should be considered.

Key words: design fixation, fMRI, design neurocognition

Received 19 December 2018
Revised 19 September 2019
Accepted 1 October 2019

Corresponding author
K. K. Fu
kfu@me.gatech.edu

Published by Cambridge University Press

Des. Sci., vol. 5, e22
journals.cambridge.org/dsj
DOI: 10.1017/dsj.2019.21

1. Introduction

Much of the engineering design research can be divided into two related but distinct categories. There are projects that focus on the tools designers use in an effort to make the design process easier, more efficient, more innovative, or generally more effective. Alternatively, there is research that aims to understand designers themselves. In doing so, researchers attempt to map out how designers solve problems and develop strategies to improve these processes. The work presented here falls in the latter category. Specifically, this work examines a phenomenon that has been consistently observed and studied in behavioral research, but much less so in neuroscientific work: *design fixation*. Design fixation has been defined as the "blind adherence to a set of ideas or concepts limiting the output of conceptual design" (Jansson & Smith 1991) and is an effect that many designers face during the design process. Since neuroimaging has been proven to be a useful method for gaining greater insight into the cognitive processes associated with specific behaviors, this research employed neuroimaging to investigate design fixation in the context of solving engineering design problems.

Design fixation often occurs in the conceptual design phase, during which an individual is engaging their creativity to generate ideas to solve a given design problem. As such, this work is informed by the prior work in the neuroscience of creativity. Studying creativity using functional magnetic resonance imaging (fMRI) comes with its own set of unique challenges, as outlined by Abraham (2012, 2013) and Benedek, Christensen & Beaty (2019). Behavioral study of creativity involves the generation of ideas in open-ended settings. The time limitation of being inside the scanner, in addition to the physical constraint of not being able to move while in the scanner in order to generate usable data, significantly challenges the study of creativity using fMRI. In addition, larger sample sizes are harder to achieve in fMRI research in comparison to behavioral research because the data collection is much more time-consuming and physically involved.

Creative cognition is seen, by some, as distinct from normative cognition because it calls for "more open-ended, unstructured or non-linear information processing strategies to be adopted" (Abraham 2013). Much of the prior work on creativity in neuroscience has focused on individual differences in creative ability, and how these manifest in the brain (Abraham 2019). Abraham discusses how the premise of "creative ability" is challenging to the research findings because it is unclear if this ability is the result of other brain-related differences, and because it relies on a presumption that creative ability is partially an innate attribute. On the contrary, Fink *et al.* found evidence of increased creative ability as the result of training in divergent thinking, with increased activity patterns in the left inferior parietal cortex and the left middle temporal gyrus (Fink *et al.* 2015). Others have studied individual or small groups of neurological patients, such as those with Parkinson's or epilepsy, and how their condition affects their creative abilities. The study presented in this paper is distinct from the prior studies in that it recognizes that participants may have differing levels of creative ability and that the impact of inducing design fixation will not necessarily be modulated by innate/learned individual differences in creative ability.

This study is exploratory in nature, with the goal of ascertaining whether design fixation can be detected in brain activation; it is not yet known which regions of the brain may be associated with design fixation. In Section 2, prior research on design fixation in behavioral studies is presented, along with a review of the current understanding of the neuroscience of creativity. Subsequently, in Section 3, more specific hypotheses are presented based on the prior research. Section 4 briefly discusses the significance of our work. Section 5 presents the methods of the study conducted here, and Sections 6–9 present the results, discussion, limitations, and conclusions, respectively, of this study.

2. Background

2.1. Design fixation

Fixation has different meanings across the fields of psychology, neuroscience, and design cognition. In psychology, Freud pioneered the term "fixation" as the "persistence of anachronistic sexual traits" (First 1970), which later evolved into a broader psychological definition of "object relationships with attachments to people or things persisting from childhood into adult life" (Akhtar 2018). In neuroscience, fixation refers to "the maintaining of the visual gaze on a single location" (Krauzlis & Goffart 2017). In design cognition research, fixation refers to

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

the "blind adherence to a set of ideas or concepts limiting the output of conceptual design" (Jansson & Smith 1991). In this study, the design cognition definition is employed.

Design fixation can have negative impacts on the design process. Consequently, this issue is relevant to design practitioners, as well as design educators (Purcell & Gero 1996). For instance, the presence of an example solution (good or bad) may result in the transfer of attributes from the example to the new solution, thus making it more difficult to develop a novel solution (Chrysikou & Weisberg 2005). While this sort of fixation can be readily observed, there are several factors, such as the commonness of the example (Purcell *et al.* 1993) and the domain of the problem (Purcell & Gero 1996; Goldschmidt 2011), that affect whether or not fixation will be present. Due to the potentially significant impact fixation can have on the output of the design process, developing more effective ways of mitigating and potentially preventing design fixation is an important area of research.

Researchers have investigated a variety of different factors that contribute to design fixation. Linsey *et al.* observed significant fixation manifesting in both students and experts when provided an example solution (Linsey, Viswanathan & Gadwal 2010). Although novice and expert designers may experience comparable levels of fixation, the effectiveness of defixation strategies may differ based on the designer's level of expertise (Viswanathan & Linsey 2013*a*). In the work by Agogué *et al.*, the authors demonstrate that fixation can differ from subject to subject based on age as well as education level (Agogué *et al.* 2014). Designing as a team versus as an individual is another factor that can affect the impact of design fixation (Fu, Cagan & Kotovsky 2010).

Youmans observed physical models having a positive impact on design fixation (Youmans 2011). Results from that study showed less fixation with the example solution when a physical prototype was used. Viswanathan and Linsey argue that physical models can supplement a designer's mental model, leading to positive impacts on fixation and idea quality (Viswanathan & Linsey 2013*b*). Design-by-analogy is related to fixation because analogy requires examining, abstracting, and mapping concepts from an outside source to the design problem at hand. Exposure to outside sources, such as example solutions, can be beneficial for the purposes of design-by-analogy, or it can be detrimental by causing fixation. The analogical distance of the example solutions from the design problem can also have an impact on design fixation. While there is evidence that example solutions that are conceptually far from the problem lead to less fixation (Purcell & Gero 1992), this is not always the case (Fu *et al.* 2013). Chan *et al.* showed that example solutions that are conceptually near can be more helpful for design-by-analogy than far ones (Chan, Dow & Schunn 2015).

Koh and De Lessio demonstrated that exposure to patent documents (a form of example solution/analogical stimuli) prior to problem solving in an effort to avoid infringement could still lead to fixation (Koh & De Lessio 2018). Moss *et al.* showed that helpful cues (examples/hints) are more effective when presented after an initial work period than at the start of problem solving (Moss, Kotovsky & Cagan 2011). Further, a meta-analysis of 43 design studies presented by Sio *et al.* reinforced evidence of the significant effect that presentation and composition of examples can have on design fixation (Sio, Kotovsky & Cagan 2015). In order to induce fixation intentionally, this study employs near-field example solutions at the very beginning of problem solving.

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

As discussed, there are numerous factors that contribute to the level of fixation experienced during problem solving. While there have been advancements in addressing these factors so that fixation can be broken or avoided all together (Smith & Linsey 2011; Vasconcelos *et al.* 2017; Crilly 2018), such strategies would benefit from a greater understanding of the cognitive mechanisms that underlie this phenomenon. The work presented here used fMRI to observe brain activity as designers solve problems. The ultimate goal is to gain insight into the areas of the brain that are active during fixation in order to develop better methods that counteract design fixation.

2.2. Studying creativity using fMRI

As the brain functions, it consumes oxygen, which is delivered by hemoglobin in the blood. As cellular activity increases in a specific region of the brain, more oxygen is consumed in that region. As a result, the blood oxygenation level can be used as an indirect measure of brain activity (Huettel, Song & McCarthy 2004). The magnetic properties of hemoglobin vary with oxygenation level, causing distinct levels of distortion when a magnetic field passes through the brain. fMRI uses this principle to measure brain activation via a blood-oxygen-level-dependent (BOLD) signal. While neuroimaging cannot determine exactly what a person is thinking, it can be used in conjunction with behavioral studies to associate specific brain regions with design tasks and provide insight into the cognitive processes, such as memory or motor planning, that may be at work.

Creativity has been studied in neuroscience primarily in three ways – individual case studies of neurological patients, series case studies of neurological patients, and series case studies of psychiatric patients (Abraham 2019). As this current study does not address neurological cases, this literature review focuses on the methods and findings of the psychiatric studies, which employ behavioral interventions and assessments similar to those used in traditional psychological studies of creativity. A typical task to induce and assess creative thinking is the alternate uses task (AUT), in which participants are given a set of everyday items and asked to generate ideas for how they could be used in ways they are not typically used (Ward 1994; Finke, Ward & Smith 1996; Abraham & Windmann 2007). The fluency of ideas generated in the AUT assessment served as a measure of the creative ability of individuals, who were then divided into three groups of high, medium, and low creative individuals and then subjected to different interventions within the scanner. Participants also took the Abbreviated Torrance Test for Adults, an additional measure of creative ability (Goff & Torrance 2002). The brain regions shown to be associated with creative conceptual expansion were the posterior regions in the inferior frontal gyrus, the middle frontal gyrus, the anterior cingulate cortex, dorsomedial prefrontal cortex, and the inferior parietal lobule (Abraham *et al.* 2018, 2012). In further studies of conceptual expansion, Abraham *et al.* examined the effect of IQ differences on creativity and found that lesions in the frontolateral regions of the brain led to less fluency or originality of ideas (Abraham *et al.* 2012).

Abraham *et al.* also examined interventions for enhancing creativity, differentiated by their level of demand. Low demand stimuli were found to enhance creativity more than high demand stimuli (Abraham *et al.* 2018). Beaty *et al.* found that high creative thinking ability was linked to the frontal and parietal regions (Beaty *et al.* 2018). In examinations of resting-state fMRI,

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

more creative individuals had more functional connectivity between the inferior prefrontal cortex and the default network, indicating more cooperation between regions associated with cognitive control and regions associated with low-level imaginative processes (Beaty *et al.* 2014).

Beaty and Silvia also examined the serial order effect, or the tendency for ideas to get better over time during concept generation, using the AUT assessment. They were able to replicate the serial order effect and also found that higher intelligence reduces the effect, which indicated that executive processes are more involved in creativity (Beaty & Silvia 2012). In later work, Beaty *et al.* asserted that creative cognition is rooted in both executive and associative processes, employing latent semantic analysis to assess similarity of verbal responses (Beaty *et al.* 2014). In a review article, Beaty *et al.* indicated that multiple creativity research studies within neuroscience show a cooperation between default and executive control networks to support "goal-directed, self-generated thought" (Beaty *et al.* 2016). Beaty *et al.* found that divergent thinking "involves cooperation between brain networks linked to cognitive control and spontaneous thought" (Beaty *et al.* 2015). During creative thinking, Madore *et al.* found an activity in the hippocampus, an indication that episodic retrieval may play an important role in idea generation, in addition to frontoparietal network activation (Madore *et al.* 2017). In a longitudinal study lasting three years, Chen *et al.* discovered that future creative ability was predicted by the right dorsolateral prefrontal cortex and by slower decreases in gray matter density in the left frontoparietal and right frontotemporal clusters (Chen *et al.* 2016).

