A neuroimaging investigation of design ideation with and without inspirational stimuli—understanding the meaning of near and far stimuli

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*Despite the fact that inspirational stimuli (e.g., analogies) have been shown to be an effective means to assist designers, little is known about the neurological processes supporting inspired design ideation. To explore the impact of inspirational stimuli on design ideation, an fMRI concept generation task was developed (*N = 21*). Results demonstrate that inspirational stimuli of any kind (near or far from the problem space) improve the fluency of idea generation. Furthermore, neuroimaging data help to uncover two distinct brain activation networks based upon reasoning with and without inspirational stimuli. We term these* inspired internal search *and* unsuccessful external search. *These brain activation networks give insight into differences between ideating with and without inspirational stimuli, and between inspirational stimuli of varying distances.*

Keywords: design cognition, analogical reasoning, interdisciplinary, conceptual design, creativity

Analogical reasoning and similar processes have been studied by the design research community for over 30 years due to the fact that inspirational stimuli hold incredible potential to increase the positive characteristics of design concepts (i.e., novelty, quality, etc.) (Chan et al., 2011; Dorst & Royakkers, 2006; Findler, 1981; Fu et al., 2013; Linsey & Viswanathan, 2014; Linsey, Markman, & Wood, 2008a; Linsey, Wood, & Markman, 2008b; Moreno et al., 2014; Murphy et al., 2014; Sternberg, 1977; Tseng, Moss, Cagan, & Kotovsky, 2008). Despite this work, very little is known about the neurological processes that support design cognition involving inspirational stimuli, including analogies. In the work presented here, functional magnetic resonance imaging (fMRI) is used to investigate design concept generation with and without the support of inspirational stimuli. The goal is to determine unique areas of the brain that are not only

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involved during concept generation but also specifically involved when reasoning about inspirational stimuli that are either close or distant from the problem domain. Obtaining insight into the neural processes that occur during cognitive processes in the course of design will allow for a more complete picture regarding how inspirational stimuli impact design problem solving strategies. In turn, this will significantly aid the development of targeted theory, methods, and tools that support the creative potential of designers.

Analogical reasoning is generally defined as the process by which information from a source is applied to a target through the connection of relationships or representations between the two (source and target) (Gentner, 1983; Moreno et al., 2014). In this work, inspirational stimuli are provided to designers and the relational mapping from the stimuli (source) to the problem (target) is left to the designer. Due to this key distinction, the stimuli provided in this work are not described as analogies themselves. However, if designers are able to construct the relational mapping from the stimuli to the problem, they are likely engaging in what many would consider analogical reasoning. As discussed in the Background section below, one common view of analogy is that there are two main component parts: retrieval and mapping (Forbus, Gentner, & Law, 1995). The use of the inspirational stimuli in this work is intended to better facilitate the retrieval of useful concepts from memory, which can then be used for subsequent mapping and concept generation by participants. This is particularly beneficial, as prior research has demonstrated that the difficulty in retrieval is the limiting factor in being able to apply analogies (Gick & Holyoak, 1980).

Using neuroimaging, it is possible to uncover additional insights regarding cognitive processes involved in specific tasks compared to what is feasible in a typical behavioral study employed by the design research community. However, there are very few studies at the intersection of neuroimaging and design research (Alexiou, Zamenopoulos, Johnson, & Gilbert, 2009; Goucher-Lambert, Moss, & Cagan, 2017; Sylcott, Cagan, & Tabibnia, 2013). One such study was research by Goucher-Lambert et al. (2017), which uncovered patterns of neural activity resulting from user-based preference judgments within the context of sustainability. When compared to prior work from the authors, this work helped to demonstrate the additional insights that can be gained from neuroimaging beyond traditional behavioral analyses (Goucher-Lambert & Cagan, 2015). One such example was the presence of a network of brain regions commonly associated with theory of mind reasoning (i.e., "what will others think of my actions") during sustainable preference judgments. Using a combination of empirical neuroimaging data and a meta-analytic database, similarities between sustainable product preference judgments and disparate tasks people engage in were determined. In a separate study from Alexiou and colleagues, the neural correlates of creativity in design during an apartment layout task were examined (Alexiou et al., 2009; Gilbert,

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Zamenopoulos, Alexiou, & Johnson, 2010). This study indicated that the dorsolateral prefrontal cortex was highly involved in design cognition during ill-structured design tasks. This region of the brain is critical to a variety of important cognitive executive functions, including working memory and cognitive flexibility. In a more recent study by Saggar et al. (2015), fMRI was used to study creativity during concept generation in a Pictionary-based game. Here, the researchers found increased activation in several brain regions during concept generation compared to control, such as left parietal, right superior frontal, left prefrontal, and cingulate regions (Saggar et al., 2015, 2016). Beaty et al. (2018) used connectome-based predictive modeling and fMRI to identify brain networks associated with high creative ability. Neural activity within these networks was able to reliably predict the creative quality of novel ideas generated by participants. Together, these works indicate that fMRI can be beneficial in discovering insights into creative problem solving relevant to design by linking specific features of design decisions to brain activation associated with separate cognitive tasks.

The present work uses neuroimaging methods to study design ideation and concept generation with and without the support of inspirational stimuli. Here, a conceptual design task inside an MRI was used to examine differences in brain activity as the distance (from the problem space) of the inspirational stimuli were varied. Inside the MRI, participants were tasked with coming up with solutions to 12 different open-ended design problems obtained from the engineering design and psychology literature. While brainstorming, participants were either provided with inspirational stimuli (near or far distances) or reused words from the problem statement (used as a control). Textual-based inspirational stimuli along a continuum of distance were obtained from prior work using a crowdsourcing technique to generate relevant stimuli (Goucher-Lambert & Cagan, 2017). With neuroimaging and behavioral analysis techniques, the impact of varying distances of inspirational stimuli was uncovered.

1 Background

While the focus of the work presented in this paper is on the impact of inspirational stimuli on design ideation and concept generation, the inspirational stimuli are meant to assist designers to engage in analogical reasoning or closely related mental processes. As such, this section provides a brief background of analogical reasoning in design research, with special emphasis on prior research relating to analogical distance in design. Additionally, work from cognitive psychology and neuroscience relating to analogies, problem solving, and creativity is discussed.

1.1 Analogical reasoning in design research

As described previously, analogical reasoning is the process by which information from a source is applied to a target through the connection of

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relationships or representations between the two (source and target) (Gentner, 1983; Moreno et al., 2014). Within the larger design-by-analogy area, researchers have explored a variety of questions. Some of these include the incubation time of analogical stimuli (Jansson & Smith, 1991; Moss, Kotovsky, & Cagan, 2007; Tseng et al., 2008), the optimal modality of the presented stimulus (Damle & Smith, 2009; Linsey, Wood, & Markman, 2008b), and the impact of expertise on analogical reasoning (Cross, 2004).

Finding and understanding approaches to inspire creativity during design activity is important to design researchers. Inspirational stimuli, including analogies, are one way inspiring creativity can be accomplished. To systematically inspire creativity, one must know how and when to provide a designer with appropriate inspirational stimuli. This is an open area of research, and previous work in design-by-analogy has shown that analogical stimuli is most effective when presented after the development of an "open goal" (i.e., aspects of the problem that remained unsolved) (Tseng et al., 2008). Tseng et al. (2008) found that when distant analogies were given after the development of an open goal, participants produced more novel and diverse concepts. On the other hand, when analogies were given before the development of an open goal, analogical stimuli that were closely related to the design space of the problem were easier to apply.

Another active area of research regarding analogies involves studying analogical distance. Primarily, research on analogical distance uses the terms "near" and "far" to discuss the distance of the analogy from the problem being examined (Fu et al., 2013; Visser, 1996). Previously, studies on analogical distance have considered near and far analogies to be a dichotomy. More recently, however, analogical distance is considered to be more of a continuum. The continuum of distance refers to the *domain* distance— a "near" analogy means that the analogy comes from the same or closely related domain, where as a "far" analogy comes from a distant domain. It has also been noted that near-field analogies share significant surface level features, and far-field analogies share little or no surface features. Common theories indicate that far analogies are more beneficial in helping people develop more novel solutions (Wilson, Rosen, Nelson, & Yen, 2010). However, other research has shown that near analogies are easier to apply to design problems, yet may lead to people becoming fixated (Jansson & Smith, 1991).

Fu et al. (2013) proposed that there exists a "sweet spot" of analogical distance that rests between an analogy being too near (where innovation is restricted and fixation and copying are likely to occur) and too far (where the analogy is too far removed from the problem space to be helpful). Additionally, the work by Fu et al. (2013) operationalizes analogical distance using a latent semantic analysis-based approach with the US patent database. Understanding

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the impact of analogical distance on the transfer of knowledge from the analogy is a critical step in stimulating positive design analogies.

1.2 Analogical reasoning in cognitive neuroscience

Despite the active research surrounding analogies in design, the cognitive mechanisms that enable the effective use of analogies during creative thinking are not well understood. From a cognitive neuroscience perspective, analogical reasoning is a relevant and active area of research; this is largely due to the fact that analogical reasoning is considered a key feature of human thinking (Krawczyk, McClelland, Donovan, Tillman, & Maguire, 2010). Neuroimaging studies in this area attempt to map the neural processes involved in analogical reasoning, often by breaking the process into component parts and studying them one piece at a time. Previous work on analogical reasoning has identified key component parts, such as selection and screening of information (Krawczyk et al., 2008), retrieving relevant information stored in long term memory (Wharton et al., 2000), as well as manipulating and maintaining retrieved information in working memory (Cho, Holyoak, & Cannon, 2007). Another way that underlying processes involved in analogical reasoning have been described are through the steps of encoding/retrieval (the source of the analog is identified and retrieved in memory), mapping (information from the source is matched or applied onto a target), and response (Forbus et al., 1995; Krawczyk et al., 2010).

Encoding and retrieval depends largely on the type (i.e. semantic vs. pictorial) and complexity of the analogy being studied. The task in the study presented here uses word-based inspirational stimuli. Previous work using word-based stimuli for analogical reasoning tasks of the form A:B: C:D has been shown to activate a temporal maintenance network associated with processing and representing the word forms associated with the task (Cho et al., 2007). Typically, the complexity of the analogical stimuli has been controlled using text-based semantic approaches, such as measuring similarity using latent semantic analysis (Green, Cohen, Raab, Yedibalian, & Gray, 2015). Additional neuroimaging studies using analogies have focused on perceptual and semantic matching, as well as simple implied analogies (Geake & Hansen, 2005).

