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INSPIRED INTERNAL SEARCH: USING NEUROIMAGING TO UNDERSTAND DESIGN IDEATION AND CONCEPT GENERATION WITH INSPIRATIONAL STIMULI

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ABSTRACT
While a large subset of work within the design research community has demonstrated that supportive stimuli (e.g., analogies) are a powerful assistive tool for designers, little is known about the cognitive processes enabling inspiration during design activity. To provide insight into this open question, a functional magnetic resonance imaging (fMRI) experiment was developed to study design concept generation with and without support from inspirational stimuli (N=21). The stimuli provided in this work were words given at varying levels of abstraction from the design problems and were meant to support cognitive processes similar to analogical reasoning. Results from this work demonstrate that inspirational stimuli of any kind (near or far from the problem space) improve the fluency of idea generation and illustrate the moments during ideation that such stimuli can be used as supportive tools. Furthermore, neuroimaging data help to uncover distinct brain activation networks based upon reasoning with and without inspirational stimuli. We find that the successful application of inspirational stimuli during concept generation leads to a specific pattern of brain activation, which we term "inspired internal search." Prior work by the authors has demonstrated an impasse-based activation network that is more prevalent in the absence of inspirational stimuli. Together, these brain activation networks provide insight into the differences between ideating with and without inspirational stimuli. Moreover these networks lend new meaning to what happens when a presented stimulus (e.g., analogy) is too far from the design problem being solved.

1. INTRODUCTION
Analogical reasoning and related 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.) [1–11]. 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) [12,4]. In this work, inspirational stimuli are provided to designers and the relational mapping from the stimulus (source) to the problem (target) is left to the designer. One major stumbling block that prevents the development of (for example) an automated design tool that generates inspirational stimuli is that very little is known about the neurological processes supporting design cognition involving inspirational stimuli. As such, the broader goal of this work is to uncover unique brain networks that are activated during concept generation both with and without the support of inspirational stimuli. Doing so will allow for greater understanding of the ways in which inspirational stimuli complement and enhance problem solving strategies during design activities. This understanding will, in turn, aid in the creation of future design theories, methods, and tools.

Neuroimaging methodologies, such as functional magnetic resonance imaging, present an emerging opportunity for incorporation into design research studies. One reason for this is that using neuroimaging it is possible to uncover additional insights regarding cognitive processes involved in specific tasks compared to what is feasible in a behavioral or computational study typically employed by the design research community. Despite this opportunity, there have been very few studies at the intersection of neuroimaging and design research thus far [13–15]. One such study was research by Goucher-Lambert et al., which uncovered patterns of neural activity resulting from userbased preference judgments within the context of sustainability [14]. When compared to prior work from the authors on dynamic user-preference (utility) models involving real-time calculated environmental impact values, this work helped to demonstrate the additional insights that can be gained from neuroimaging beyond traditional behavioral analyses [16]. 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 was examined [13,17]. 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 wide variety of important cognitive executive functions, including working memory and cognitive flexibility. In a more recent study by Saggar et al., fMRI was used to study creativity during concept generation in a Pictionary-based game [18]. 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 [19,18]. 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 data.

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 literatures. 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 [20].

2. BACKGROUND

In both the design research and cognitive science literatures, the most related work is referred to as "analogical reasoning". As such, a brief background of analogical reasoning in each of these communities is presented here.

2.1 Analogical Reasoning in Engineering Design

Understanding how to inspire creativity during design activity is an important area of investigation for design researchers. Along these lines, knowing how and when to provide a designer with relevant inspirational stimuli is an open area of research. 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. when a solution is sought, but aspects of the problem remained unsolved) [10]. 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 [5,21]. 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 shares surface features with the target and comes from the same or closely related domain. Conversely, 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 [22]. However, other research has shown that near analogies are easier to apply to design problems, yet may lead to people becoming fixated [23].

Fu et al. 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) [5]. Additionally, the work by Fu et al. operationalizes analogical distance using a latent semantic analysis-based approach with the US patent database. Understanding the impact of analogical distance on the transfer of knowledge from the analogy is a critical step in stimulating positive design analogies.

2.2 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 [24]. 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: 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 [24].

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 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 associated word forms [25]. Typically, the complexity of the analogical stimuli has been controlled using text-based semantic approaches (i.e. measuring similarity with latent semantic analysis) [26].

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 [28]. Specifically, several neuroimaging studies have indicated anterior regions of the PFC in analogical reasoning [26,28–30]. The rostrolateral prefrontal cortex (RLPFC) has been identified as an area of the brain that supports higher-level cognitive functions such as analogical reasoning and episodic memory retrieval. Finally, only a limited number of fMRI studies have examined analogical distance [24,31]. These studies have suggested that regions in the left frontopolar cortex are involved in judging analogical distance. However, the limited complexity of the 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 with and without inspirational stimuli was explored using fMRI. Here, it was predicted that ideating with inspirational stimuli would lead to an increase in brain activity in the prefrontal cortex associated with integrating sourced inspirational information into target domains. Furthermore, due to the verbal nature of the task, increased activation in the temporal lobe was expected to be involved while processing and integrating 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.