Sylcott *et al.* used fMRI to investigate how consumers make preference judgments when considering tradeoffs between product form and function (Sylcott *et al.* 2013). Results from this work show some common and some unique areas of activation when comparing choices based on form or function. Goucher-Lambert *et al.* employed fMRI to explore preference decisions involving product sustainability (Goucher-Lambert, Moss & Cagan 2016). Results from this work highlighted the importance of moral reasoning and theory of mind processing in product evaluations influenced by social factors such as sustainability. In a subsequent work by Goucher-Lambert *et al.*, fMRI was used to examine the neurological activity associated with multi-attribute product preference judgments with a focus on sustainability (Goucher-Lambert, Moss & Cagan 2017). Results from this work showed a decrease in the importance of aesthetic attributes and an increase in the importance of functional attributes when sustainability is considered.

Fink *et al.* explored whether creative cognition can be enhanced through idea sharing (Fink *et al.* 2010). This cognitive stimulation was found to have a positive impact on originality. Observation of this task with fMRI showed the improvement to be associated with increased activation in areas including the right temporoparietal cortex, medial orbitofrontal gyrus, and the cingulate gyrus, extending to the precuneus bilaterally. In work by Alexiou *et al.*, fMRI greater activation was observed in the anterior cingulate cortex, middle temporal gyrus, and middle frontal gyrus when designing a solution for an open-ended problem versus solving a well-bounded problem (Alexiou *et al.* 2009; Alexiou, Zamenopoulos & Gilbert 2011). Finally, Goucher-Lambert *et al.* have used fMRI to examine the effect of supportive stimuli during ideation. Distinct activation patterns in the bilateral middle and superior temporal gyri and

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

the precuneus/cuneus were found to be associated with successful inspiration (Goucher-Lambert, Moss & Cagan 2018*a*).

The objective of this research is to leverage neuroimaging technology to gain greater insight into the cognitive processes that underlie design fixation. Using fMRI to document any unique activation patterns when a designer becomes fixated and/or defixated during the solution process will enable researchers to develop more effective strategies for mitigation and avoidance.

3. AIMS

The overarching goal of this research is to leverage fMRI to study the brain activity of engineering designers during conceptual design activities in order to understand whether and where design fixation can be detected in a person's brain when they are solving a design problem.

3.1. Hypotheses

As design fixation is related to cognitive processing, it is of interest to study whether design fixation can be detected in brain activation, and it is not yet known which regions of the brain may be associated with design fixation. Based on previous research, the following three hypotheses were formulated:

Hypothesis 1. Fixated thought relies on distinct cognitive processes. Therefore, fixation, and its mitigation, can be detected in a person's brain as they are working on a design problem. Particular regions of the brain will be identified as more active.

This is a general exploratory hypothesis, derived from the consistent evidence of design fixation found in behavioral studies in design cognition (Jansson & Smith 1991; Purcell & Gero 1996; Linsey *et al.* 2010).

Hypothesis 2. Design fixation is associated with the anterior and dorsal prefrontal cortex (which is involved in high-level cognition processes), the secondary visual cortex, and areas associated with language and memory.

This hypothesis is derived from studies that have shown the dorsolateral prefrontal cortex to be associated with executive processes, such as attention and working memory (Curtis & D'Esposito 2003). As one of the indicators of design fixation is feature transfer, it is plausible that information is passed through working memory during this process. Additionally, viewing example solution images may lead to activation in the secondary visual cortex, an area associated with visual processing (Arslan 2016).

Hypothesis 3. Motor and premotor areas of the brain (areas that are activate while people imagine movement) are active during the process of generating solutions for mechanical design problems.

It is expected that part of the ideation process will involve imagining the use of any potential solution. Hypothesis 3 is derived from previous work where mental object manipulation has led to activation patterns similar to those observed when subjects physically manipulate objects (Vingerhoets, De Lange & Vandemaele 2002).

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

4. Significance

If the aims are achieved, and if particular regions of the brain can be identified as more active during fixation, further insight into the nature and properties of fixation may come to light. Nearly all design fixation findings have been outside the realm of neuroimaging, presenting a critical research opportunity to connect the design cognition literature to the neuroimaging literature and potentially unveil mechanisms or strategies that have been previously unconsidered.

5. Method

5.1. Participants

Participants were students enrolled in a major academic institution located in the southeast region of the United States. All participants were undergraduate engineering majors. There were a total of 20 participants; however, 2 declined to complete the demographic survey. Of the 18 respondents, 10 were female and 8 were male. Sixteen of the participants were between 20 and 22 years of age and two were between 17 and 19 years of age. Except for one bio-medical engineering major, all participants were mechanical engineering majors. All participants were industrial design minors. Two participants were in their second year of undergraduate study, 5 were in their third year, and 11 were in their fourth year.

5.2. Experimental methods and design

As movement and responses must be highly limited during an fMRI scan, the experiment was conducted with visual stimuli and verbal responses from the participants. Each participant was in the MRI scanner for 1 hour. After receiving consent from the participant and screening for MRI safety and suitability, each participant was placed on the bed of the scanner. The scanner used was a 3-Tesla Siemens Trio Magnetic Resonance Imaging system.

The study is a within-subject design with two conditions – a control condition (No Example design solution given) and a fixation condition (example design solution given). These conditions are referred to as the No Example and Example conditions, respectively, in this paper. The control condition involved visual exposure to an open-ended design problem, described via text. The fixation condition involved visual exposure to similar text-based open-ended design problems but additionally included a hand-sketched visual example solution to the design problem. Participants were exposed to 10 design problems in total, 5 of which were from the control condition (No Example solution) and 5 of which were from the fixation condition (included Example solution). As shown in Figure 1, there were four possible cases that a participant might have experienced. The four cases varied the design problem order and whether control or fixation condition stimuli were seen first. Participants were assigned to one of the four cases randomly – with five participants per case in the final data set. The cases were established in this manner to account for fatigue, influence of particular orders, and/or effects of particular design problems. The 10 design problems are listed below in Table 1, and the example solutions given are shown in Figure 2.

After placement in the MRI scanner and before the functional scan phase, participants underwent a localizer scan (15 seconds), T1 structural scan (6 minutes 17 seconds), gradient field-mapping scan (2 minutes), and resting-state

Table 1. Design problems (full list with constraints can be found in Appendix A)

Design Problems	
DP1:	Design a device to clean whiteboards more efficiently than a typical whiteboard eraser.
DP2:	Design a desk that is capable of hiding whatever is on the desk from people sitting beside and behind the desk.
DP3:	Design a wearable device that converts everyday human motion into electrical potential energy stored in a battery.
DP4:	Design a braking mechanism to stop railroad trains in the case of an emergency that acts in addition to the already-present brakes to more efficiently stop the train.
DP5:	Design a rack to hold wet umbrellas brought into a room.
DP6:	Design a suitcase that has a mechanism by which it can weigh itself for the purpose of assisting people in packing for flights.
DP7:	Design a device to safely store people's wallets and phones and protect them from theft on the beach.
DP8:	Design a device that assists someone with opening a jar whose lid is on too tight for the person to open it using just his or her hands.
DP9:	Design a set of roller skates capable of performing on gravel and dirt.
DP10:	Design a device to shell peanuts without harming the nut inside.

Figure 1. Rotating stimulus set for four cases of experiment, varying by order of design problem and Example vs. No Example condition.

scan (10 minutes). A localizer scan produces a low-resolution structural image that obtains the placement of the head in the scanner so that the field of view is directly around the brain. A T1 structural scan produces a high-resolution image of the brain, which is taken to allow for later mapping of individual brains to the atlas brain when analyzing results. The gradient field-mapping scan is

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

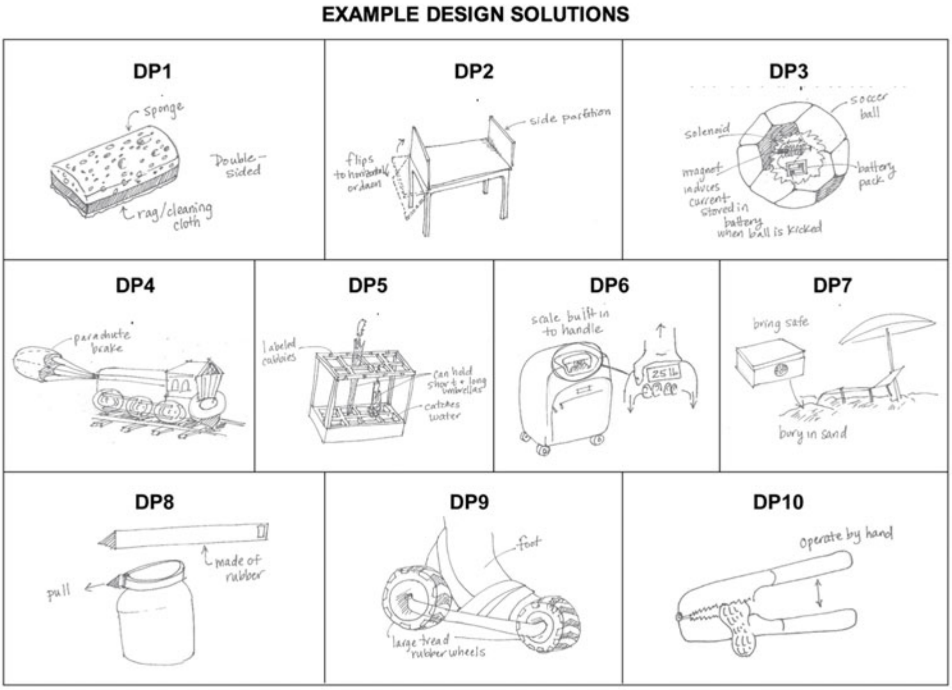

Figure 2. Design problem example solutions given for each design problem.