Regardless of the type or complexity of the analogy being studied, information regarding the analogy needs to be retrieved in some way from memory. Areas of the prefrontal cortex (PFC) are heavily involved with executive controls of retrieving information from working memory (A. E. Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006). Specifically, several neuroimaging studies have indicated anterior regions of the PFC in analogical reasoning (Gonen-Yaacovi et al., 2013; Green et al., 2006, 2015; Kowatari et al., 2009). The rostrolateral prefrontal cortex (RLPFC) has been identified as an area of the brain that supports higher level cognitive functions such as

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analogical reasoning and episodic memory retrieval (Westphal, Reggente, Ito, & Rissman, 2016). In particular, a study by Wharton et al. (2000) implicated that the left prefrontal and inferior parietal cortices are important in mediating analogical mapping. Finally, only a limited number of fMRI studies have examined analogical distance (Green, 2016; Krawczyk et al., 2010). These studies have suggested that regions in the left frontopolar cortex are involved in judging analogical distance. However, the limited complexity of the analogical stimuli used for these experiments make it difficult to hypothesize how such results may translate to a more open-ended problem, such as those found in design.

In the present study, the neural correlates of design ideation involving inspirational stimuli are explored using fMRI. Here, it was predicted that inspirational stimuli conditions would lead to an increase in brain activity in the prefrontal cortex associated with integrating sourced inspirational stimuli into target domains. Furthermore, due to the verbal nature of the task, increased activation in the temporal lobe was expected to be associated with the processing and integration of linguistically based knowledge. Behaviorally, it was expected that inspirational stimuli would have an overall positive impact on ideation (increase in fluency and novelty of concepts), concurrent with the engineering design literature.

2 Methodology

To examine the cognitive mechanisms underpinning design and concept generation with and without inspirational stimuli, an open-ended problem-solving task was developed. The task required participants to quickly think of multiple solutions to 12 different open-ended design problems. During idea generation, participants were provided with additional inspirational stimuli, which were intended to aid in generating solutions. Behavioral and brain activation data were examined to determine the impact of inspirational stimuli on idea generation and problem solving. Conditions where participants were given inspirational stimuli were contrasted against a control condition in which words from the problem statement were reused in place of unique stimuli.

2.1 Participants

For this experiment, 21 healthy, right-handed, fluent English-speaking adults (13 male/8 female, mean = 27yrs, SD = 5.4yrs) were selected for participation in the study. All participants were graduate level students at a major U.S. university specializing in engineering, design or product development. These included Design (Interaction Design), Mechanical Engineering (Design Focus), Human−Computer Interaction, and Integrated Innovation (Product Development). Participants were recruited through an email solicitation to relevant departments and screened through an online MRI safety questionnaire. Written informed consent was obtained from all participants prior to

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beginning experimental data collection in accordance with protocol approved by the University's Institutional Review Board. For their participation, all participants were compensated with $40 for the 2 h session (0.5hr training, 1hr brain scan, 0.5hr post session interview) and provided with digital images of their brain.

2.2 *fMRI session procedure*

The task completed in the MRI scanner was a conceptual design-thinking task, where participants were asked to develop as many solutions as they could to 12 open-ended design problems in the allotted time for each. The subjects indicated when they came up with a solution so that the neural activity at those points could be examined. The experiment was broken into three separate conditions: two where participants were given inspirational stimuli (Near, or Far), and a third where participants were given words from the design problem (Control). Each participant saw 4 problems from each condition type, however the specific problem–condition pairs that a given participant saw was broken into three counterbalanced groups (Table 1).

The problems and inspirational stimuli used in this experiment were the same as those used in a prior research study from Goucher-Lambert and Cagan (2017), where inspirational stimuli were obtained using a combined crowdsourcing and text-mining technique. Over 1300 crowd-workers were asked to provide text-based solutions to the same design problems explored in this work. A text-mining approach was then used to extract commonly used words from the crowd solutions, and bin them into different distances (i.e., near, far, etc.) based on word frequency. Near inspirational stimuli represented approximately the top 20 percent most frequently used words, while far stimuli were words that were only used once. That work also explored the impact of the inspirational stimuli using a human subjects experiment with ~100 upper-division engineering students (Goucher-Lambert & Cagan, 2017). The introduction and use of crowdsourcing to obtain inspirational stimuli was motivated in part by the difficulty of finding relevant stimuli to use across a variety of design problems. Overall, that work demonstrated an agnostic approach using the naïve crowd to identify words, assessed analytically for their "distance", that were then used as inspirational stimuli for designers. The inspirational stimuli in the present experiment were a subset of the extracted words from that prior work.

Table 1 Condition by problem for each experimental group

Problem	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Group A	Near	Cntrl	Far	Near	Far	Cntrl	Far	Cntrl	Near	Cntrl	Far	Near
Group B	Far	Near	Cntrl	Far	Cntrl	Near	Cntrl	Near	Far	Near	Cntrl	Far
Group C	Cntrl	Far	Near	Cntrl	Near	Far	Near	Far	Cntrl	Far	Near	Cntrl

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The exact problems and words used for the fMRI experiment are shown in Table 2. These problems were inspired by those used in the design-by-analogy literature. However, it should be noted that the problem statements were modified from their original form to remove problem constraints. Furthermore, the problem domains of these questions varied dramatically. In the current work, the overall goal is to gain insights into the overall processes involved in reasoning with and without inspirational stimuli during design ideation. To investigate this research question it was necessary to obtain a wide variety of problems so that general effects could be inferred regarding reasoning with inspirational stimuli. While the design output of participants

Table 2 Problem statements and inspirational stimuli used for fmri experiment

Problem	*Near Words*	*Far Words*	*Control Words*
1. A lightweight exercise device that can be used while traveling (Linsey & Viswanathan, 2014).	pull, push, band, resist, bar	roll, tie, sphere, exert, convert	lightweight, exercise, device, while, travelling
2. A device that can collect energy from human motion (Fu et al., 2013).	store, charge, shoe, pedal, step	beam, shake, attach, electrons, compress	device, collect, energy, human, motion
3. A new way to measure the passage of time (Tseng et al., 2008).	light, sand, count, fill, decay	crystal, drip, pour, radioactive, gravity	new, way, measure, passage, time
4. A device that disperses a light coating of a powdered substance over a surface (Linsey, Wood, et al., 2008b).	spray, blow, fan, shake, squeeze	rotor, wave, cone, pressure, atomizer	light, coating, surface, powdered, substance
5. A device that allows people to get a book that is out of reach (Cardoso & Badke-Schaub, 2011).	extend, clamp, pole, hook, reel	pulley, hover, sticky, voice, angle	device, allows, people, book, reach
6. An innovative product to froth milk (Toh & Miller, 2014).	spin, whisk, heat, shake, chemical	surface, pulse, gas, gasket, churn	an, innovative, product, froth, milk
7. A way to minimize accidents from people walking and texting on a cell phone (Miller, Bailey, & Kirlik, 2014).	alert, flash, camera, sensor, motion	emit, react, engage, lens, reflection	minimize, accidents, walking, texting, phone
8. A device to fold washcloths, hand towels, and small bath towels (Linsey, Markman, & Wood, 2012).	robot, press, stack, table, rotate	deposit, cycle, rod, funnel, drain	fold, wash, cloths, hand, towels
9. A way to make drinking fountains accessible for all people (Goldschmidt & Smolkov, 2006).	adjust, lift, hose, hose, nozzle	shrink, catch, attach hydraulic, telescopic	way, drinking, fountains, accessible, people
10. A measuring cup for the blind (Jansson & Smith, 1991; Purcell, Williams, Gero, & Colbron, 1993).	braille, touch, beep, sound, sensor	preprogram, recognize, pressure, holes, cover	measuring, cup, for, the, blind

(*continued on next page*)

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Table 2 (*continued*)

Problem	*Near Words*	*Far Words*	*Control Words*
11. A device to immobilize a human joint (Wilson et al., 2010).	clamp, lock, cast, harden, apply	shrink, inhale, fabric, condense, pressure	device, to, immobilize, human, joint
12. A device to remove the shell from a peanut in areas with no electricity (Viswanathan & Linsey, 2013).	crack, crank, blade, squeeze, conveyor	melt, circular, wedge, chute, wrap	device, remove, shell, peanut, areas

cannot be examined here, additional work by the authors looks to provide more insight into specific effects of the inspirational stimuli on solutions (for the same design problems) (Goucher-Lambert & Cagan, 2017). Furthermore, pilot testing by the authors confirmed that each of these problems required similar time to generate solutions, and that multiple high-level solutions could be obtained within a 120-s window.

For each participant, the experiment was conducted over a continuous 2-h block. After receiving a standardized experiment and task description, prior to going into the fMRI machine all participants completed the same practice design problem presented identically to how problems would appear during the fMRI. Participants then discussed the ideas they had generated with a researcher, and were provided with brief feedback regarding the detail of their solutions to standardize the level of design solutions across participants for data collection purposes during the fMRI. All participants were instructed to indicate they had thought of a new design solution once they had reached sufficient detail to express their idea using a sentence or two. Pilot testing indicated that this method provided relative consistency across participants during the experiment.

An outline of timing for each problem during the fMRI experiment is shown in Figure 1. Also displayed in Figure 1 is an example of the stimuli presentation for various portions of the experiment. For each design problem, participants were first presented with a self-paced instruction screen, which allowed them to start the design problem once they were ready to begin. Following this, the design problem was presented in isolation for 7 seconds. A variable crosshair-jitter (0.5—4sec) broke up viewing the design problem and the start of the stimuli presentation. This allowed brain activity associated with the initial problem presentation to be differentiated from that associated with processing the inspirational stimuli. In total, participants had 2 minutes to think of design solutions. These 2 minutes were broken into two separate blocks of 1 minute each. Between each problem-solving block was an additional task (discussed in more detail below). During the first 1-minute block (WordSet1), 3 words were given to participants. The remaining two words were presented during the second problem-solving block (WordSet2). This was done in order

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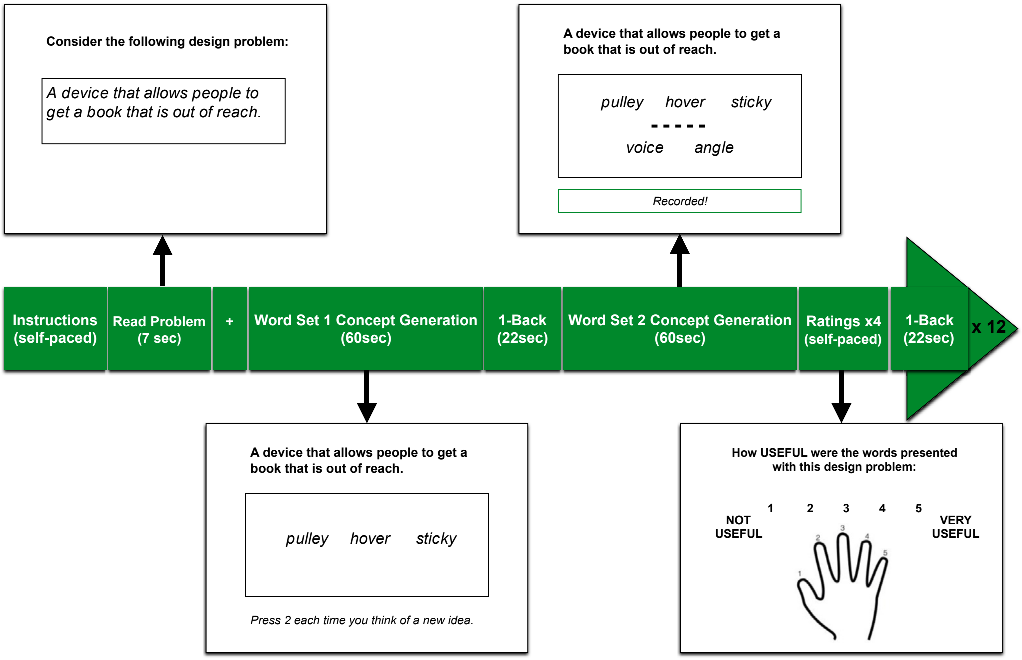

Figure 1 FMRI session problem outline with timing and stimuli presentation example

to stagger the presentation of inspirational stimuli throughout the problem-solving period. Another reason for adding additional stimuli in the second problem-solving block was to provide a mechanism for new connections in WordSet2 if participants had exhausted their use of the inspirational stimuli presented in WordSet1.