3. METHODOLOGY

3.1 Experiment Overview and 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 a fixed amount of time. Subjects indicated when they had developed a solution in order to correlate neural activity to those points in time. 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 that a given participant saw was broken into three counterbalanced groups.

The problems and stimuli used in this experiment were the same as those used in a prior research study from Goucher-Lambert and Cagan [20]. Finding inspirational stimuli for a given design problem is a challenge in and of itself. In the prior work, inspirational stimuli were obtained using a combined crowdsourcing and text-mining approach. This resulted in an agnostic method using a naïve crowd to identify words, assessed analytically for their "distance", that were then used as inspirational stimuli for designers. The inspirational stimuli in the experiment presented in this paper were a subset of the extracted words from that study. The exact problems and words used for the fMRI experiment are shown in Table 1. Each of the problems used for this experiment are reworded (and at times simplified to remove additional constraints) problems from the design research literature.

TABLE 1: PROBLEM STATEMENTS AND STIMULI USED FOR THE FMRI EXPERIMENT.

Problem	Near	Far	Control
1. A lightweight exercise device that can be used while traveling [7].	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 [5].	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 [10].	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 [6].	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 [32].	extend, clamp, pole, hook, reel	pulley, hover, sticky, voice, angle	device, allows, people, book, reach
6. An innovative product to froth milk [33].	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 [34].	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 [35].	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 [36].	adjust, lift, hose, hose, nozzle	shrink, catch, attach hydraulic, telescopic	way, drinking, fountains, accessible, people
10. A measuring cup for the blind [23,37].	braille, touch, beep, sound, sensor	preprogram, recognize, pressure, holes, cover	measuring, cup, for, the, blind
11. A device to immobilize a human joint [22].	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 [38].	crack, crank, blade, squeeze, conveyor	melt, circular, wedge, chute, wrap	device, remove, shell, peanut, areas

For each participant, the experiment was conducted over a continuous 2-hour 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 and trained how to respond when a solution was identified. 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.

An outline of timing for each problem during the fMRI experiment is shown in Figure 1, along with 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 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 to stagger the presentation of 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 inspiration in WordSet2 if participants had exhausted their use of the 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 idea generation and problem solving to return to a baseline level. Tasks that go on longer than approximately 1 minute can have temporal frequencies that overlap with typical MRI signal drift [39]. 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.

Experimental stimuli were presented in the MRI using the E-Prime Software package [40]. Subjects lay supine in the scanner, and viewed stimulus 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. Each new idea was indicated by pressing a button with the index finger, while responses to rating questions following each problem utilized other digits.

3.2 fMRI Data Acquisition and Pre-Processing

Functional MRI data were collected from a Siemens 3 Tesla 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 3mm x3mm, 3mm slice thickness, no gap, repetition time TR=1000ms, echo time TE=30ms, flip-angle=64deg, multiband acceleration factor = 3, matrix size=70x70, field of view=210mm, Coronal phase encoding direction = P>>A). The MB scanning acquisition allows for a reduction in the TR, resulting in full brain volumes collected in

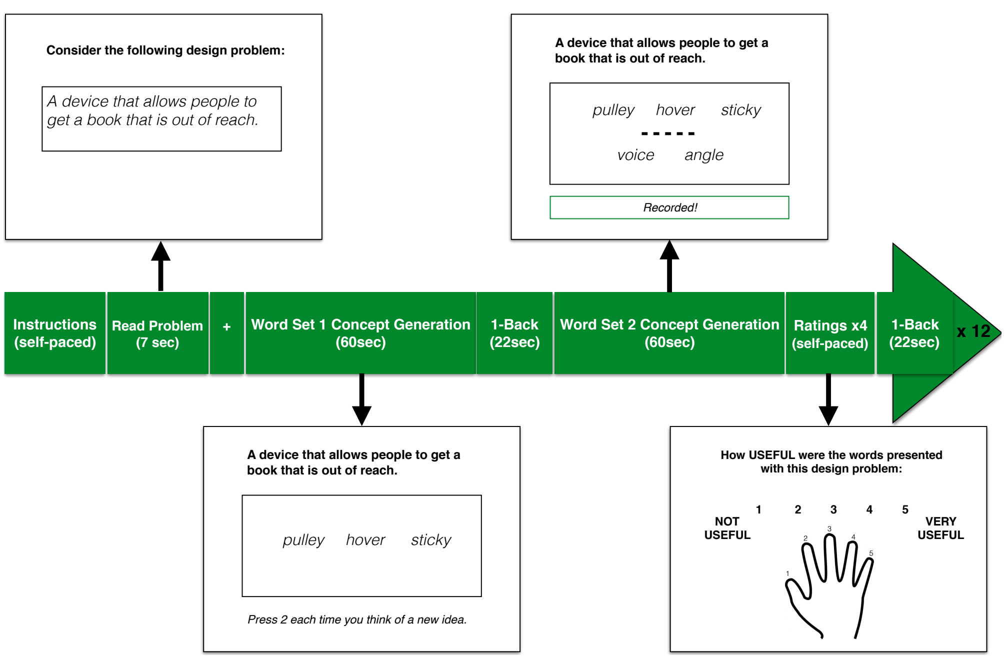

FIGURE 1: FMRI SESSION PROBLEM OUTLINE WITH TIMING AND STIMULUS PRESENTATION EXAMPLE

one-third of the time compared to traditional acquisition approaches [41]. 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 (0.8mm x 0.8mm x0.8mm, 176 sagittal slices, TR=2300ms, TI=900ms, flip angle=9 deg, Generalized Autocalibrating Partial Parallel Acquisition=2).