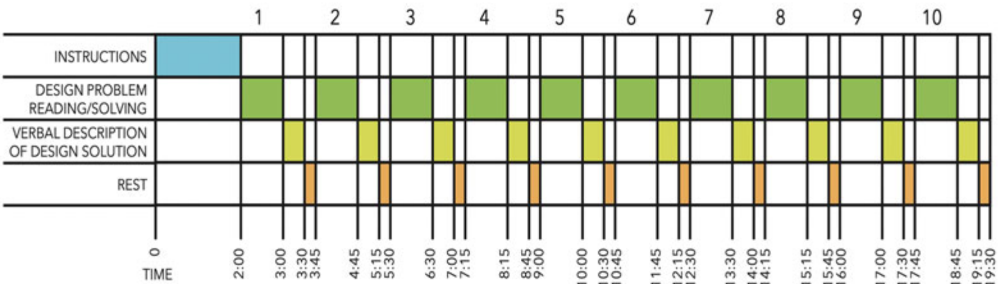

Figure 3. Study task timing, including instruction period, design problem reading/solving period, verbal description of design solution period, and rest period.

taken to identify specific aspects of the magnetic field for each participant. The resting-state scan, which was not analyzed in the results discussed in this paper, is used to measure changes in brain connectivity by examining how it organizes itself into networks while at rest. The timing of the functional scan phase of the study is described visually in Figure 3. Each participant was given 2 minutes to read the study instructions. The researcher verbally described these instructions to the participant before they entered the MRI and also while they were reading them inside the scanner. The instructions were given as follows:

"During the next 15 minutes, you will view 10 different design problems for one minute each. Take that one minute to think of a design solution. Audio will then be recorded for 30 seconds while you verbally describe your design solution."

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

Next, the participant read one design problem, observed the example design solution for the fixation condition stimuli (if applicable), and thought about a design solution to that problem for 1 minute. During this 1 minute, the screen showed the text of the design problem, and, if the Example condition was being run for that design problem, the screen showed the sketch of the example solution in addition to the text of the design problem. The participant then verbally described the design solution they conceived within 30 seconds. During this 30 seconds, the screen showed the amount of time left to verbally respond, counting down from 30 seconds, 20 seconds, 10 seconds, and 5 seconds remaining. The audio data was recorded by a microphone placed in front of the participant's mouth in the scanner. Example verbal responses can be found in Appendix B. In 3 of the 20 cases, the audio recorder malfunctioned and audio data was not collected. The participant was given 15 seconds to rest before viewing the next design problem. During this 15 seconds, the screen showed a short message telling participants to rest for 15 seconds. The process of reading–speaking–resting was repeated nine times, for a total of 10 design problems solved during the functional scan (17 minutes, 30 seconds).

Following the scanning portion of the study, participants took a survey to indicate their background knowledge, previous exposure to the design problems, and other factors that may impact the results, as well as whether they ran out of ideas. The total participation time per person was a maximum of 1 hour and 30 minutes. Each participant was compensated with US$20 for their time and effort and received a CD with the anatomical MRI scans of their brain. They were also provided with a copy of the consent form.

5.3. Imaging parameters

MRI acquisition was performed with a 3-Tesla Siemens Trio Magnetic Resonance Imaging system with a 12-channel head coil located at the GSU/GT Center for Advanced Brain Imaging in Atlanta, Georgia. Functional whole-brain volumes were collected using an echo-planar imaging sequence, with separate runs for each film excerpt and the following parameters: TR $=$ 2000 ms; TE $=$ 30 ms; flip angle $= 90^\circ$; acquisition matrix $= 68 \times 68$; 3 mm isotropic voxels, 37 slices; gap $= 17\%$. The structural scan used the following parameters: TE $=$ 3.98 ms; TR $=$ 2250 ms; flip angle $= 9^\circ$; acquisition matrix $= 256 \times 256$; 1 mm isotropic voxels, 176 slices.

5.4. Analysis path

fMRI data analysis was performed using Analysis of Functional Neuroimages (AFNI) software (Cox 1996). Preprocessing steps were performed using the "afni_proc.py" script and included (1) spike detection and truncation in the voxel time series, (2) slice timing correction, (3) image alignment from fMRI space to anatomical space, (4) warping of subject's anatomical image to MNI (Montreal Neurological Institute) standard space, (5) spatial smoothing using a 3D Gaussian filter with 6 mm FWHM (full width at half maximum) kernel, (6) masking, and (7) motion correction. A general linear model analysis was conducted on the data for each participant using AFNI's 3dDeconvolve tool. This included six head movement parameters and constant, linear, and quadratic trends as nuisance regressors. Experimental regressors included one each for first 50 seconds of the Example and No Example conditions, one each for last 10 seconds of the Example and No Example conditions, and one for verbal response.

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

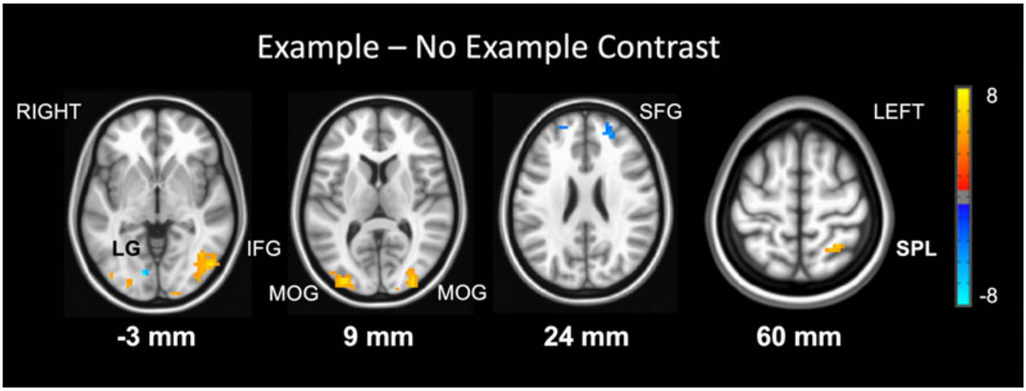

Figure 4. Group T-maps from the Example vs. No Example contrast. Significant $q = 0.05$; $p = 5.4 \times 10^{-4}$ positive activation is shown in warm colors and negative activation is shown in cool colors. LG = lingual gyrus; IFG = inferior temporal gyrus; MOG = middle occipital gyrus; SFG = superior frontal gyrus; SPL = superior parietal lobule.

For each individual, a whole-brain map of beta coefficients associated with the last 10 seconds of the "reading/problem solving" condition were created. Two contrasts (Example–No Example) and (No Example–Example) were then created. Whole-brain Type-1 error rate was controlled using the false discovery rate method with $q = 0.05$ (Benjamini & Hochberg 1995). Contrasting the Example condition to the No Example condition, the last 10 seconds of the "reading/problem solving" phases of the study were examined, just prior to the beginning of the verbal response. This window was chosen to ensure activation from the problem solving activity had time to occur while pre-empting any activation from speaking. Results were averaged across 20 participants. Significant positive activation in this contrast would indicate effects from the Example condition, while significant deactivation would indicate effects from the No Example condition.

A region of interest (ROI) analysis was also done, specifically looking at the superior frontal gyrus (SFG) and again examining the last 10 seconds of the "reading/problem solving" phases of the study, just prior to the beginning of the verbal response. This ROI mask was taken from the AFNI atlas CA_ML_18_MNIA and was chosen based on prior results found in this region by Alexiou *et al.* (2009). Note that this atlas is based on the MNI_ANAT template space, while the MNI template space was used for visualizing T-map results. Finally, a one-way analysis of variance was performed comparing the average beta values within the above ROI across participants for a given design problem, and across conditions, to the novelty and quality results of the concepts generated.

6. Results

6.1. fMRI results

6.1.1. Whole-brain group analysis

Results from the whole-brain group level analysis can be seen in Figure 4, with further detail provided in Table 2. When comparing the combined brain T-maps of Example to No Example conditions, significant positive activation was observed in the right inferior temporal gyrus (IFG), left middle occipital gyrus (MOG), and

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

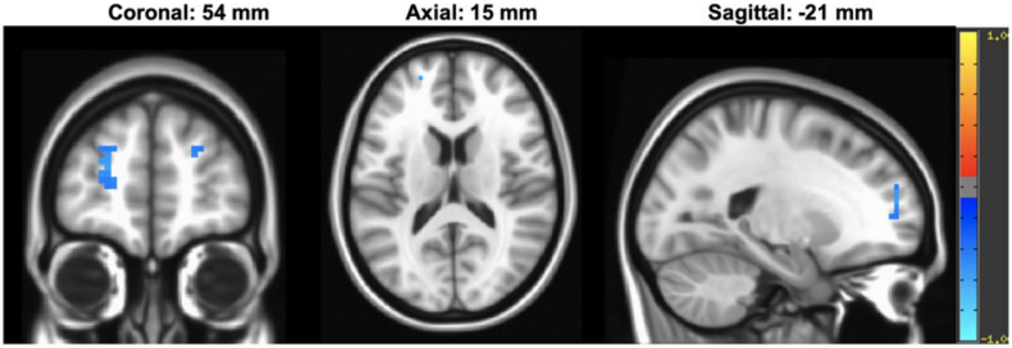

Figure 5. T-maps; region of interest (ROI) superior frontal gyrus results comparing Example to No Example condition, showing deactivation (No Example condition positive activation) in left superior frontal gyrus; 17 contiguous voxels, results shown on MNI brain, left = left, $q = 0.05$, $p = 0.0031$, range $= -8$ to 8.

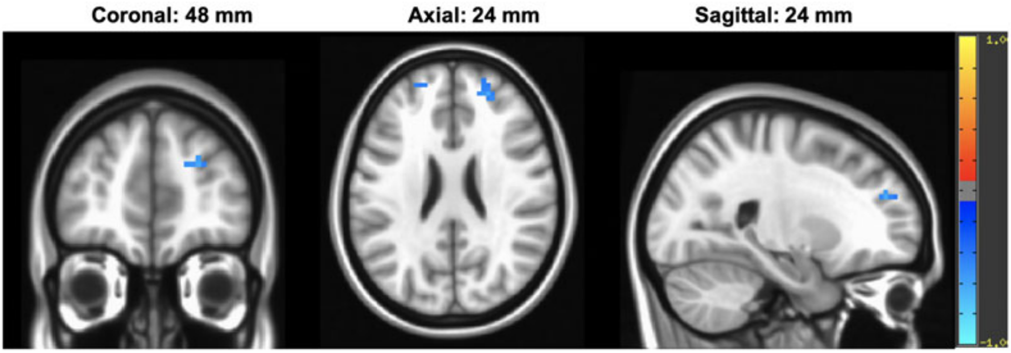

Figure 6. T-maps; region of interest (ROI) superior frontal gyrus results comparing Example to No Example condition, showing deactivation (No Example condition positive activation) in right superior frontal gyrus; 15 contiguous voxels, results shown on MNI brain, left = left, $q = 0.05$, $p = 0.0031$, range $= -8$ to 8.

right superior parietal lobule (SPL). Significant deactivation (or positive activation for the No Example condition) was found in the left lingual gyrus (LG). All T-maps are overlaid on the MNI brain, with a threshold of 15 contiguous voxels and a range of -8 to 8, corrected to $q = 0.05$ significance. The group results include 20 participants.