The additional task was a 1-Back memory task, in which a single letter was displayed on the screen, one at a time. Participants were asked to indicate whether or not the new letter matched the previous letter on the screen. Providing this additional task between the experimental blocks of interest allowed for the hemodynamic response related to design ideation to return to a baseline level. Tasks that go on for longer than approximately 1 minute can have temporal frequencies that overlap with typical MRI signal drift (Chein & Schneider, 2003). A high-pass filter is applied during data processing to remove drift, so limiting task duration is important to prevent this filter from removing the signal of interest.

Following WordSet2, participants answered 4 questions targeted to gain insight into their perception of the presented inspirational stimuli and of their own solutions. These four questions were all ratings on a scale from 1 to 5, and were answered at the end of every design problem. Two of these were intended to assess the inspirational stimuli that were presented for each design problem

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by 1) asking how useful the stimuli were in helping to think of new ideas, and 2) how relevant the stimuli were to the design problem. The other two questions sought to determine participants' subjective perception regarding the overall 1) novelty (uniqueness) and 2) quality of the solutions they had developed for that problem.

Experimental stimuli were presented in the MRI using the E-Prime Software package (Schneider, Eschman, & Zuccolotto, 2002). Subjects lay supine in the scanner, and viewed stimuli displayed using a monitor with a mirror fixed to the head mounted coil. To indicate that they had thought of a new design solution, participants used a response glove strapped to their right hand. Pressing a button with the index finger indicated each new idea, while responses to rating questions following each problem utilized all digits.

2.3 fMRI data acquisition

The fMRI session involved a 1-h brain scan. Functional MRI data were collected from a Siemens 3 T Magnetom Verio MRI scanner (SYNGO MR B17 software) using a 32-channel phased array head coil. Functional images were acquired using a T2*-weighted multiband (MB) echo-planar imaging (EPI) pulse sequence (45 oblique axial slices, in-plane resolution 3 mm × 3 mm, 3 mm slice thickness, no gap, repetition time TR = 1000 ms, echo time TE = 30 ms, flip-angle = 64deg, multiband acceleration factor = 3, matrix size = 70 × 70, field of view = 210 mm, Coronal phase encoding direction = P >> A). The MB scanning acquisition allows for a reduction in the TR, resulting in full brain volumes collected in a third of the time compared to traditional acquisition approaches (Preibisch, Castrillón G., Bührer, & Riedl, 2015). Twelve runs of functional data were acquired; each consisting of approximately 200 volume acquisitions. The exact number was dependent on the time taken during the self-reported ratings, which typically resulted in ± 10 volume acquisitions. In addition, high-resolution anatomical scans were acquired for each participant using a T1-weighted MP-RAGE sequence (0.8 mm × 0.8 mm ×0.8 mm, 176 sagittal slices, TR = 2300 ms, TI = 900 ms, flip angle = 9 deg, Generalized Autocalibrating Partial Parallel Acquisition = 2).

2.4 fMRI data preprocessing

Raw neuroimaging data were pre-processed and analyzed using the AFNI (Analysis of Functional NeuroImages) software package (March 1, 2017 version 17.0.11) (Cox, 1996). A custom automated Nipype (Python language) pre-processing script was used to complete the pre-processing of the neuroimaging data into a form suitable for data analysis (Gorgolewski et al., 2011). Pre-processing steps within the pipeline used for the analyses included slice scan-time correction, 3D rigid-body motion correction, high-pass temporal filtering, and spatial smoothing. Slice time correction aligned all slices within a brain volume to the first slice in that volume. Next, data from the functional

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image acquisitions were realigned to the first image of each run, and then again from this image, to the first run of each subject. The rigid-body rotation, translation, and three-dimensional motion correction algorithm examined the data to remove any time points where excessive motion occurred from the analysis. A 110 s high-pass Gaussian filter from the FSL suite was used to remove low-frequency artifacts in the data (Jenkinson, Beckmann, Behrens, Woolrich, & Smith, 2012). To reduce signal noise, the signal from each voxel was spatially smoothed using a Gaussian kernel (7 mm FWHM). Smoothing reduces the impact of high frequency signal, and enhances low frequency signal. This causes more pronounced spatial correlation in the data set. An anatomical image from each subject was co-registered to his or her corresponding functional images. The structural and functional images were transformed into Talairach space with 3 mm isometric voxels using AFNI's *auto_tlrc* algorithm.

2.5 *Individual level fMRI data analysis*

Individual participant fMRI data acquisitions were analyzed using a voxel-wise general linear model (GLM). Multiple hemodynamic response models were constructed to examine the impact of inspirational stimuli on conceptual design and problem solving. These were broken up into two major classes of models: response models and block models.

To examine brain activation around the time a concept was generated, a response model was used. To do this, individual GLMs were fit around participant response times within each block. Analysis of pilot data showed that this often led to higher levels of signal detection in each of the experimental conditions. Two different response-based GLM models were used. The first of these were tent functions, $TENT(b,\ c,\ n)$, which are n parameter piecewise-linear functions that interpolate the hemodynamic response function between time points b to c after the stimuli onset (Ward, 2015). In this case, the button responses from participants (which indicated they had thought of a solution to the design problem) were used as the stimuli onset times. Based on a hypothesized time lag from initial generation of a solution to button press and an examination of pilot data, it was determined that time points between 5 and 7 s prior to the button presses showed the most brain activation data. This was likely due to the fact that participants had already thought of and worked through the process of generating a new idea well before they indicated it. In this experiment, the AFNI hemodynamic model $TENT(-7,\ 8,\ 8)$ was used.

The second individual GLM model for response times was based upon the SPMG 2-parameter gamma variate regression model,

$$h_{SPM1}(t) = e^{-t}\left(\frac{t^5}{a_1} - \frac{t^{15}}{a_2}\right) \tag{1}$$

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$$h_{SPM2}(t) = \frac{d}{dt}(h_{SPM1}(t)) \tag{2}$$

where $a_1 = \frac{1}{12}$ and $a_2 = \frac{1}{6*15!}$ (Ward, 2015). This model has 2 regression parameters for each voxel element. This model is beneficial, because it takes into account some of the time variance associated with the blood-oxygen-level-dependent (BOLD) response signal through the temporal derivative. Here the time inputs were the response times with minus either 5, or 7 s to account for the lag associated between idea generation and the button press.

In addition to the brain activity around when concepts were generated, the activity of the entire problem-solving block was also of interest. Here, a mixed model that incorporated the response regressors (discussed previously) and the block regressors was used. Including response level regressors in the block-level model has shown to be an effective way to measure sustained activity during task-level processing (Petersen & Dubis, 2012). This allowed for an examination of widespread brain activation networks that may be present across the entire problem-solving period, while accounting for brain activity due to idea generation. Another way to consider this is that at a block level, the resulting activity between contrasts is representative of *unsuccessful search*. Here, unsuccessful search is defined as the remaining brain activity during the search for design solutions without having a solution. By taking away periods of productive idea generation captured in the response models, the block level analysis is capturing brain activity that is representative of searching for new problem insights. Neural activity at the block level was explored using the brain activation data from both WordSet1 and WordSet2 combined (2 × 60sec), as well as separately (60sec). The GLM block regressors were 1-parameter models with fixed shapes constructed using the AFNI BLOCK hemodynamic response type.

Regardless of model selection described above, the outputs from this are coefficient values from the regression model. These coefficients represent the mean activation level for each condition being modeled within a given brain voxel. Some contrasts of interest were included *a priori*; these were the conditions against themselves in each of the wordsets (i.e., (*Control WordSet1*) − (*Control WordSet2*)), and cross condition comparisons (i.e., *Near* − *Control*).

2.6 Group level fMRI data analysis

To analyze group level effects, AFNI's 3dttest was used to perform t-tests for the various contrasts of interest. If a contrast was run for all participants during the individual level analysis, then a 1-sample t-test was performed. This compared the mean voxel contrast estimate across subjects to 0. If a contrast was not included beforehand, then a paired sample t-test was used. Here the inputs were the individual conditions of interest. All results were corrected for multiple comparisons using family-wise error (FWE) cluster

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size thresholding. AFNI's 3dttest tool was used to determine the optimal cluster size, allowing for an FWE corrected p value of $p = 0.05$ (individual voxel p value $= 0.005$, variable cluster size dependent on the specific contrast).

2.7 Behavioral data analysis

Behavioral data collected during the fMRI session centered upon two factors: 1) the number and timing of generated solutions and 2) the ratings provided by participants for each of the design problems (relevancy and usefulness of provided inspirational stimuli and self ratings for novelty (uniqueness) and quality of design solutions). Raw times were exported for each design response solution and coded to the specific condition and problem-solving block (WordSet1 vs. WordSet2). Raw experiment onset and response times were re-calibrated to remove participant specific variations from the variable crosshair-jitter (randomized between 0.5 and 4sec). Scores for each of the self-reported metrics were exported as raw values on the described range from 1 to 5. One-way ANOVAs were used to compare the mean values between the three experimental conditions (Near, Far, Control).

3 Results

This section discusses the behavioral and neuroimaging results from the fMRI design ideation and problem solving experiment. First, behavioral results are presented, as they help to better frame and interpret the results from the neuroimaging analyses. Next, results from multiple fMRI models are presented. This includes response models, which are locked to times of idea generation, and block level models, where the brain activation from within an entire problem-solving block (i.e., Near Condition, WordSet2) is averaged.

3.1 Behavioral analysis

3.1.1 Participants' self-ratings of inspirational stimuli and design output

Mean values from participant self reported ratings are shown in Figure 2. Each value in the figure represents the mean rating (scale from 1 to 5) across participants for each of the three conditions. There were a total of 84 averaged responses for each metric. This amounted to the four problems of each condition that all of the 21 participants who completed the study saw. Using a repeated measures ANOVA, no effect was observed between conditions for participants' self-ratings for the novelty ($F(2, 40) = 0.43$, $p = 0.43$), or quality of their solutions ($F(2, 40) = 0.46$, $p = 0.63$).

In addition to questions about their developed solutions, participants also provided ratings on how relevant and how useful they perceived the inspirational stimuli to be. For each of these metrics, a highly significant effect was observed. For example, there was a clear trend in how related participants

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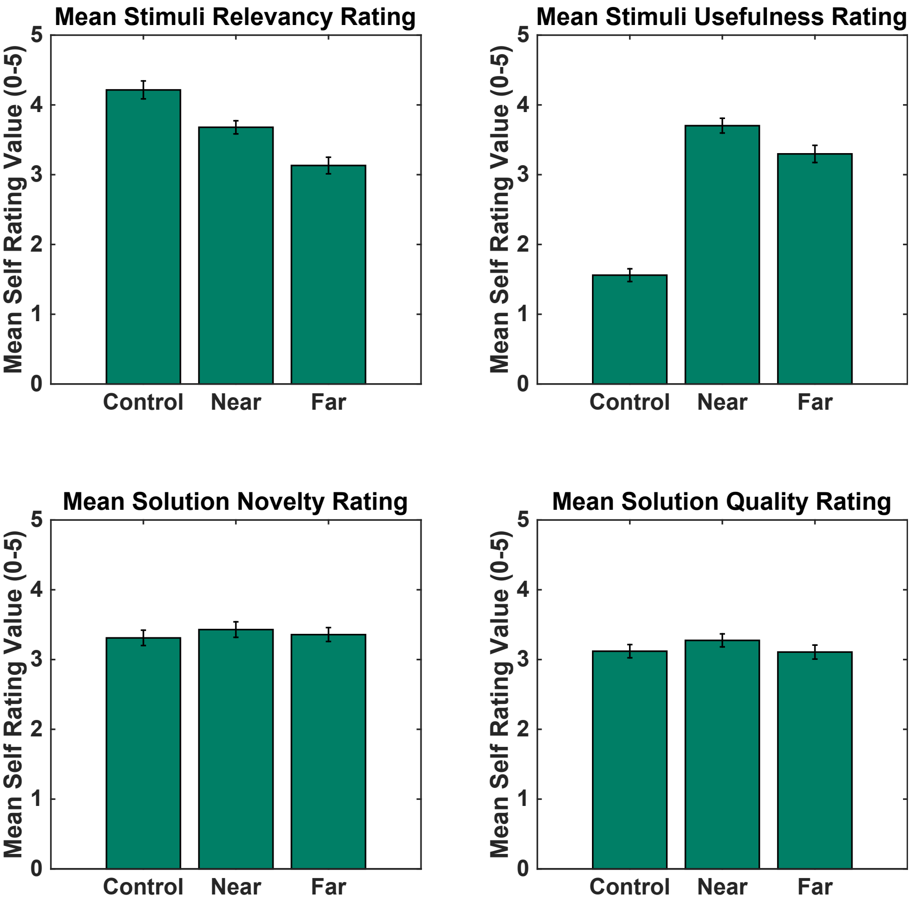

*Figure 2 Mean ± 1 S.E participant self-ratings for relevance and usefulness of inspirational stimuli, and novelty and quality of design solutions (N = 84 per bar— 21 participants*4 samples of each condition)*

rated the inspirational stimuli as being to the design problem. Across this metric, participants perceived all conditions to be significantly different from one another (F (2, 40) = 9.37, p <<0.01). When comparing the inspirational stimuli conditions only, this effect was also robust. Near stimuli (mean = 3.7, SD = 0.97) were rated as being more relevant to the design problems than far stimuli (mean = 3.29, SD = 1.12) across all participants (F (1, 20) = 25.22, p <<0.01). Similarly, there was a significant trend seen for how participants judged the usefulness of inspirational stimuli. The mean usefulness of the three conditions was different with a high degree of statistical significance (F (2, 40) = 76.73, p <<0.01). Not surprisingly, participants rated control stimuli (re-used words from the design problem) as not useful (mean = 1.56, SD = 0.84). More interestingly, participants rated near inspirational stimuli (mean = 3.68, SD = 0.87) as being more useful than far inspirational stimuli (mean = 3.13, SD = 1.10). Additionally, a separate contrast

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between the near and far conditions for the usefulness metric confirmed the significance of this difference (F (1, 20) = 11.12, $p << 0.01$).

3.1.2 Participant solution output by conditions; quantity and timing

To gain insight into the number of ideas generated, as well as when during the problem-solving block they were generated, an analysis of participant solution response times was conducted. The raw quantities of ideas are shown in Figure 3. This histogram plot bins the solutions generated by participants into 10-s increments, providing more resolution into when within the problem-solving block ideas were completed. The top set of histogram plots in Figure 3 represents the number of solutions generated in the first problem-solving blocks (WordSet1) for each of the three conditions. It can be seen that participants, regardless of condition, were most fluent in idea generation during the early stages of the problem-solving block. Participants' design output steadily decreased as the problem-solving block progressed.

Despite the apparent trend in WordSet1 showing that inspirational stimuli help to promote idea generation compared to the control, it is not statistically significant (F (2, 40) = 1.52, $p = 0.23$). Additionally, there was a high degree of variability in idea fluency between subjects. For example, across the four design problems in WordSet1 for the near condition, participants generated a mean value of 24.90 ideas. However, the standard deviation on this value was high at 7.61 ideas. The other two conditions displayed similar characteristics (Far: mean = 24.33, SD = 8.27; Control: mean = 23.10, SD = 7.45).

For all conditions, participants generated significantly less ideas in WordSet2 compared to WordSet1 (Near:(F (1, 20) = 49.17, $p << 0.01$); Far:(F (1, 20) = 75.35, $p << 0.01$); Control:(F (1, 20) = 79.62, $p << 0.01$)). The data from WordSet1, suggests that more ideas were generated in Near > Far > Control, though this result was not statistically significant. However, a significant difference between the mean values of solution quantities for WordSet2 (Near: mean = 17.19, SD = 6.87; Far: mean = 15.67, SD = 6.10; Control: mean = 13.24, SD = 5.41 was observed (F (2, 40) = 10.53, $p << 0.01$). Pairwise comparisons between conditions confirmed that this difference was driven by the control condition (Control vs. Far: F (1, 20) = 6.97, $p = 0.02$; Control vs. Near: F (1, 20) = 19.70, $p << 0.01$; Far vs. Near: F (1, 20) = 3.70, $p = 0.06$). Based on these results, inspirational stimuli appear to assist designers in continuing a higher level of sustained activity as quantified by the number of recorded solutions.

A visual inspection of the histogram plots (Figure 3) seems to indicate that solutions in the control condition during the second problem-solving block were generated at a different point relative to the block onset. Ideas were less likely

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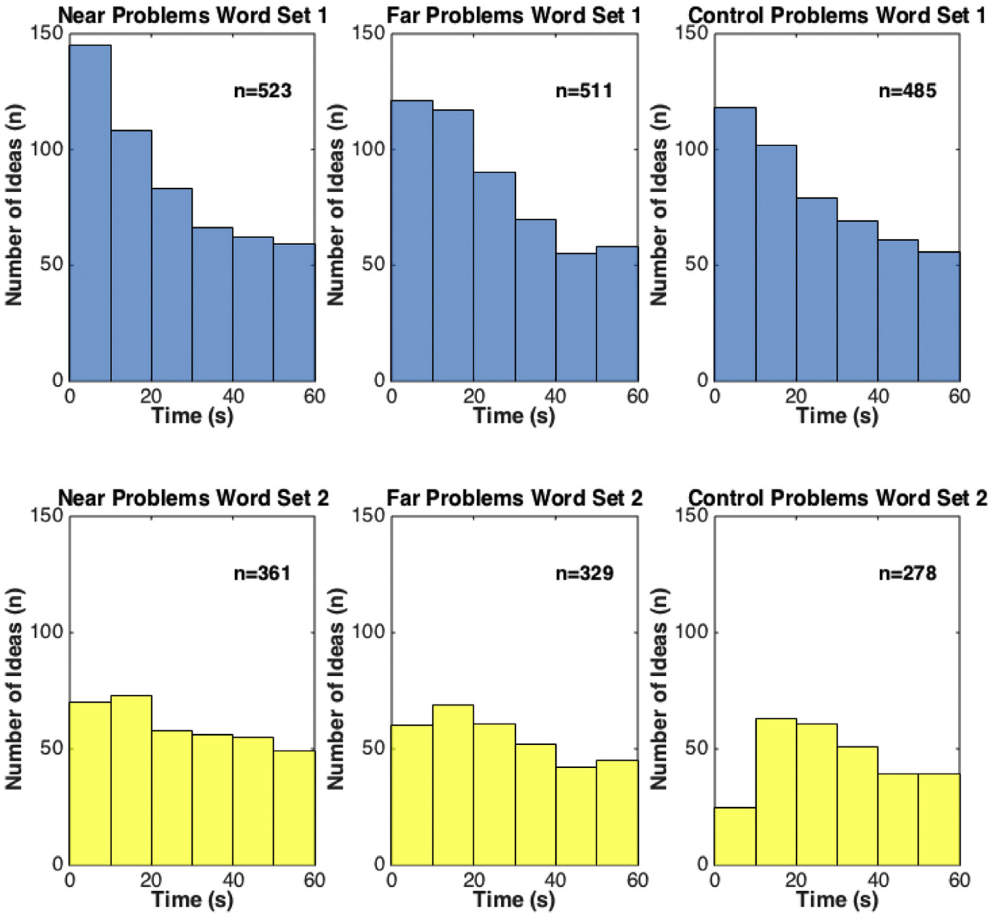

Figure 3 Histogram plot showing number of solutions generated in each condition over time. Plots are split based on problem solving block

to occur during the first portion of the block, compared to the conditions with inspirational stimuli. To investigate this phenomenon further, kernel-smoothing functions were plotted for each condition within each problem-solving block (Figure 4). These plots were generated using the MATLAB *ksdensity* function, which returns a probability density for the sample data based upon a normal kernel function. The resulting figure illustrates an estimation of the probability that a solution was generated at a given point in time for each relevant condition type.