6.1.2. ROI SFG group analysis

Results from the ROI SFG group level analysis can be seen in Figures 5 and 6, with further detail provided in Table 3. When comparing the combined brain T-maps of Example to No Example conditions, significant deactivation (or positive activation for the No Example condition) was observed in the left SFG (Figure 5) and right SFG (Figure 6).

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

Table 2. fMRI results from Example vs. No Example contrast

Laterality	Region	*t*-value at peak	Size (voxels)	MNI coordinates of peak voxel *x*	*y*	*z*
Increases (Example Condition causes positive activation)						
Right	Inferior temporal gyrus	6.79	421	−51	72	−3
Left	Middle occipital gyrus	7.03	169	33	93	9
Right	Superior parietal lobule	6.16	18	−30	51	60
Decreases (No Example Condition causes positive activation)						
Left	Lingual gyrus	−7.29	15	12	81	−3

Table 3. fMRI superior frontal gyrus ROI results from Example vs. No Example contrast

Laterality	Region	*t*-value at peak	Size (voxels)	MNI coordinates of peak voxel *x*	*y*	*z*
Decreases (No Example Condition causes positive activation)						
Left	Superior frontal gyrus	−4.80	17	21	−54	15
Right	Superior frontal gyrus	−4.95	15	−24	−48	24

6.2. Design problem solving results

Design solutions were analyzed for feature transfer from example design solutions to detect fixation as well as quality and novelty. Each of these metrics and the corresponding results are discussed next in Sections 6.2.1–6.2.3.

6.2.1. Example design solution feature transfer

Using the audio data collected during scanning, the design problem solutions were transcribed and analyzed for evidence of fixation, quality, and novelty. To detect the presence of design fixation, each example solution was analyzed for features that could have caused fixation, leading to participants copying these features into their own design problem solutions. These features are shown in Table 4. Features included in this list are only those that are very specific to the example solution shown. The selection of these features is in line with prior studies of fixation and their selection of features for feature transfer analysis (Linsey *et al.* 2010).

Each design problem solution was then analyzed to determine how many of these features had been copied from the example problem to the solution. Both Example and No Example condition design data were analyzed using the No Example condition as a baseline to determine if these features are simply elements of commonly generated solutions or were truly being copied from the example. The results of this analysis are shown in Figure 7, showing percentage of feature transfer for both conditions by design problem. The overall percentage of example features in the design solutions is higher for the Example condition than the No Example condition. Example features were used more in the No Example condition for design problems 6, 7, and 9 only. Levene's test for homogeneity of

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

Table 4. Key features of design solutions that could be copied in design fixation

Design problem	Features
DP1: Design a device to clean whiteboards more efficiently than a typical whiteboard eraser.	• Sponge • Double-sided
DP2: Design a desk that is capable of hiding whatever is on the desk from people sitting beside and behind the desk.	• Flips horizontal/to down position
DP3: Design a wearable device that converts everyday human motion into electrical potential energy stored in a battery.	• Soccer ball • Solenoid
DP4: Design a braking mechanism to stop railroad trains in the case of an emergency that acts in addition to the already-present brakes to more efficiently stop the train.	• Parachute brake
DP5: Design a rack to hold wet umbrellas brought into a room.	• Can hold short and long umbrellas • Labeled cubbies • Water catchment
DP6: Design a suitcase that has a mechanism by which it can weigh itself for the purpose of assisting people in packing for flights.	• Display on handle
DP7: Design a device to safely store people's wallets and phones and protect them from theft on the beach.	• Locking safe • Bury in sand
DP8: Design a device that assists someone with opening a jar whose lid is on too tight for the person to open it using just his or her hands.	• Made of rubber • Pull action
DP9: Design a set of roller skates capable of performing on gravel and dirt.	• Large treads
DP10: Design a device to shell peanuts without harming the nut inside.	• Plier handle squeeze

variances indicated that there are no significant differences between the variances ($p = 0.066$); however, the data was not found to be normally distributed. As such, a Friedman Test was performed, which is appropriate for the comparison of means in a within-subjects experiment with non-normally distributed data. The independent variable was the Example/No Example treatment, and the dependent variable was the overall percent of features from the example solution used in the participant's design solution. Results indicated that there were significant differences between the Example (mean $= 0.23$, $n = 85$) and No Example (mean $= 0.15$, $n = 85$) conditions for percentage of features transferred (Chi-Square $= 3.6$, $p = 0.05$). These results indicate that fixation was successfully induced by the example solutions provided.

6.2.2. Design solution quality

The design problem solutions were also coded for quality. For each design problem, the requirements embedded in the design problem statement were used to evaluate the quality of the design using a rubric-based assessment. Designs were evaluated on a scale from -2 to 2, with each level explicitly defined for each evaluation criteria. These ratings were then normalized, shifting all scores

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

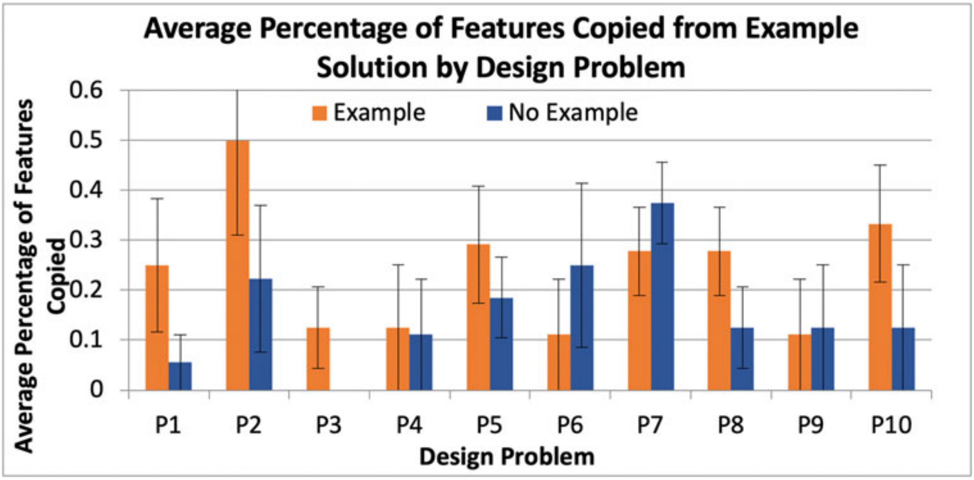

Figure 7. Percentage of participants who employed example feature in design solution for both Example and No Example conditions, error bars show ± one standard error.

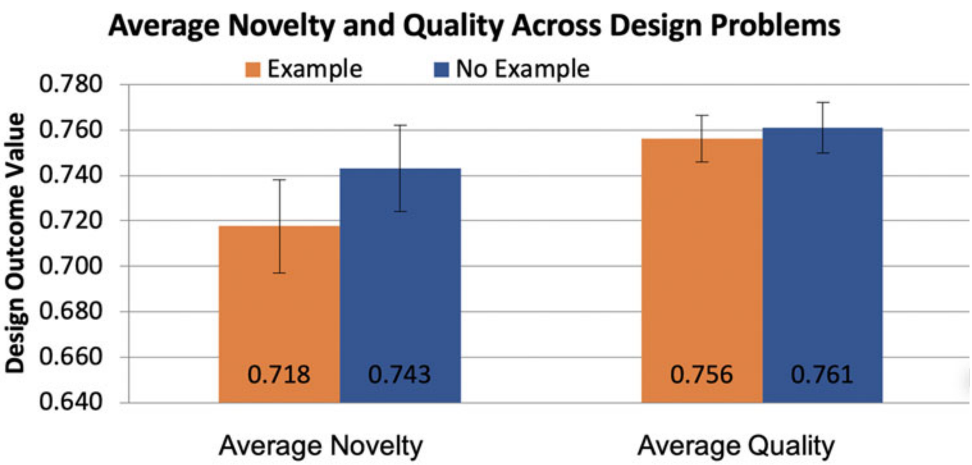

Figure 8. Average novelty and quality of design solutions across design problems, error bars show ± one standard error.

to be between 0 and 1. Two independent coders evaluated the design concepts, achieving 80.1% agreement on quality ratings. The coders were both senior-level undergraduate researchers in engineering, with previous experience rating design concepts. This inter-rater agreement level indicates a robust quality metric. Two outliers were identified in the data using the 1.5IQR rule and were removed prior to analysis. Levene's test for homogeneity of variances indicated that there were no significant differences between the variances ($p = 0.599$); however, the data was not found to be normally distributed. Thus, a Friedman Test was performed, which is appropriate for the comparison on means in a within-subjects experiment with non-normally distributed data. The independent variable was the Example/No Example treatment and the dependent variable was the quality of the design

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

Table 5. Spearman's rho correlations between average beta values over SFG ROI with feature transfer, quality, and novelty correlations

			AvgBetaROI	Quality	Novelty	FeatureCopy
Spearman's rho	AvgBetaROI	Correlation coefficient	1.000	−0.069	−0.168[a]	−0.067
		Sig. (2-tailed)	–	0.375	0.030	0.391
		N	168	166	168	168

[a]Correlation is significant at the 0.05 level (2-tailed).

solution. Results indicated that there were no significant differences between the Example (mean $= 0.75$, $n = 83$) and No Example (mean $= 0.76$, $n = 83$) conditions for quality of design solution (Chi-Square $= 0.05$, $p = 0.82$). These results are plotted in Figure 8, along with novelty results across design problems, which will be discussed next in Section 6.2.3.

6.2.3. Design solution novelty

Design solutions were analyzed for novelty using the Shah *et al.* metric (Shah, Vargas-Hernandez & Smith 2003) with two independent coders. As with the quality ratings, the coders were both senior-level undergraduate researchers in engineering, with prior experience in rating design concepts. An inter-rater agreement of 81.8% was achieved, indicating a robust novelty metric. Novelty scores were also normalized, so all values fall between 0 and 1. The average novelty score by condition, with all design problems pooled together, is plotted in Figure 8. Levene's test indicated that variances were not significantly different ($p = 0.670$); however, the data was not found to be normally distributed. Thus, a Friedman Test was performed, which is appropriate for the comparison of means in a within-subjects experiment with non-normally distributed data. The independent variable was the Example/No Example treatment and the dependent variable was the novelty of the design solution. Results indicated that there were no significant differences between the Example (mean $= 0.71$, $n = 85$) and No Example (mean $= 0.74$, $n = 85$) conditions for novelty of design solution (Chi-Square $= 3.12$, $p = 0.07$).

6.2.4. Summary

Participant design solutions were analyzed for feature transfer, quality, and novelty. The Example and No Example conditions with the 10 design problems pooled were not significantly different from one another for quality or novelty; however, the feature transfer analysis indicated that participants in the Example condition did experience fixation at a statistically significant level.

6.3. Comparison of fMRI results to design problem solving results

Using the same SFG ROI, the beta values were averaged over the whole ROI for each participant, for each design problem, and each condition. Two outliers were identified in the data using the 1.5IQR rule and removed prior to analysis. The correlations between average beta values and novelty, quality, and feature transfer

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

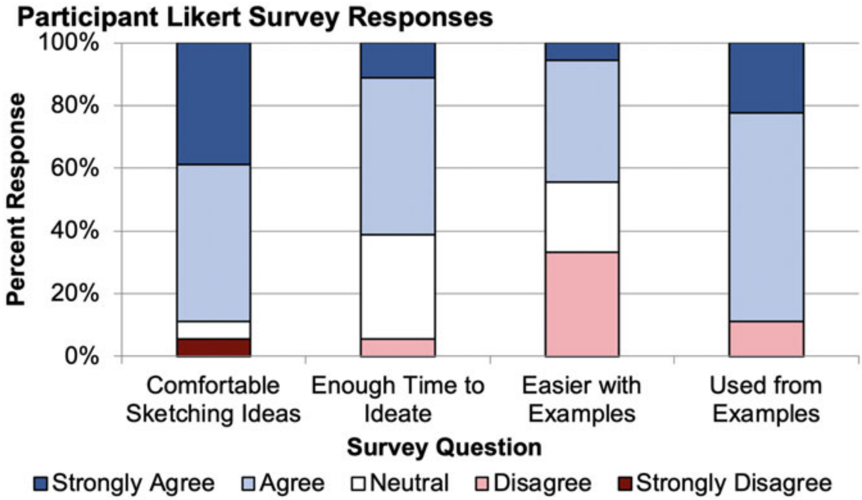

Figure 9. Percentages of Participant Responses to Likert Scale Survey Questions.

were analyzed using Spearman's rho as the average beta data were found to be non-normally distributed. The outcomes of these analyses, by condition and by design problem, are shown in Table 5. A significant negative correlation between the average beta values and novelty scores was found ($r = -0.168$, $p = 0.030$).

Levene's test indicated homogeneity of variances of the average beta values data ($p = 0.92$); however, the data was not found to be normally distributed. Thus, a Friedman Test was performed, which is appropriate for the comparison on means in a within-subjects experiment with non-normally distributed data. The independent variable was the Example/No Example treatment and the dependent variable was the average beta value. Results indicate that there the average beta values were not significantly different across the Example (mean $= -0.02$, $n =$ 83) vs. No Example (mean $= -0.02$, $n = 83$) conditions (Chi-Square $= 0.59$, $p = 0.44$).

6.4. Post-experiment survey results

After the conclusion of the scanning portion of the experiment, each participant was surveyed about their experience. Two of the 20 participants chose not to complete the survey. Response data from selected questions is presented in Figure 9. A clear majority of participants felt comfortable sketching their ideas. When asked directly about the time constraints, most participants indicated that they were given enough time to come up with solutions. Still, in the comment section, five of the participants suggested that the time constraint limited them to a single solution. However, these participants all indicated that they either agreed or strongly agreed that there was enough time to ideate in an earlier time constraint question. Only one participant disagreed that there was enough time to ideate.

Nearly half of the respondents, 8 of the 18, reported having difficulty coming up with solutions that shared no commonality with the provided example solution, indicating that some level of fixation took place. Four of the eight students that expressed difficulty generating designs distinct from the example also disagreed

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

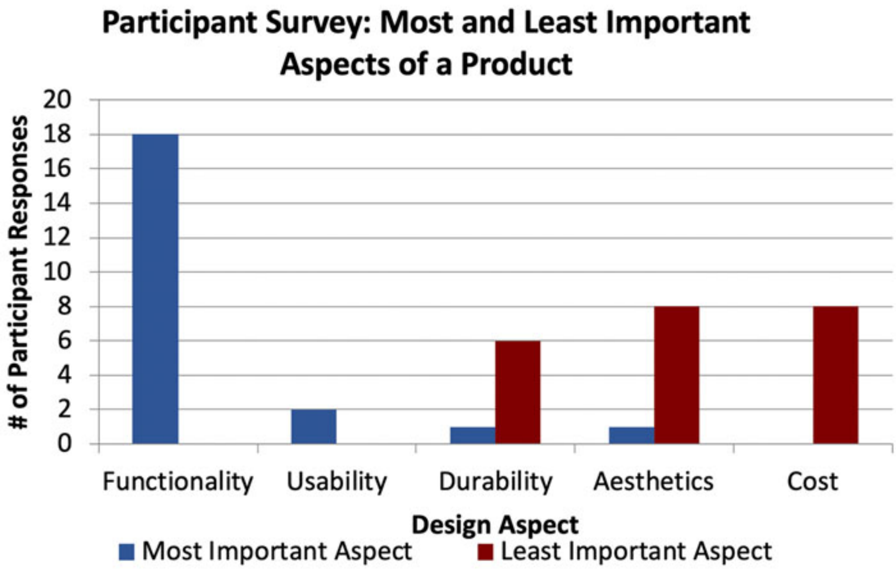

Figure 10. Participant Survey Responses for Most and Least Important Aspects of a Product.

that the examples made it easier for them to come up with a solution. Six of the participants who agreed that design generation was easier with the example solution also indicated that they used the examples to help develop their solutions. When asked whether it was easier to come up with a design solution when provided an example, only 4 of the 18 participants reported that the examples facilitated their thought process.

Participants were also asked which aspect of the design they considered most and least important. A summary of those responses is shown in Figure 10. Participants overwhelmingly chose functionality as the most important design aspect. Responses were more divided about the least important aspects, with two-thirds of the participants splitting their choices evenly between aesthetics and cost. The focus on functionality is consistent with the regions of activation that were observed, as opposed to areas having to do with emotional cost–benefit analysis.

Finally, participants indicated the perceived impact of the example solutions on their problem solving. As a reminder, each participant solved five problems with an example solution and five without an example solution. Figure 11 shows the responses to these questions. Most respondents to this question confirmed that they drew from the example solutions, and 64.2% of all respondents to this question felt it was easier to generate a design concept after being exposed to the example solution.

7. Discussion

Hypothesis 1 pertains to the detection and observation of fixation in a designer's brain as they work on generating design solutions. This hypothesis was supported by the results of this study. Results from the survey show that participants had

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

Impact of Examples

	Easier with Examples	Not Easier with Examples
Used from Examples	9	5
Did not Use from Examples	0	1

Figure 11. Survey responses showing perceived impact of design examples on ideation.

difficulty generating solutions that were distinct from the example solutions, providing evidence that fixation occurred on some level. It is likely that the presence of the example, as well as the accompanying fixation, is a contributing factor to the unique pattern of activation that is observed when comparing the Example condition to the No Example condition. While no activation was found in the prefrontal cortex as theorized in Hypothesis 2, activation was found in the occipital lobe, where the visual cortex is located. Activation in the middle occipital gyrus (MOG) is consistent with the participants expending mental effort to process the information in the image of the example solution. As previously noted, nearly half of the participants reported difficulty coming up with solutions that were completely different from the examples. The activation in the precuneus region could have resulted from participants trying to recall prior experience with aspects of the design problems as well as attempts to contextualize the example solution. Hypothesis 3 was also supported by the results of this study. The areas where activation was found are often associated with spatial processing and are very close to the region associated with goal-directed movement.

The parietal lobule, associated with the dorsal stream, and the IFG, associated with the ventral stream, contribute to image processing by facilitating the recognition of an object's location and identity, respectively. Recent findings have caused some researchers to conclude that the parietal and occipital brain areas play a significant role in mental imagery (Fink *et al.* 2014). This activation pattern may be the result of the subjects imagining their potential solutions. As a major part of the visual cortex, the MOG also plays an important role in the semantic processing of visual images (Vandenberghe *et al.* 1996). The activation observed in these areas during the example condition is consistent with the subjects expending effort to process the picture provided as an example solution. Additionally, the MOG is linked to the extrastriate body region described by Astafiev *et al.* (Astafiev *et al.* 2004). This region, located in the lateral occipital cortex, is associated

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

with perception of body movement and goal-directed movements. This pattern may be the result of the subjects imagining how they would interact with their solutions. Our brains are able to predict and compensate for changes in the mechanical behavior of a system by altering our internal models. This strategy may be accompanied by increased activation in the MOG (Shadmehr & Holcomb 1997).

Qiu *et al.* used fMRI to observe activation during "Aha and No-aha" conditions as subjects solved visually based word puzzles. Among other areas, increased activation was observed in the precuneus and inferior occipital gyrus and linked to the "Aha" effects indicating that the inferior occipital gyrus may have a role in the re-arrangement of visual stimulus (Qiu *et al.* 2010). Moreover, a variety of creative tasks have been associated with some increased activation in the MOG (Howard-Jones *et al.* 2005; Ellamil *et al.* 2012; Aziz-Zadeh, Liew & Dandekar 2013; Boccia *et al.* 2015; Chen *et al.* 2015). In a work by Chrysikou and Thompson-Schill, subjects were tasked with thinking up uncommon uses for familiar objects. Solutions that were judged to be perceptually based (i.e., containing properties visible or available without prior knowledge of the object's identity (e.g., tennis racket: to use as a snow shoe) or properties visible or available without prior knowledge of the object's identity (e.g., chair: to use as firewood)) were accompanied by greater activation in the middle occipital cortex (Chrysikou & Thompson-Schill 2011). The MOG activation present in this study may indicate a focus on incorporating attributes from the example solutions.

When compared to the No Example condition, deactivation was observed in the LG, an area associated with processing letter images and visual memories. This pattern of activity suggests that the presence of the example image may have shifted the focus of the subjects' mental effort from the design prompt to the example image and potentially limited their thinking. Deactivation was also observed in the left and right SFG. These areas are close in proximity to the prefrontal cortex, which has been argued to be a major contributing area to creativity (Dietrich 2004) and divergent thinking (Beaty *et al.* 2017). Based on the ROI analysis, a significant negative correlation between the average beta values in the SFG ROI and novelty scores was found. This indicates that, within this study, as novelty scores increase, activity in the SFG decreases across conditions and design problems. A meta-analysis of 45 fMRI studies yielded insights into some of the areas commonly associated with musical, verbal, and visuospatial creative activities (Boccia *et al.* 2015). In this context, verbal activities included tasks such as finding uncommon uses for everyday objects. The analysis found that verbal creative activities were more likely to be associated with activation in several areas, including the prefrontal cortex, the middle and superior temporal gyri, the MOG, the right inferior frontal gyrus, and the LG. The pattern of deactivation observed in this work may indicate a decrease in creative processes when an example is provided.

Design problem solving results did not indicate statistically significant differences in novelty or quality between the Example and No Example conditions. However, significant differences in feature transfer indicated that fixation was successfully induced, as has been consistently done in prior studies that use paper-based design ideation. The results indicate statistically significant differences between the fixation conditions in the fMRI data, as well. With this information, we will be able to design subsequent studies with imaging

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

techniques that target the areas of interest found here without restricting motion to such a high degree. One promising technology is functional near-infrared spectroscopy (fNIRS). This technology, which uses infrared light to acquire BOLD signals in more natural environments, has already been used successfully in some investigations of design-related activities (Shealy, Hu & Gero 2018).