When examining the probability density functions (PDFs) for WordSet1, each of the conditions displays the same trend. Ideas were most likely to occur early in the block, with a peak probability approximately 10 s after the block onset. However, in the second block (WordSet2), this is no longer the case. During this time, the control condition has a very different shape compared to both of the inspirational stimuli conditions, which maintain a shape

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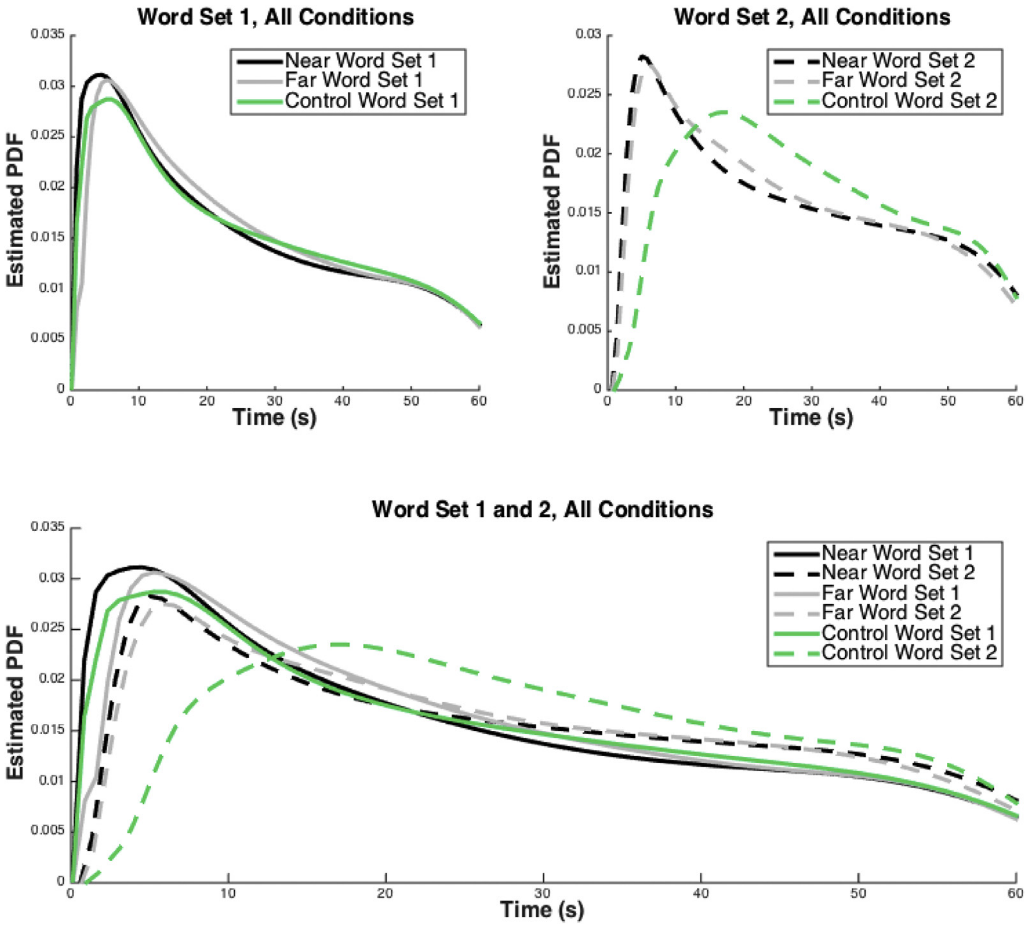
Word Set 1, All Conditions

Word Set 2, All Conditions

Word Set 1 and 2, All Conditions

Figure 4 Kernel smoothing function estimates for solutions generated in each condition word set. Probability of solution generation timing is inconsistent in second block of the control condition

consistent with WordSet1. For the control condition, the probability of coming up with a solution is more uniform across the block length, and has a shifted maximum by $\sim$7 s, to $\sim$17 s past the block onset. To statistically verify this perceived effect, pairwise two-sample Kolmogorov−Smirnov (K−S) tests were run. For all within condition pairwise comparisons, no K−S test yielded significant effects below a significance threshold of $p=0.05$, with the exception of the Near vs. Control conditions for WordSet2 ($p = 0.005$), and the Far vs. Control conditions for WordSet2 ($p = 0.028$). Together, this indicates that the impact of inspirational stimuli on problem solving is most apparent in the second problem-solving block. If not given inspirational stimuli (i.e. Control WordSet2) idea generation is reduced, and shifted out in time relative to the block onset.

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3.2 fMRI analysis

Whole brain analyses of collected fMRI data were conducted in order to determine significant areas of brain activity as a result of considering inspirational stimuli when solving open-ended design problems. A whole brain analysis refers to the fact that brain activity is modeled within all brain voxels independently. This differs from a region of interest analysis where activation is only examined amongst a subset of voxels. As discussed in the methods section above, multiple types of whole brain analyses were conducted. These models differed based upon the types of insight sought. They are broken into two major classes: response models and block models. Time-locked response models examined the research question specifically at time points related to when participants indicated they had come up with a design solution. The response model contrasts below examine brain activity around the successful generation of a solution concept. Block models averaged brain activity across the entire concept generation blocks, while accounting for brain activation during successful concept generation (block models include the response level regressors). This provides insight into the unsuccessful search for a design solution. Results from each of these types of models are discussed in detail below.

3.2.1 Time-locked response models: brain activation during ideating with inspirational stimuli against control

To examine differences in brain activity specifically associated with ideating with the inspirational stimuli compared to the control (words from the problem statement), response models were constructed. These models contrasted the brain activity from each of the two inspirational stimuli conditions added together (Inspirational Stimuli = Near + Far) against the control. In order for parity between the two contrasted elements (Inspirational Stimuli and Control) to be maintained, brain activation for the control condition was multiplied by two (Inspirational Stimuli − 2*Control). AFNI's TENT model (piecewise-linear) was used; specifically modeling time points 7 to 5 s prior to participants' response indications. As previously mentioned, these time points were shown to produce the peak hemodynamic response based upon pilot subjects.

A contrast between the inspirational stimuli and control conditions during the first problem-solving block (WordSet1) yielded no significant brain activation clusters at a family wise error (FWE) cluster size thresholding of $p < 0.05$. However, the same contrast during the second problem-solving block (WordSet2) yielded multiple significant areas of activation. These regions (and Brodmann areas), along with the x, y, z coordinates of the peak activation within the cluster, the cluster size (k), and maximum *Z-score* in the cluster are shown in Table 3. A visual representation of these activation clusters is shown in Figure 5 by mapping the clusters onto a 3D rendering of a template brain.

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Table 3 Inspirational stimuli − control contrast brain activation clusters— for time locked response model. Individual voxels corrected to $p < 0.005$

	Region	*B.A*	x	y	z	k	Z-max	alpha
1	L middle/inferior temporal gyrus	22, 21	64.5	28.5	2.5	242	4.66	<0.03
2	R superior temporal gyrus, angular gyrus, inferior parietal gyrus	39	−40.5	55.5	17.5	174	3.88	<0.04
3	R middle/superior temporal gyrus	22, 21	−49.5	22.5	−9.5	136	4.41	<0.05
4	R/L precuneus, cuneus	7, 31	−1.5	67.5	32.5	101	3.62	<0.08

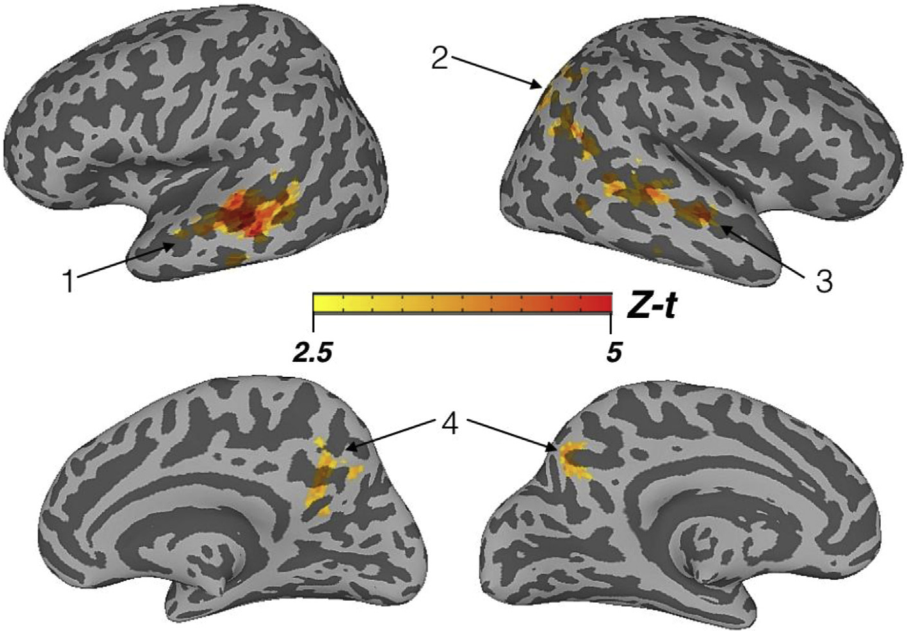

Figure 5 Inspirational stimuli − control contrast brain activation clusters—for time locked response model. Cluster numbering corresponds to Table 3

Brain activation from this contrast (Inspirational Stimuli − 2*Control, Word-Set2) shows activity in the bilateral middle and superior temporal gyri and the precuneus/cuneus. The right lateralized activation extends into the angular gyrus, and inferior parietal gyrus. There were no resulting negative areas of activation (i.e., areas more active in the control condition). Therefore, the resulting brain activity from the condition contrast can be positively associated with ideating with inspirational stimuli. Previous research has shown that bilateral temporal lobe activation precedes moments of insight (Kounios & Beeman, 2009). Temporal lobe activation is generally consistent with word representation and meaning, and has been shown to be a key driver in memory retrieval (Bonner & Price, 2013). Furthermore, the right lateralized temporal-parietal activation is consistent with prior research which shows the parietal lobe directs attention to memory retrieval of concepts (Ciaramelli, Grady, & Moscovitch, 2008). Together this presents evidence of increased

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semantic processing, word-meaning/retrieval, word representation, directing attention to memory, and moments of insight when participants are ideating with the support of the inspirational stimuli. Due to the null results during WordSet1 when comparing the brain activation data from Inspirational Stimuli vs. Control, it is also possible that the impact of the inspirational stimuli on ideation is most salient after other means of idea generation have been exhausted by the participant.

To gain further insight into reasoning with inspirational stimuli at the time of concept generation, the near and far conditions were contrasted separately against the control for both WordSet1 and WordSet2. Contrasting each inspirational stimuli condition against the control separately should provide more insight into the processes that are uniquely similar (or different) at varying distances of inspirational stimuli. Finally, the near and far inspirational stimuli were contrasted against each other to see if there were any specialized differences between the two conditions. For these analyses, the SPM 2-Gamma model was used with times 7 s prior to the response.