The design problem solved in experiments like this one can significantly impact the results in design data outcomes. The level of difficulty or commonness of, or subjects' familiarity with, the problem are likely to impact the feature transfer, quality, and novelty of design solutions, as shown in prior work (Chan *et al.* 2011). One way to mitigate this variability is to test multiple design problems within the same experimental setup to determine whether effects are robust to changes in the design problem. Generalizability of experimental results in design science is always limited by the context in which the data was collected; this is an ongoing challenge to human subject-based research in design. A study by Kumar and Mocko used latent semantic analysis to compare the design problems used in design cognition research, finding high correlation with the goal of a problem, functional requirements, non-functional requirements, and reference to an existing product, and low correlation with information about the end user. This indicates the importance of using similar or benchmarked design problems in experimental design to increase the ability to compare results across experiments (Kumar & Mocko 2016).

When reflecting upon how these results might influence design practice, it is important to remember that the literature indicates that designers are often not even aware of their own design fixation (Linsey *et al.* 2010). When choosing the process, tools, steps, and order of the design activities, the results from this study indicate that it is important for designers to consider that their mental effort may be diverted away from their desired task of ideation if fixation has occurred. For example, if a designer is examining pre-existing solutions for benchmarking and market research analysis, exposing themselves to these "example solutions" prior to or during concept generation may cause them to experience fixation. Diminished focus or mental energy used on a task can lead to fatigue, lower productivity, and frustration. If fixation may have been induced, designers might proactively choose to use mitigation techniques to invigorate their ideation process and outcomes.

8. Limitations

One of the limitations of this study was the slight disconnect between the modes in which the example was presented (a static image) and how the subjects responded (verbal description). Different activation may have been observed if the subject had been given a verbal description of the example solution. Results may have also differed if they had been able to sketch their solutions. This was not possible in an fMRI environment. With verbal responses in fMRI studies, there are always challenges with motion of the head or jaw while speaking, which may lead to unusable or flawed data due to changes in the magnetic field due to the motion. Mitigating factors to this challenge include the fact that the contrasts examined in the analysis are not during talking periods, and the motion analysis tracking head movement of the participants indicated that no one moved more than 3 mm during the study. Birn *et al.* confirmed that verbal response in fMRI research can produce robust results (Birn, Cox & Bandettini 2004).

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

This study focused on developing mechanical design solutions. Results from the survey show that subjects were by far most concerned about the functionality of the solution. Since different areas of the brain are associated with processing different types of information, it is possible that fixation during the design of something aesthetic, for example, may look completely different than the fixation observed in this study. Fixation and design outcomes have been shown to be affected by other factors, such as problem framing (Dorst & Cross 2001), level or number of constraints (Bonnardel 2000), and familiarity with or commonness of the design problem (Chan *et al.* 2011). Particularly when it comes to constraints on a design problem space, too many constraints can impede creativity, but a few may help to simplify the design problem and induce more creativity (Caniëls & Rietzschel 2015). These are factors that could be explored in future work.

As can be seen in the study design, the Example condition viewed images that were not present in the No Example stimuli, creating a more complex set of stimuli for the Example condition. It cannot be ruled out that the image had an impact on the activation patterns in the Example condition; however, it is argued that fixation is directly related to visual stimulus and cannot necessarily be decoupled from it. The control (No Example) condition could have alternatively included an unrelated "dummy" image to balance the extra visual processing required by the fixation (Example) condition. However, in prior research, the authors have found that, as humans are wont to do, participants try to find patterns and relate any stimuli to the problem at hand, even when it is intended to be completely unrelated and random. This phenomenon could have muddled the measurable impact of the example solution in a different way. The Example vs. No Example condition is closer to what participants would encounter in real-world problem solving – making the choice between looking at examples or other solutions during ideation vs. not doing so. Higher order visual regions in the inferior temporal cortex, along ventral and dorsal pathways, showed significant activation in response to the Example condition. These are regions that are more involved in integrating the objects and their space and visual memory (Miller, Li & Desimone 1991), rather than lower-level visual processing. Goucher-Lambert *et al.* found that when participants were exposed to either no analogical inspiration or inspiration that was too far from the design problem, they showed evidence of unsuccessful design ideation with corresponding activation of regions associated with visual processing (Goucher-Lambert, Moss & Cagan 2019, 2018*b*). This activation was found in the absence of image-based stimuli as the inspiration was text-based. Saggar *et al.* developed a Pictionary-based paradigm to examine creativity and improvisation using fMRI (Saggar *et al.* 2017, 2015); they found increased activation in left frontoparietal regions (or the "visual sketchpad") in response to stimuli that were solely text-based, as well. Thus, the activation found is unlikely to be caused solely by that additional complexity (presence of the image) of the Example condition. Nonetheless, this is an important limitation of the study to consider, particularly for future neuropsychological studies of design fixation.

Finally, total fMRI study duration is limited to approximately 60 minutes to account for fatigue of subjects. That time is subdivided into smaller chunks of actual scanning, during which subjects must remain completely still to ensure that the data is readable. Ideally, the participants would have been given more time to ideate. The limitation of one concept generated per design problem was derived from this time constraint. However, prior research has shown that obtaining

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

novelty results from single design solution data is particularly challenging as novelty tends to increase over the course of idea generation (Tsenn *et al.* 2014). This limitation could be addressed by using more mobile neural imaging techniques, such as electroencephalogram (EEG) or fNIRS, so that subjects can complete a long-form ideation task. This would allow us to learn more about the effect of fixation over time and for more ideas to be generated per design problem, thus improving the assessment of novelty of ideas. The fMRI study was run first so that a picture of the whole-brain activity could be obtained. In collecting signals across the entire brain, some of the regions involved were identified to be on the cortical surface; as such, techniques such as EEG and fNIRS, which are sensitive to the cortex, could be used to allow for longer data collection and enable a more typical design environment for data collection. Fink *et al.* have used EEG and fMRI to jointly study creativity using the same intervention (Fink *et al.* 2009). This initial exploratory study has laid the foundation for follow-up studies with these alternative techniques.

9. Conclusions

Design fixation and its mitigation have emerged as important topics. This work sought a better understanding of the neural mechanisms behind fixation as a first step in developing new approaches to mitigation. Neuroimaging has proven to be a powerful tool for gaining insight into cognitive processes. The results from this study showed that specific areas of the brain could be isolated and identified as being activated in the presence of fixation. These findings encourage further study of design fixation using a neurological approach. Design problem solving data indicated that these fixation effects were detectable at a statistically significant level when examining feature transfer. The left LG and SFG were found to be less active in the example condition; these areas are in close proximity to the prefrontal cortex, which is associated with creative output. The spatial patterns of activation provide evidence of the shift in mental resources that can occur when a designer becomes fixated. For designers, this might be a tradeoff to consider when deciding how and when to benchmark existing solutions to the problem, relative to when they perform their ideation. As understanding of these neural mechanisms continues to improve, the effectiveness of mitigation strategies will also improve, creating a positive effect on the output of ideation activities.

Acknowledgments

We would like to thank the members and the leadership of CABI for their guidance, instruction, and expert contributions to this research. In particular, we would like to thank Dr. Eric Schumacher for his support and valuable feedback on this work, Nytavia Wallace for her support and scanning expertise during data collection, and Derek Smith for his guidance and assistance with analysis.

Financial support

This work was generously supported by a GSU/GT Center for Advanced Brain Imaging Neuroscience Research Seed Grant.

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

Appendix A. Full list of 10 design problems given during the study

(1) **Design a device to clean whiteboards more efficiently than a typical whiteboard eraser**

  (a) The device should eliminate as much marker from the white board as possible

  (b) The device should be at least as easy to use as a typical whiteboard eraser

  (c) The device should enable the whiteboard to be cleaned faster than it could be with a typical whiteboard eraser

(2) **Design a desk that is capable of hiding whatever is on the desk from people sitting beside and behind the desk, with the intention of it being used for exams to prevent cheating**

  (a) The desk should not hinder the student's ability to participate normally in lecture or in class discussions when an exam is not ongoing

  (b) The desk should be able to be set up in its state to prevent cheating in as little time as possible

  (c) The desk should provide the student as much room to work on it as a standard desk

(3) **Design a wearable device which converts everyday human motion into electrical potential energy stored in a battery**

  (a) The device should not hinder one's ability to perform everyday tasks

  (b) The device should be safe

  (c) The device should be able to be put on and taken off by the person wearing it

  (d) The device should be comfortable to wear

(4) **Design a braking mechanism to stop railroad trains in the case of an emergency which acts in addition to the already-present brakes to more effectively stop the train**

  (a) The mechanism should not bring the train to so sudden a stop as to put the occupants in danger

  (b) The mechanism should reduce the distance required to stop by the train

  (c) The mechanism should be deployable in all weather conditions

  (d) The mechanism should be deployable in tunnels as well as outside

(5) **Design a rack to hold wet umbrellas brought into a room**

  (a) The rack should be designed so that no water spills on the floor or gets left on the wall of the room

  (b) It should be easy and intuitive to place one's umbrella on the rack and retrieve it later

  (c) The umbrellas should be stored such that one can later recognize where one left his or her umbrella

(6) **Design a suitcase that has a mechanism by which it can weigh itself for the purpose of assisting people in packing for flights**

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

   (a) The suitcase should display its total weight including the weight of the suitcase itself and its contents
   (b) The suitcase itself should not exceed 50 pounds, the average accepted weight for checked bags with no additional charge
   (c) The suitcase should provide as much room as a standard suitcase, and should be as easily used as one

(7) **Design a device to safely store people's wallets and phones and protect them from theft on the beach**
   (a) The device should somehow make it more difficult for a thief to gain access to someone's wallet or phone which was left on the beach
   (b) The device should allow the owners to get back their things whenever they want
   (c) The device should be compatible with the beach and should perform in sand

(8) **Design a device which assists someone with opening a jar whose lid is on too tight for the person to open it using only his or her hands**
   (a) The device should be usable by one person
   (b) The device should not damage or destroy the jar or the lid
   (c) The device should allow the jar to be opened in no longer than a minute
   (d) The device should be safe to use in an inside environment

(9) **Design a set of roller skates capable of performing on gravel and dirt**
   (a) The skates must be safe to ride on gravel and dirt
   (b) The skates must effectively preserve most of the user's momentum while riding on gravel or dirt
   (c) The skates must not deteriorate as a result of riding in gravel or dirt

(10) **Design a device to shell peanuts without harming the nut inside**
   (a) The device should be low cost and easy to manufacture
   (b) The device should not use electricity

Appendix B. Example verbal responses for design problem solutions

Participant 2, No Example condition, design problem 1:

"a solution to this would be a uh some sort of um dry erase mark dry erase like uh eraser uh a [dirty black] one that has like a water reservoir built into it so like when you wipe it it kinda [goes ahead and] moistens the white board and then has perhaps maybe a dryer inside so when you push it across in a specific direction wets it and then dries it immediately so that way you don't have to scrub at all"

Participant 2, Example condition, design problem 6:

"Um the problems with this uh design to be honest uh not to just copy that the picture but that's probably the best way to do it uh I know there's a lot of common uh luggage weight uh devices [that you could just use] to implement that into the handle so when you pick it up it'll tell you how much it weighs you could have it set to like [kinda] give you alarms when it hits certain uh um weight

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

requirements like it's too heavy and uh yeah have some [kind of LED] display to display the"

Participant 9, No Example condition, design problem 7:

"Ahh, [to] start with like a plastic pouch of some sort of a [liquid . . .] or a wallet is so its water-tight. Umm, I guess it's some sort of [pill], something that [opens . . .], a bottle [that's not like the] ocean. Insert a [sensor for motion] so that if it is stolen it'll have an alarm bell that will go off really loudly."

Participant 9, Example condition, design problem 5:

"Ahh, I would use something very similar to the example, drawing from the [cubbies] except I would enclose all around the outside using some sort of flexi-glass or a super material so that you can identify your umbrella. And then it would have a removable drip tray or a [tradeable] drip tray at the bottom."

References

Abraham, A. & **Windmann, S.** 2007 Creative cognition: The diverse operations and the prospect of applying a cognitive neuroscience perspective. *Methods* **42**, 38–48.

Abraham, A. 2012 The neuroscience of creativity: A promising or perilous enterprise? In *Creativity and Cognitive Neuroscience* **(ed. A. P. Alejandre)**, pp. 15–24. Fundación Tomás Pascual y Pilar Gómez-Cuétera, Madrid.

Abraham, A., **Pieritz, K.**, **Thybusch, K.**, **Rutter, B.**, **Kröger, S.**, **Schweckendiek, J.**, **Stark, R.**, **Windmann, S.** & **Hermann, C.** 2012 Creativity and the brain: uncovering the neural signature of conceptual expansion. *Neuropsychologia* **50**, 1906–1917.

Abraham, A., **Beudt, S.**, **Ott, D. V.** & **Von Cramon, D. Y.** 2012 Creative cognition and the brain: dissociations between frontal, parietal–temporal and basal ganglia groups. *Brain Research* **1482**, 55–70.

Abraham, A. 2013 The promises and perils of the neuroscience of creativity. *Frontiers in Human Neuroscience* **7**, 246.

Abraham, A., **Rutter, B.**, **Bantin, T.** & **Hermann, C.** 2018 Creative conceptual expansion: A combined fMRI replication and extension study to examine individual differences in creativity. *Neuropsychologia* **118**, 29–39.

Abraham, A., **Asquith, S.**, **Ahmed, H.** & **Bourisly, A. K.** 2018 Comparing the efficacy of four brief inductions in boosting short-term creativity. *Journal of Cognitive Enhancement* **3**, 1–9.

Abraham, A. 2019 The neuropsychology of creativity. *Current Opinion in Behavioral Sciences* **27**, 71–76.

Agogué, M., **Poirel, N.**, **Pineau, A.**, **Houdé, O.** & **Cassotti, M.** 2014 The impact of age and training on creativity: A design-theory approach to study fixation effects. *Thinking Skills and Creativity* **11**, 33–41.

Akhtar, S. 2018 *Comprehensive Dictionary of Psychoanalysis*. Routledge.

Alexiou, K., **Zamenopoulos, T.**, **Johnson, J. H.** & **Gilbert, S. J.** 2009 Exploring the neurological basis of design cognition using brain imaging: some preliminary results. *Design Studies* **30**, 623–647.

Alexiou, K., **Zamenopoulos, T.** & **Gilbert, S.** 2011 Imaging the designing brain: A neurocognitive exploration of design thinking. In *Design Computing and Cognition '10* **(ed. J. S. Gero)**, pp. 489–504. Springer, London.

Arslan, O. E. 2016 Computational basis of neural elements. In *Artificial Neural Network for Drug Design, Delivery and Disposition* **(ed. M. Puri, Y. Pathak, V. K. Sutariya, S. Tipparaju & W. Moreno)**, pp. 29–82. Academic Press.

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

Astafiev, S. V., **Stanley, C. M.**, **Shulman, G. L.** & **Corbetta, M.** 2004 Extrastriate body area in human occipital cortex responds to the performance of motor actions. *Nature Neuroscience* **7**, 542–548.

Aziz-Zadeh, L., **Liew, S. L.** & **Dandekar, F.** 2013 Exploring the neural correlates of visual creativity. *Social Cognitive and Affective Neuroscience* **8**, 475–480.

Benjamini, Y. & **Hochberg, Y.** 1995 Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series* B **57**, 289–300.

Beaty, R. E., **Benedek, M.**, **Wilkins, R. W.**, **Jauk, E.**, **Fink, A.**, **Silvia, P. J.**, **Hodges, D. A.**, **Koschutnig, K.** & **Neubauer, A. C.** 2014 Creativity and the default network: A functional connectivity analysis of the creative brain at rest. *Neuropsychologia* **64**, 92–98.

Beaty, R. E., **Benedek, M.**, **Kaufman, S. B.** & **Silvia, P. J.** 2015 Default and executive network coupling supports creative idea production. *Scientific Reports* **5**, 10964.

Beaty, R. E., **Benedek, M.**, **Silvia, P. J.** & **Schacter, D. L.** 2016 Creative cognition and brain network dynamics. *Trends in Cognitive Sciences* **20**, 87–95.

Beaty, R. E., **Christensen, A. P.**, **Benedek, M.**, **Silvia, P. J.** & **Schacter, D. L.** 2017 Creative constraints: Brain activity and network dynamics underlying semantic interference during idea production. *NeuroImage* **148**, 189–196.

Beaty, R. E., **Kenett, Y. N.**, **Christensen, A. P.**, **Rosenberg, M. D.**, **Benedek, M.**, **Chen, Q.**, **Fink, A.**, **Qiu, J.**, **Kwapil, T. R.**, **Kane, M. J.** & **Silvia, P. J.** 2018 Robust prediction of individual creative ability from brain functional connectivity. *Proceedings of the National Academy of Sciences* **115**, 1087–1092.

Beaty, R. E. & **Silvia, P. J.** 2012 Why do ideas get more creative across time? An executive interpretation of the serial order effect in divergent thinking tasks. *Psychology of Aesthetics, Creativity, and the Arts* **6**, 309–319.

Beaty, R. E., **Silvia, P. J.**, **Nusbaum, E. C.**, **Jauk, E.** & **Benedek, M.** 2014 The roles of associative and executive processes in creative cognition. *Memory and Cognition* **42**, 1186–1197.

Benedek, M., **Christensen, A. P.**, **Fink, A.** & **Beaty, R. E.** 2019 Creativity assessment in neuroscience research. *Psychology of Aesthetics, Creativity, and the Arts* **13**, 218–226; doi:http://dx.doi.org/10.1037/aca0000215.

Birn, R. M., **Cox, R. W.** & **Bandettini, P. A.** 2004 Experimental designs and processing strategies for fMRI studies involving overt verbal responses. *Neuroimage* **23**, 1046–1058.

Boccia, M., **Piccardi, L.**, **Palermo, L.**, **Nori, R.** & **Palmiero, M.** 2015 Where do bright ideas occur in ourbrain? Meta-analytic evidence from neuroimaging studies of domain-specific creativity. *Frontiers in Psychology* **6**, 1–12.

Bonnardel, N. 2000 Towards understanding and supporting creativity in design: Analogies in a constrained cognitive environment. *Knowledge-Based Systems* **13**, 505–513.

Caniëls, M. C. J. & **Rietzschel, E. F.** 2015 Organizing creativity: Creativity and innovation under constraints. *Creativity and Innovation Management* **24.2**, 184–196.

Chan, J., **Fu, K.**, **Schunn, C.**, **Cagan, J.**, **Wood, K.** & **Kotovsky, K.** 2011 On the benefits and pitfalls of analogies for innovative design: Ideation performance based on analogical distance, commonness, and modality of examples. *Journal of Mechanical Design* **133**, 081004–081015; doi:https://doi.org/10.1115/1.4004396.

Chan, J., **Dow, S. P.** & **Schunn, C. D.** 2015 Do the best design ideas (really) come from conceptually distant sources of inspiration? *Design Studies* **36**, 31–58.

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

Chen, Q. L., **Xu, T.**, **Yang, W. J.**, **Li, Y. D.**, **Sun, J. Z.**, **Wang, K. C.**, **Beaty, R. E.**, **Zhang, Q. L.**, **Zuo, X. N.** & **Qiu, J.** 2015 Individual differences in verbal creative thinking are reflected in the precuneus. *Neuropsychologia* **75**, 441–449.

Chen, Q., **Beaty, R. E.**, **Wei, D.**, **Yang, J.**, **Sun, J.**, **Liu, W.**, **Yang, W.**, **Zhang, Q.** & **Qiu, J.** 2016 Longitudinal alterations of frontoparietal and frontotemporal networks predict future creative cognitive ability. *Cerebral Cortex* **28**, 103–115.

Chrysikou, E. G. & **Weisberg, R. W.** 2005 Following the wrong footsteps: fixation effects of pictorial examples in a design problem solving task. *Journal of Experimental Psychology: Learning, Memory and Cognition* **31**, 1134–1148.

Chrysikou, E. G. & **Thompson-Schill, S. L.** 2011 Dissociable brain states linked to common and creative object use. *Human Brain Mapping* **32**, 665–675.

Cox, R. W. 1996 AFNI: Software for analysis and visualization of functional magnetic resonance neuroimages. *Computers and Biomedical Research* **29**, 162–173.

Crilly, N. 2018 'Fixation' and 'the pivot': Balancing persistence with flexibility in design and entrepreneurship. *International Journal of Design Creativity and Innovation* **6**, 52–65.

Curtis, C. E. & **D'Esposito, M.** 2003 Persistent activity in the prefrontal cortex during working memory. *Trends in Cognitive Sciences* **7**, 415–423.

Dietrich, A. 2004 The cognitive neuroscience of creativity. *Psychonomic Bulletin and Review* **11**, 1011–1026.

Dorst, K. & **Cross, N.** 2001 Creativity in the design process: co-evolution of problem–solution. *Design Studies* **22**, 425–437.

Ellamil, M., **Dobson, C.**, **Beeman, M.** & **Christoff, K.** 2012 Evaluative and generative modes of thought during the creative process. *NeuroImage* **59**, 1783–1794.

Finke, R. A., **Ward, T. B.** & **Smith, S. M.** 1996 *Creative Cognition: Theory, Research, and Applications*. Cambridge Mass, MIT Press.