For Near WordSet1 − Control WordSet1, Far WordSet1 − Control WordSet1, Near WordSet1 − FarWordSet1, and Near WordSet2 − Far WordSet2, there were no significant clusters of activation found. This indicates that using the current analysis models, the brain activity between these contrasts is not different with strong enough statistical power. As seen previously, differences between the conditions during the first problem solving stage appear to be negligible. This is likely due to the fact that participants were able to freely generate ideas, and did not necessarily need additional inspiration from the stimuli to help promote ideation.

There were significant differences in brain activity for the near and far conditions against the control condition in the second problem-solving block. These activation networks are summarized in Table 4 and Figure 6. There are some similarities to be drawn between both condition contrasts here, and the Inspirational Stimuli vs. Control contrast shown in Figure 5. Mainly, both the near and far conditions show positive activation in the left lateralized middle/superior temporal gyrus. This activation is likely linked to participants actively using the given inspirational stimuli and attempting to either retrieve their meaning from memory, or apply the usage of those words in new ways.

In addition to the left lateralized temporal activation, the Near - Control contrast for WordSet2 also had significant positive activation in the right middle temporal gyrus and medial temporal pole, bilateral cingulate gyrus, and left lateralized insula. As was present in the Inspirational Stimuli vs. Control contrast shown previously, the activation in the Near − Control contrast seems to indicate a diverse network of brain areas associated with semantic processing and memory retrieval. The Far − Control contrast for WordSet2 shows a similar

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Table 4 Near − control (A) and far − control (B) contrasts for wordset 2 responses. Individual voxels corrected to $p < 0.005$

	Region	*B.A*	x	y	z	k	Z-max	alpha
(A)Near WordSet2 − Control WordSet2								
1	L superior temporal gyrus, insula	13, 41	55.5	37.5	17.5	208	4.35	<0.01
2	R/L cingulate gyrus	24	4.5	13.5	35.5	208	4.31	<0.01
3	L insula, superior temporal gyrus	21	34.5	−4.5	−0.5	207	4.19	<0.01
4	R middle/superior temporal gyrus, medial temporal pole	21, 38	−40.5	−1.5	−27.5	100	4.10	<0.05
5	L postcentral gyrus, precentral gyrus	3, 4	−37.5	19.5	38.5	91	4.32	<0.05
(B) Far WordSet2 − Control WorSet2								
1	L middle/superior temporal gyrus	22	40.5	22.5	−6.5	172	4.46	<0.05

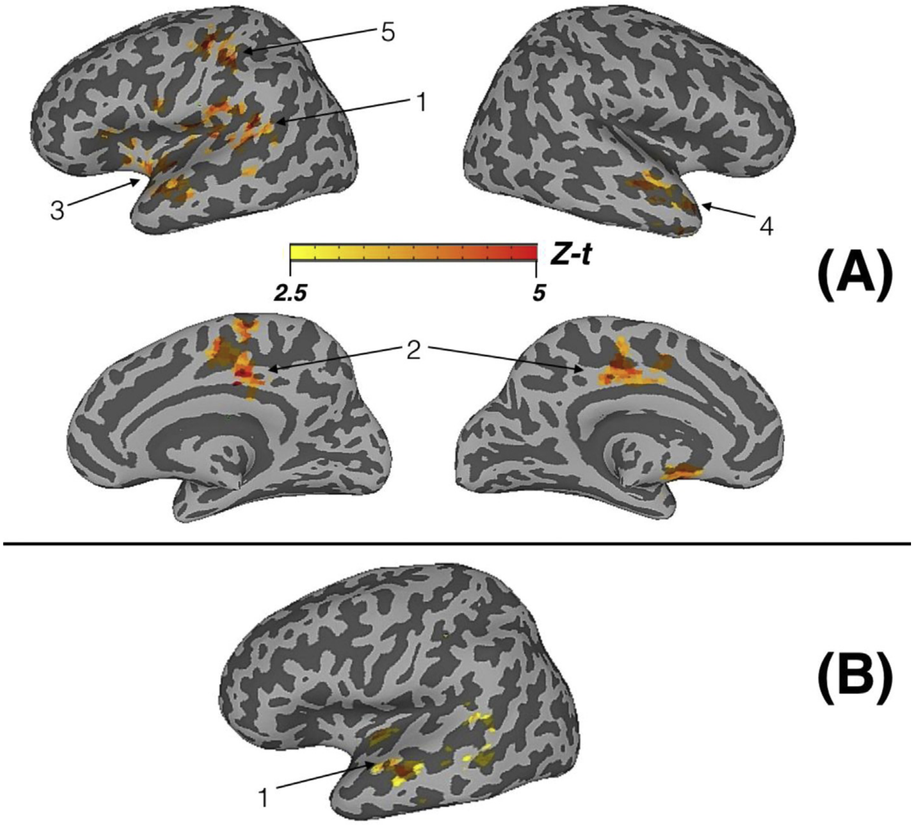

Figure 6 Near − control (A) and far − control (B) contrasts for wordset 2 responses. Cluster numbering corresponds to Table 4

activation network to the Near − Control contrast, however only one cluster of activation survived statistical thresholding (L middle temporal gyrus).

3.2.2 Block models: brain activation patterns during the unsuccessful search for design solutions

Instead of modeling brain activation only around specific time points associated with participant responses, the average levels of activation during entire

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problem solving blocks can also be examined. As discussed in the methods section, a mixed event-related/block design was used to examine brain activity over the course of the entire problem-solving period. This gives a more holistic sense of brain activity while ideating about solutions, as the sharp areas of increased productivity during idea generation is masked by other forms of brain signal that are present throughout the duration of the block. In a sense, conducting a block level analysis over the entirety of the 60-s block provides insight into brain activity when people are unsuccessful (or have reached an impasse), and are struggling to develop a new solution. This is because the mixed-model incorporates the response-level regressors. As a result, fine-grained activation patterns associated with successful ideation and mental search are modeled and the resulting brain signal is consistent with the unsuccessful search for ideas.

Contrasts were completed for all Condition and WordSet combinations. From this analysis, only one contrast yielded significant group level results: the Near − Control WordSet2 contrast. As previously seen, there is mounting empirical evidence from this work that demonstrates that the impact of inspirational stimuli only truly takes effect in the second problem solving block. This is a heuristic supported by the lack of significance in block level contrasts involving WordSet1. For the Near − Control WordSet2 block level contrast, the significant resulting brain activity clusters are all “negative”. This means that activity during the Control WordSet2 condition was greater than the Near WordSet2 condition. As mentioned previously, the significant areas of activation from this contrast are likely to represent areas associated with unsuccessful search during problem solving. From this analysis, it appears that unsuccessful search is most present in the Control WordSet2 block.

All significant clusters of activation from this contrast are shown in Table 5 and Figure 7. At the block level, increases in brain activity are seen in the primary visual cortex (V1), such as the bilateral lingual and calcarine gyri, as well as both posterior and anterior regions of the cingulate gyrus. This robust activation in the occipital gyrus (cluster 1) during the control condition points to increased time examining the problem statement when participants are unable to generate a solution. Prior research has linked increased visual activation to solving by analysis (as opposed to solving with insight), because participants have not yet found a source for insight (Kounios et al., 2006). In addition to

Table 5 Near − control contrast for wordset 2 block. Individual voxels corrected to $p < 0.005$

	Region	*B.A*	x	y	z	k	Z-max	alpha
1	R/L lingual gyrus, calcarine gyrus	18, 19	4.5	67.5	2.5	798	−4.58	<<0.01
2	R/L superior medial frontal gyrus	8, 9, 32	4.5	−37.5	35.5	157	−3.74	<0.02
3	R/L posterior cingulate gyrus, paracentral lobule	31, 24	−1.5	22.5	31.5	72	−4.2	<0.08

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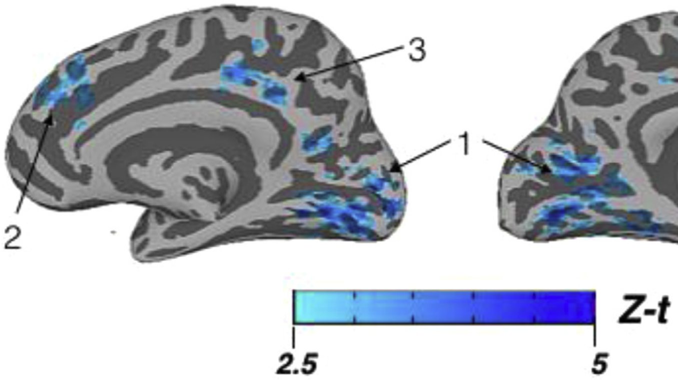

Figure 7 Near − control contrast for wordset 2 block. Cluster numbering corresponds to Table 5

visual processing related brain regions, other areas of activation for this contrast were found in the posterior cingulate cortex (PCC). Research in cognitive neuroscience has still not reached a consensus regarding the exact role of the PCC. However, a comprehensive review of the role of the PCC in neuroimaging studies found that it may play a role switching between internal and external attention (Leech & Sharp, 2014) (though to be fair, not much is generally known about switching between internal and external attention (Burgess, Dumontheil, & Gilbert, 2007)). This type of activity makes sense, as switching between attention states would be necessary for participants as they continue to search for inspiration when at an impasse.

3.2.3 Condition self-contrasts; additional insights to condition specific features and further evidence of an unsuccessful search network

To this point, all analyses of the empirical neuroimaging data have focused on contrasting experimental conditions against each other. These contrasts were performed at both the block level (Section 3.2.2) and using time points modeled around participant responses (Section 3.2.1). Increased bilateral temporal activation was observed in the inspirational stimuli conditions around the time of the response, while a network based on the unsuccessful search for a solution appeared at the block level specific to the control condition. Additional analyses were conducted in order to gain further insight into specific features of the proposed unsuccessful search network and changes within the individual conditions between the WordSet1 and WordSet2.

Of primary interest was comparing problem solving within a given condition between the first and second experiment block. To do this, WordSet1 was contrasted against WordSet2 for each of the three conditions. Resulting areas of brain activity for these analyses are shown in Table 6 and Figure 8. A few things stand out about these contrasts. First, Control WordSet1- Control

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Table 6 Control wordset1 − control wordset2 (A), near wordset1 − near wordset2 (B), and far wordset1− far wordset2 (C) contrasts response model. Individual voxels corrected to p < 0.005

Region	*B.A*	x	y	z	k	Z-max	alpha
(A) Control WordSet1 − Control WordSet2							
1 L insula, putamen	13	31.5	−13.5	8.5	131	3.88	<0.02
2 L postcentral gyrus, inferior parietal lobule	3, 40	37.5	31.5	53.5	96	3.69	<0.04
(B) Near WordSet1 − Near WordSet2							
1 R superior/middle frontal gyrus	9, 10	−25.5	−46.5	5.5	124	−4.19	<0.02
(C) Far WordSet1 − Far WordSet2							
1 R/L lingual gyrus, cuneus	18, 19, 30	−4.5	70.5	5.5	432	−4.75	<<0.01
2 R/L precuneus, paracentral lobule, cingulate gyrus	7, 31	7.5	43.5	50.5	221	−4.48	<0.01

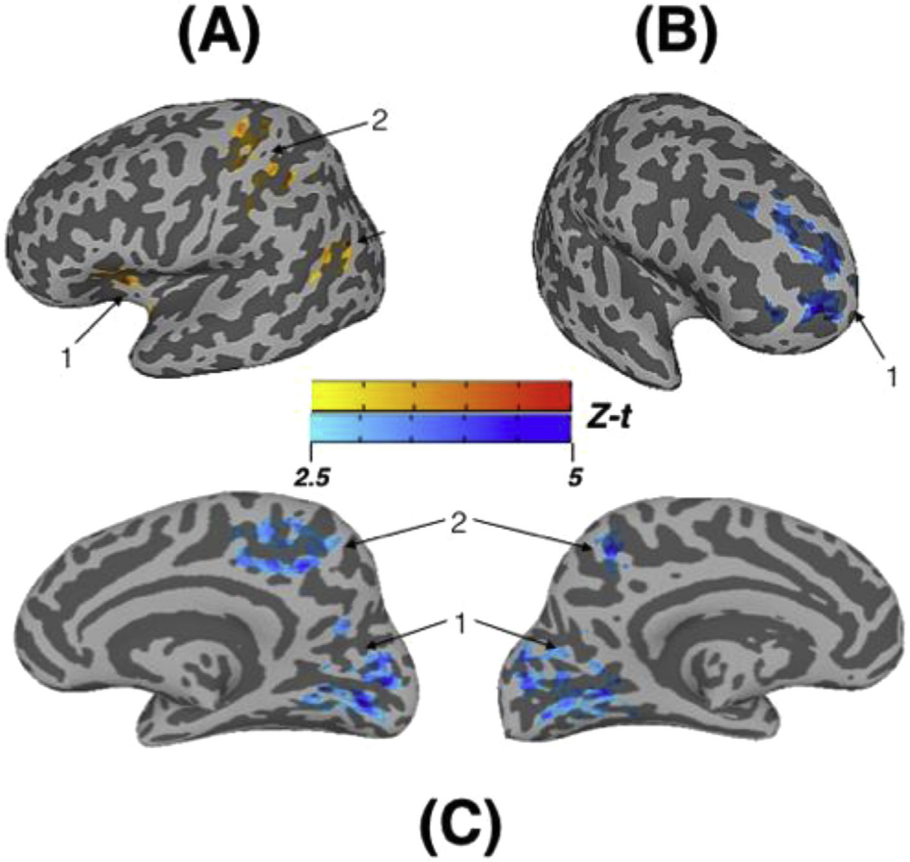

Figure 8 Control wordset1 − control wordset2 (A), near wordset1 − near wordset2 (B), and far wordset1− far wordset2 (C) response model contrasts. Cluster numbering corresponds to Table 6

WordSet2 is the only contrast with positive activation resulting from the within condition contrast. There are a few similarities between this activation network and the contrast between Near WordSet2 − Control WordSet2. This indicates that problem solving during the first block was similar across all

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conditions, regardless of whether or not there was inspirational stimuli, implying that inspirational stimuli are most effective after significant time is spent on the problem (i.e. in WordSet2).

For the inspirational stimuli conditions, the within condition contrasts yielded vastly different results. There was only one significant cluster in the Near WordSet1- Near WordSet2 comparison, which was the superior/middle frontal gyrus. This region of the brain is typically associated with executive function, and response inhibition (Cho et al., 2007). However, the far condition contrast yielded a robustly significant network resembling the proposed unsuccessful search network seen previously (Figure 7). Speculatively, neuroimaging data from the Far WordSet1 − FarWordSet2 contrast suggests that participants are using a separate mental search strategy for far stimuli than with near stimuli. In essence, it appears that far inspirational stimuli share both positive characteristics of stimuli supported design ideation, and negative characteristics of unsuccessfully searching for solutions. This could be due to the fact that far inspirational stimuli are at times too far, and are in turn ignored by participants (similar to the control condition).

3.2.4 Further identification of unsuccessful search brain regions using an ancillary block modulation analysis

A key result from the neuroimaging analyses is that there appears to be a consistent network of brain regions (most notably areas in the occipital lobe including the lingual gyrus, cuneus, and calcarine gyrus) associated with the unsuccessful search for a design solution. This was evident at the block level when contrasting Near WordSet2 − Control WordSet2. Many similar brain regions were active when contrasting Far WordSet1- Far WordSet2. Logically, it appears that there is consistency in these findings. To try and determine whether there was support for this connection directly within the empirical data, an ancillary modulation analysis was completed.

The modulation analysis combined features of the block models and behavioral response data by modulating the amplitude of the block regressors based upon the number of responses participants made in a given block. Said otherwise, this analysis assumed that there was proportionality between the level of brain activity and the number of solutions the participant came up with during a given block. So, if a participant came up with fewer ideas during a block, then there would be a *higher* level of activity within regions associated with unsuccessful search (because they “found” fewer solutions to the problem).

This modulation analysis indicated that there was brain activity in regions attributed to unsuccessful search in all three of the experimental conditions. This in and of itself is not particularly surprising, due to the fact that unsuccessful periods of ideation are reasonably expected to occur when attempting

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to solve a difficult conceptual problem. Because the resulting values from this analysis are unweighted, it was not possible to directly compare the associated brain regions in one condition against another. To make this comparison, a region of interest (ROI) mask was created for the most statistically significant subset of these unsuccessful search regions (Table 7). Following this, the mean level of brain activity for each participant during all experimental conditions (WordSet2 only) was sampled within these ROIs to see whether there was a statistically significant difference between the conditions.[1]

The extracted ROIs are listed in Table 7. The mean activity values from these ROIs were not statistically different, except for ROI 2 (Figure. 9). For this ROI, the mean activation was highest in the control condition (F (2, 62) $= 3.10$, $p = 0.05$). When comparing the mean activation for the near and control conditions within the extracted ROIs, the difference is significant (F (1, 41) $= 6.23$, $p = 0.02$). This shows that there was significantly more brain activity inside of the "unsuccessful search ROI" during the control condition. This ROI encompasses much of the same brain regions identified previously

Table 7 Regions of interest for unsuccessful search analysis

Region		*B.A*	x	y	z	k
1	L middle/superior frontal gyrus	9, 32	31.5	−40.5	−3.5	881
2	R/L lingual gyrus, posterior cingulate	30, 19, 18	19.5	67.5	−18.5	508
3	R medial frontal gyrus, anterior cingulate	9, 32	−16.5	−46.5	8.5	267
4	R cerebellum	N/A	−43.5	52.5	−42.5	219
5	R precentral gyrus, paracentral lobule	6	−10.5	−46.5	50.5	154
6	L angular gyrus, middle occipital gyrus	39, 40	34.5	67.5	11.5	129

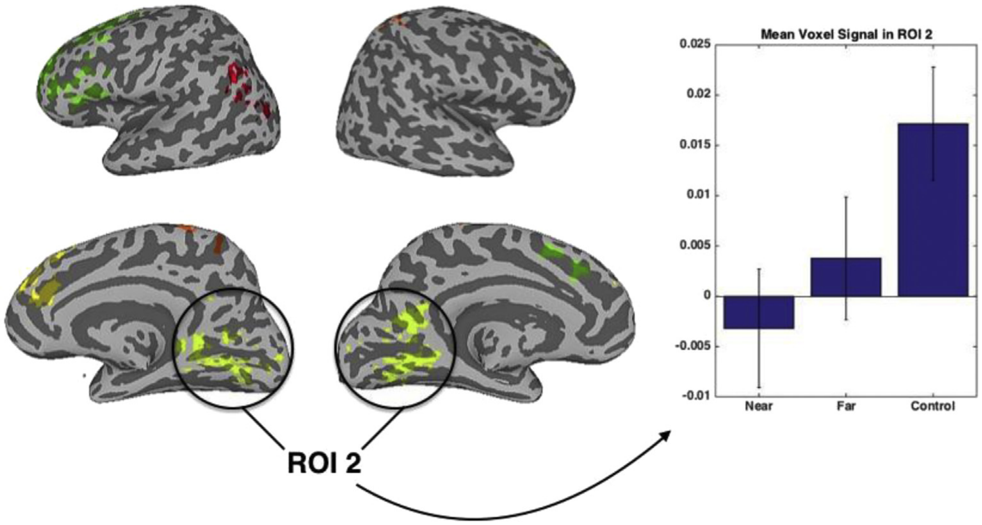

Figure 9 Unsuccessful search ROI from modulation analysis. Control condition shows highest level of activity

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as being related to unsuccessful search (Figure 7). Mainly, these are occipital regions (for example lingual gyrus) and a portion of the posterior cingulate. The modulation and ROI results here, along with the distributive results from the block level and individual condition contrasts, lends strong support for the presence of specific brain activation during periods of unsuccessful search for design solutions. Unsuccessful search is most strongly correlated with the control condition, implying that occurs more frequently in the absence of inspirational stimuli.

4 Discussion

4.1 Discussion of results

This experiment combined behavioral and neuroimaging methods to investigate the impact of inspirational stimuli on ideation during conceptual design problem solving. Behavioral results show that participants are more fluent in generating concepts when they are given inspirational stimuli. While this work was not able to assess the quality or novelty of participant solutions, self-response ratings indicate that there is no significant difference between the conditions across these metrics. Additional work by the authors provides a more detailed account of the impact of the inspirational stimuli on design output using a behavioral human subjects study (Goucher-Lambert & Cagan, 2017).

The behavioral results show that inspirational stimuli help participants generate more concepts than in the control condition. However, this impact was only observed during the second problem solving block. Generally speaking, an increase in idea fluency is thought to be a positive characteristic due to the assumption that generating more ideas will lead to more high quality ideas (Terwiesch & Ulrich, 2009). In addition, the fact that participants in this study had more success using inspirational stimuli later during problem solving is consistent with prior research regarding open goals (Moss et al., 2007). Research from Tseng et al. (2008) also found that analogies were more helpful after an open-goal already existed for the problem. Pilot testing for this study shows participants take ∼3 s on average to read the design prompt. However, the time allotment during the experiment for reading the problem statement is 7 s in order to promote the establishment of an initial open-goal. This time may have been insufficient, as participants seem to only value external help from the inspirational stimuli once they exhaust generating their own (non-stimulated) ideas. Overall, inspirational stimuli, such as analogies— especially those that are near to the problem space— help sustain a more productive level of ideation for a longer period of time. Future work should examine the impact of allotted time on output for various types (e.g., distances) of inspirational stimuli. For example, it is possible that

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the impact of the far inspirational stimuli may be greater if a longer time is allotted for ideation.