Fink, A., **Koschutnig, K.**, **Hutterer, L.**, **Steiner, E.**, **Benedek, M.**, **Weber, B.**, **Reishofer, G.**, **Papousek, I.** & **Weiss, E. M.** 2014 Gray matter density in relation to different facets of verbal creativity. *Brain Structure and Function* **219**, 1263–1269.

Fink, A., **Benedek, M.**, **Koschutnig, K.**, **Pirker, E.**, **Berger, E.**, **Meister, S.**, **Neubauer, A. C.**, **Papousek, I.** & **Weiss, E. M.** 2015 Training of verbal creativity modulates brain activity in regions associated with language- and memory- related demands. *Human Brain Mapping* **36**, 4104–4115.

Fink, A., **Grabner, R. H.**, **Gebauer, D.**, **Reishofer, G.**, **Koschutnig, K.** & **Ebner, F.** 2010 Enhancing creativity by means of cognitive stimulation: Evidence from an fMRI study. *NeuroImage* **52**, 1687–1695.

Fink, A., **Grabner, R. H.**, **Benedek, M.**, **Reishofer, G.**, **Hauswirth, V.**, **Fally, M.**, **Neuper, C.**, **Ebner, F.** & **Neubauer, A. C.** 2009 The creative brain: Investigation of brain activity during creative problem solving by means of EEG and fMRI. *Human Brain Mapping* **30**, 734–748.

First, E. 1970 Fixation. In *Basic Psychoanalytic Concepts on Metapsychology, Conflicts, Anxiety and Other Subjects* **(ed. H. Nagera)**. Routledge.

Fu, K., **Cagan, J.** & **Kotovsky, K.** 2010 Design team convergence: the influence of example solution quality. *Journal of Mechanical Design* **132**, 111005-11.

Fu, K., **Chan, J.**, **Cagan, J.**, **Kotovsky, K.**, **Schunn, C.** & **Wood, K.** 2013 The meaning of "near" and "far": the impact of structuring design databases and the effect of distance of analogy on design Output. *ASME Journal of Mechanical Design* **135**, 021007–021019; doi:https://doi.org/10.1115/1.4023158.

Goff, K. & **Torrance, E. P.** 2002 *Abbreviated Torrance Test for Adults Manual*. Scholastic Testing Service, Inc.

https://doi.org/10.1017/dsj.2019.21 Published online by Cambridge University Press

Goldschmidt, G. 2011 Avoiding design fixation: Transformation and abstraction in mapping from source to target. *Journal of Creative Behavior* **45**, 92–100.

Goucher-Lambert, K., **Moss, J.** & **Cagan, J.** 2016 Using neuroimaging to understand moral product preference judgments involving sustainability. In *Presented at the ASME. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 28th International Conference on Design Theory and Methodology Charlotte, N.C*, ASME.

Goucher-Lambert, K., **Moss, J.** & **Cagan, J.** 2017 Inside the mind: using neuroimaging to understand moral product preference judgments involving sustainability. *Journal of Mechanical Design* **139**, 041103–041114; doi:https://doi.org/10.1115/1.4035859.

Goucher-Lambert, K., **Moss, J.** & **Cagan, J.** 2018*a* Inspired internal search: using neuroimaging to understand design ideation and concept generation with inspirational stimuli. In *Presented at the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE, Quebec City, Quebec, Canada*, ASME.

Goucher-Lambert, K., **Moss, J.** & **Cagan, J.** 2018*b* Unsuccessful external search: using neuroimaging to understand fruitless periods of design ideation involving inspirational stimuli. In *International Conference on-Design Computing and Cognition*, pp. 37–54. Springer.

Goucher-Lambert, K., **Moss, J.** & **Cagan, J.** 2019 A neuroimaging investigation of design ideation with and without inspirational stimuli – understanding the meaning of near and far stimuli. *Design Studies* **60**, 1–38.

Howard-Jones, P. A., **Blakemore, S. J.**, **Samuel, E. A.**, **Summers, I. R.** & **Claxton, G.** 2005 Semantic divergence and creative story generation: An fMRI investigation. *Cognitive Brain Research* **25**, 240–250.

Huettel, S. A., **Song, A. W.** & **McCarthy, G.** 2004 *Functional Magnetic Resonance Imaging*, vol. 1. Sinauer Associates, Sunderland, MA.

Jansson, D. G. & **Smith, S. M.** 1991 Design fixation. *Design Studies* **12**, 3–11.

Koh, E. C. & **De Lessio, M. P.** 2018 Fixation and distraction in creative design: the repercussions of reviewing patent documents to avoid infringement. *Research in Engineering Design* **29**, 351–366.

Krauzlis, R. J., **Goffart, L.** & **Hafed, Z. M.** 2017 Neuronal control of fixation and fixational eye movements. *Philosophical Transactions of the Royal Society of London, vol. Series B, Biological Sciences* **372**.

Kumar, V. & **Mocko, G.** 2016 Similarity of engineering design problems to enable reuse in design research experiments. In *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, ASME, pp. DETC2016–60474.

Linsey, J. S., **Tseng, I.**, **Fu, K.**, **Cagan, J.**, **Wood, K. L.** & **Schunn, C.** 2010 A study of design fixation, its mitigation and perception in engineering design faculty. *Journal of Mechanical Design* **132**, 041003–041015; doi:https://doi.org/10.1115/1.4001110.

Linsey, J., **Viswanathan, V. K.** & **Gadwal, A.** 2010 The influence of design problem complexity on the attainment of design skills and student perceptions. In *Presented at the IEEE EDUCON 2010 Conference*, IEEE.

Madore, K. P., **Thakral, P. P.**, **Beaty, R. E.**, **Addis, D. R.** & **Schacter, D. L.** 2017 Neural mechanisms of episodic retrieval support divergent creative thinking. *Cerebral Cortex* **29**, 150–166.

Miller, E. K., **Li, L.** & **Desimone, R.** 1991 A neural mechanism for working and recognition memory in inferior temporal cortex. *Science* **254**, 1377–1379.

Moss, J., **Kotovsky, K.** & **Cagan, J.** 2011 The effect of incidental hints when problems are suspended before, during, or after an impasse. *Journal of Experimental Psychology: Learning Memory and Cognition* **37**, 140–148.

Purcell, A. T. & **Gero, J. S.** 1992 Effects of examples on the results of a design activity. *Knowledge-Based Systems* **5**, 82–91.

Purcell, A. T. & **Gero, J. S.** 1996 Design and other types of fixation. *Design Studies* **17**.

Purcell, A. T., **Williams, P.**, **Gero, J. S.** & **Colbron, B.** 1993 Fixation effects: Do they exist in design problem solving? *Environment and Planning B: Planning and Design* **20**, 333–345.

Qiu, J., **Li, H.**, **Jou, J.**, **Liu, J.**, **Luo, Y.**, **Feng, T.**, **Wu, Z.** & **Zhang, Q.** 2010 Neural correlates of the "Aha" experiences: Evidence from an fMRI study of insight problem solving. *Cortex* **46**, 397–403.

Saggar, M., **Quintin, E. M.**, **Kienitz, E.**, **Bott, N. T.**, **Sun, Z.**, **Hong, W. C.**, **Chien, Y. H.**, **Liu, N.**, **Dougherty, R. F.**, **Royalty, A.** & **Hawthorne, G.** 2015 Pictionary-based fMRI paradigm to study the neural correlates of spontaneous improvisation and figural creativity. *Scientific Reports* **5**, 10894.

Saggar, M., **Quintin, E. M.**, **Bott, N. T.**, **Kienitz, E.**, **Chien, Y. H.**, **Hong, D. W.**, **Liu, N.**, **Royalty, A.**, **Hawthorne, G.** & **Reiss, A. L.** 2017 Changes in brain activation associated with spontaneous improvization and figural creativity after design-thinking-based training: a longitudinal fMRI study. *Cerebral Cortex* **27**, 3542–3552.

Shadmehr, R. & **Holcomb, H. H.** 1997 Neural correlates of motor memory consolidation. *Science* **277**, 821–825.

Shah, J. J., **Vargas-Hernandez, N.** & **Smith, S. M.** 2003 Metrics for measuring ideation effectiveness. *Design Studies* **24**, 111–134; doi:https://doi.org/10.1016/S0142-694X(02)00034-0.

Sio, U. N., **Kotovsky, K.** & **Cagan, J.** 2015 Fixation or inspiration? A meta-analytic review of the role of examples on design processes. *Design Studies* **39**, 70–99.

Smith, S. M. & **Linsey, J.** 2011 A three-pronged approach for overcoming design fixation. *Journal of Creative Behavior* **45**, 83–91.

Sylcott, B., **Cagan, J.** & **Tabibnia, G.** 2013 Understanding consumer tradeoffs between form and function through metaconjoint and cognitive neuroscience analyses. *Journal of Mechanical Design* **135**, 101002–101015; doi:https://doi.org/10.1115/1.4024975.

Shealy, T., **Hu, M.** & **Gero, J.** 2018 Neuro-cognitive differences between brainstorming, morphological analysis, and triz. In *Presented at the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Quebec City, Quebec, Canada*, ASME.

Tsenn, J., **Atilola, O.**, **McAdams, D. A.** & **Linsey, J. S.** 2014 The effects of time and incubation on design concept generation. *Design Studies* **35**, 500–526.

Vandenberghe, R., **Price, C.**, **Wise, R.**, **Josephs, O.** & **Frackowiak, R. S. J.** 1996 Functional anatomy of a common semantic system for words and pictures. *Nature* **383**, 254–256.

Vasconcelos, L. A., **Chen, C.-C.**, **Taysom, E.** & **Crilly, N.** 2017 To copy or not to copy: The influence of instructions in design fixation experiments. In *Presented at the Design Computing and Cognition '16*, Springer.

Vingerhoets, G., **De Lange, F. P.**, **Vandemaele, P.**, **Deblaere, K.** & **Achten, E.** 2002 Motor imagery in mental rotation: An fMRI study. *Neuroimage* **17**, 1623–1633.

Viswanathan, V. K. & **Linsey, J. S.** 2013*a* Design fixation and its mitigation: A study on the role of expertise. *Journal of Mechanical Design* **135**, 051008–051023; doi:https://doi.org/10.1115/1.4024123.

Viswanathan, V. & **Linsey, J.** 2013*b* Role of sunk cost in engineering idea generation: an experimental investigation. *ASME Journal of Mechanical Design* **135**, 121002–121014; doi:https://doi.org/10.1115/1.4025290.

Ward, T. B. 1994 Structured imagination: The role of category structure in exemplar generation. *Cognitive Psychology* **27**, 1–40.

Youmans, R. J. 2011 The effects of physical prototyping and group work on the reduction of design fixation. *Design Studies* **32**, 115–138.