Neuroimaging results add insight into the mental processes that underpin design ideation with and without the support of inspirational stimuli. A key result from the neuroimaging analyses in this work is the significant involvement of several temporal brain regions during the inspirational stimuli (near and far) conditions compared to control. Temporal brain areas are known to be integral for semantic memory and knowledge of objects, words, and facts (Bonner & Price, 2013). A meta-review of semantic processing by Binder and Desai (2011) showed the middle temporal gyrus to be one of the most reliably activated brain regions across a range of semantic processing and memory experiments. Furthermore, this work identifies left-lateralized activation in the parietal and temporal lobes that is positively associated with design ideation using inspirational stimuli. An additional study investigating analogical reasoning and memory linked similar areas in the middle temporal gyrus extending into the inferior parietal region as being associated with memory retrieval (Westphal et al., 2016). Prior work has also established that interactions between the parietal and temporal regions are linked to the direction of attention to the products of memory retrieval (Ciaramelli et al., 2008).

Inspirational stimuli conditions activate temporal brain regions related to semantic word processing, word concept recognition, and memory. How are these processes relevant to design? One explanation is that this mechanism of inspired semantic processing and retrieval of meaning of the inspirational stimuli is what helps participants generate new ideas. A recent review of the literature on the cognitive neuroscience of insight during problem-solving suggests that activation of the right anterior and superior temporal gyrus (similar to the activation in the Inspirational Stimuli vs. Control contrast in the present study) is indicative of insight during problem solving (Kounios & Beeman, 2014). A separate study found dual support for activation in the right temporal gyrus related to insight in a combined EEG and fMRI experiment (Jung-Beeman et al., 2004). The theory put forward by Beeman and colleagues is that the right hemisphere codes semantics more coarsely. Due to this, the distance between two concepts in the right hemisphere is less than that in the left hemisphere (i.e., the representation in the right hemisphere does not make as many fine distinctions between concepts as the left does). So while this may make the right hemisphere representation of semantics less useful for language, it enables the connection of more distant ideas as might occur during abstract reasoning involving inspirational stimuli. Additional fMRI work on idea generation suggests that similar activation in the middle temporal lobe is active for associative and constructive functions that allow for the generation of novel ideas (Ellamil, Dobson, Beeman, & Christoff, 2012). Associations are seen as being critical for both episodic memories and relational processing (Aminoff, Gronau, & Bar, 2007). As such, the temporal brain activation in the

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present study appears to be indicative of inspiration during design from the inspirational stimuli.

It should be noted that a limitation of this work is the negative impact of reverse inference conclusions on the interpretation of the collected neuroimaging data. In essence, reverse inference conclusions result from reasoning backward from observed brain activity and making claims about particular behavioral or cognitive processes that were not directly tested (Poldrack, 2006). The work in this manuscript is generally exploratory and the results can be used to generate more specific brain-based hypothesis for future testing. Additionally, a separate limitation is that there is no way to definitively link whether a newly generated concept incorporates a given stimulus because participant concepts were not recorded in the MR scanner. Future work should examine whether other mechanisms (besides the presented words) lead to idea generation in either of the inspirational stimuli conditions.

4.2 Insights for design research: two distinct mental processes for concept generation with and without inspirational stimuli

Based on the results of this study, there appear to be two different types of broad solution strategies. When given inspirational stimuli (e.g., analogies), neuroimaging data help to observe what we term *inspired internal search*. During this time, participants seem to be recognizing meaning in the inspirational stimuli and making connections with retrieved concepts from memory in order to stimulate new ideas. A review of the literature found similar brain regions to be positively associated with moments of insight and creativity (Ellamil et al., 2012; Kounios & Beeman, 2009). In the present task, the successful use of inspirational stimuli allows participants to be more successful at generating design concepts for multiple open-ended problems.

Conversely, in the absence of inspirational stimuli, participants engage in what we call *unsuccessful external search*. An increase in activity in primary visual processing-related brain regions, which make up the center of the unsuccessful external search brain network, indicates that participants continue to search the design problem space for clues and insight. Prior research has also linked an increase in visual processing with participants being unable to solve problems with insight (Kounios et al., 2006). Furthermore, behavioral data from this experiment support the notion that individuals are less successful at generating ideas without support from inspirational stimuli (near or far).

When examining differences between near and far inspirational stimuli during design conceptualization, there were unexpected findings. Mainly, these findings center on the unique features of brain activation data for the far inspirational stimuli in this experiment. While reasoning with the near inspirational stimuli led to the activation of a brain network consistent with the positive

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qualities of inspired ideation, this level of statistical significance was not seen with the far inspirational stimuli (Figure 6B). While a direct comparison between the two inspirational stimuli conditions did not produce significant results, what appears to be emerging is that the more distant inspirational stimuli are beneficial less often than the near stimuli. At times, far inspirational stimuli trigger characteristics of unsuccessful external search *and* inspired internal search; this is likely due to the fact that the usefulness of far-field stimuli is dependent on the situation. If the inspirational stimuli are too far, then they are ignored (similar to the control condition). If the words are useful (not too far), the brain activity mirrors the activation seen in inspired internal search. Both behavioral and neuroimaging data support this duality of far inspirational stimuli occupying both sets of characteristics, depending on the participant and the problem.

Based on the results of this study, it appears that near-field stimuli are more beneficial to design than far-field stimuli. Not only are more ideas generated with near stimuli, but also inspired internal search seems to promote abstract thought that would typically be associated with productive problem solving. This adds to a body of work that suggests that near-field stimuli may actually be more likely to support more innovative ideas (Chan, Dow, & Schunn, 2015). Another explanation for the results in the present study which suggest near-field stimuli are superior to far-field stimuli is that the near stimuli here might actually occupy a space similar to the proposed "sweet spot" (Fu et al., 2013). A more accurate description of the near and far conditions from this work may be "closer" and "further". The origin of the stimuli here is based on a prior study which used a large population ($N > 1000$) of crowdsourced workers (Goucher-Lambert & Cagan, 2017). One plausible impact of this approach is that the participants in the prior study may have been seeking concepts that were uncommon. Due to the high volume of participants, this may have had an overall effect of causing *all* inspirational stimuli to seem more distant.

This research has applications for designers who are solving open-ended problems. The brain activation data enabled us to observe the effect of inspirational stimuli that were too far for a given design problem. In this situation, the features of the source information are ignored and participants continue unsuccessful external search for insight into the problem. This result highlights the need to further classify inspirational stimuli (e.g., analogies) appropriately into a sweet spot. In the design research literature, there are inconsistencies between what is considered "near" and "far". One benefit of the present work is that it provides additional meaning to this concept. For example, this work provided insight into what is broadly discussed as "analogical distance" in design and what it means for an analogy to be outside of a useful range. For an inspirational stimulus to be valuable to a designer, it needs to allow for inspired internal search. That is, the inspirational stimulus needs to be

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recognized as applicable to the problem and then utilized to retrieve relevant information from memory. These results indicate a temporal-parietal brain network active during design ideation involving inspirational stimuli, which previous research has linked to solving problems with insight and creativity during idea generation. Future design tools should look to identify inspirational stimuli that activate these brain regions, as they will be more likely to aid designers. Furthermore, our evidence supports the idea that additional external stimuli are ignored while inspired internal search is ongoing. This suggests that designers are more likely to successfully utilize external stimuli if they are currently at an impasse, rather than actively working on a solution.

A design tool of the future would provide a designer with the right inspirational stimuli at the right time in order to enhance their ability to solve a given design problem. Achieving this goal will take additional research. However, insights into the cognitive processes during stimuli-supported design ideation, such as in this work, provide a platform for this long-term goal to become a reality. First, the results of this work indicate that the cognitive mechanisms that underpin useful characteristics of design ideation involving inspirational stimuli occur after the establishment of open goals for the design problem. While prior research has shown this effect behaviorally during design problem solving, the present work is the first example of showing this effect on a neural level. The next step is to identify useful characteristics of inspirational stimuli that can enhance a designer's capabilities. This work demonstrates that an inspirational stimulus is helpful to a designer when it directs internal attention to memory. Here, we show that directing attention to internal memory via a temporal-parietal network in the brain is the signature process associated with reasoning with inspirational stimuli during design. Without this, participants are unlikely to think of non-salient memories that could potentially inspire new solutions. Future work should assess whether inputs for non-semantic inspirational stimuli show brain activation in similar regions. In the case of visual-spatial stimuli, it appears likely that there would also be an increase in brain activity within regions of the inferior parietal lobe, due to the importance of this region in spatial sensing (Watson & Chatterjee, 2012). However, even if the modality of the inspirational stimuli were to change, the critical neurological feature of its successful utilization during design would likely remain directing attention internally to products of memory retrieval.

5 *Conclusion*

The work presented in this paper used a neuroimaging experiment to investigate the neural correlates of design ideation and problem solving with and without the support of inspirational stimuli. The inspirational stimuli in this work were meant to support cognitive processes similar to analogical reasoning. The stimuli appeared at varying distances (near and far from the

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problem space) and were compared against a control condition in which words were re-used from the problem statement. Behavioral and neuroimaging results show that inspirational stimuli are most beneficial after a prolonged period of trying to solve a problem. Neuroimaging analyses support different solution and search strategies present in the various conditions. Mainly, fMRI data suggest that there are two different strategies, which we term *inspired internal search* (positive strategy involving inspirational stimuli), and *unsuccessful external search* (negative strategy involving impasse during concept generation). During inspired internal search, significant areas of activation are observed in bilateral temporal, and left parietal regions of the brain. These brain regions are notable, as prior research has linked them to semantic word-processing, directing attention to memory retrieval, and insight during problem solving. Conversely, unsuccessful external search shows increased activation in brain regions associated with visual processing and directing attention outward. Less distant inspirational stimuli trigger activation consistent with inspired internal search, while the control condition (no inspirational stimuli) is consistent with unsuccessful external search. More distant inspirational stimuli show features of both search types, indicating that when stimuli are too distant from the problem, participants continue to search through the external world (design problem and given words) in search of insight. Further work is needed to identify specific problem classes that may benefit from each strategy. Additionally, more work is needed to accurately characterize when far inspirational stimuli becomes too far and exhibits characteristics of unsuccessful driven external search. Taken together, this work demonstrates the effectiveness of inspirational stimuli, such as analogies, on a neural level, thereby opening the door for further advancements in the development of new design theory and methods.

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Notes

1. It should be noted that this method of ROI mask generation and sampling is similar to the analyses conducted in work by Goucher-Lambert, Moss, and Cagan (2016), using the external neuroimaging database—Neurosynth. However, here the ROI mask was created based on a specialized analysis of the empirical data.

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