Raw neuroimaging data were pre-processed and analyzed using the AFNI (Analysis of Functional NeuroImages) software package (March 1, 2017 version 17.0.11) [42]. 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 [43]. 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 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 high-pass Gaussian filter was used to remove low-frequency artifacts in the data. To reduce signal noise, the signal from each voxel was spatially smoothed using a Gaussian kernel (7mm 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 their corresponding functional images. The structural and functional images were transformed into Talairach space with 3mm isometric voxels using AFNI's *auto_tlrc* algorithm.

3.3 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 an engineering design or product development focused graduate program. 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 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 hours session (0.5hr training, 1hr brain scan, 0.5hr post session interview) and provided with digital images of their brain.

3.4 fMRI 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 stimulus onset [44]. In this case, the button responses from participants (which indicated they had thought of a solution to the design problem) were used as the stimulus onset times. Based on a hypothesized time lag from generating a solution to button press, and from an examination of pilot data, it was determined that time points between 5-7 seconds 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,

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

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

where $a_1 = \frac{1}{12}$ and $a_2 = \frac{1}{6*15!}$ [44]. This model has 2 regression parameters for each voxel element. This 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 minus either 5 or 7 seconds to account for the lag between idea generation and button press.

3.5 Behavioral Data Analysis

Behavioral data collected during the fMRI session centered upon the number and timing of generated solutions. A separate behavioral study from the authors using a 100+ participant data-set uncovered the effects of the current analogical stimuli on idea generation [20]. In the current work, raw times were exported for each design response solution and coded to the specific condition and problem-solving block (WordSet1 vs. WordSet2). Raw times were adjusted to remove the effect of the variable jitter, which may have shifted the raw solution time in relation to its "true" time within the block. One-way ANOVAs were used to compare the mean values between the three experimental conditions (Near, Far, Control).

4. RESULTS

4.1 Behavioral Results

To gain insight into the number of ideas generated, as well as the timing within 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 2. This histogram plot bins the solutions generated by participants into 10-second increments, providing more resolution into when within the problem-solving block ideas were completed. The top set of histogram plots in Figure 2 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, participants generated on average 24.9 ideas across the four design problems in WordSet1 for the near condition. However, the standard deviation on this value was high at 7.6 ideas. The other two conditions displayed similar characteristics.

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:($F(1, 20) = 79.62$, $p << 0.01$)). As seen in WordSet1, more ideas were generated in Near>Far>Control. This indicates that having inspirational stimuli is beneficial to generating more ideas. Here, a significant difference between the mean values of solution quantities for WordSet2 was observed ($F(2, 40) = 10.53$, $p << 0.01$).

A visual inspection of the histogram plots Figure 2 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 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 3). These plots show 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 seconds 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 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 ~7 seconds, to ~17 seconds past the block onset.

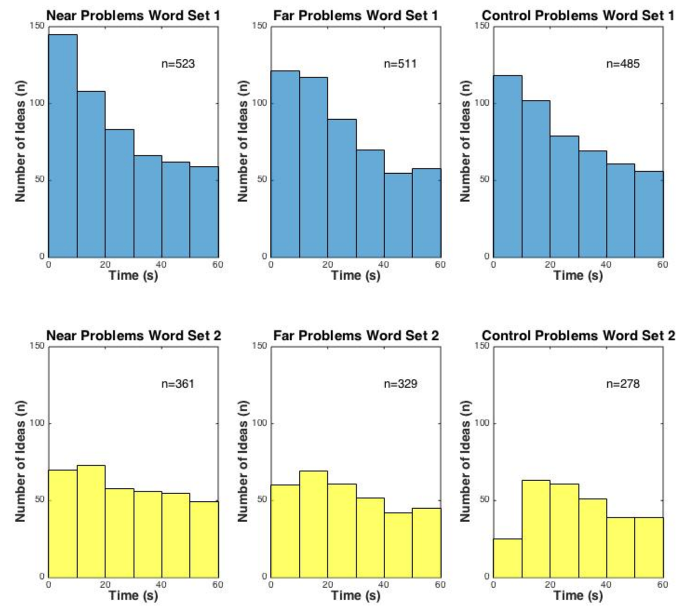

FIGURE 2: HISTOGRAM PLOT SHOWING NUMBER OF SOLUTIONS GENERATED IN EACH CONDITION OVER TIME. PLOTS ARE SPLIT BASED ON PROBLEM SOLVING BLOCK.

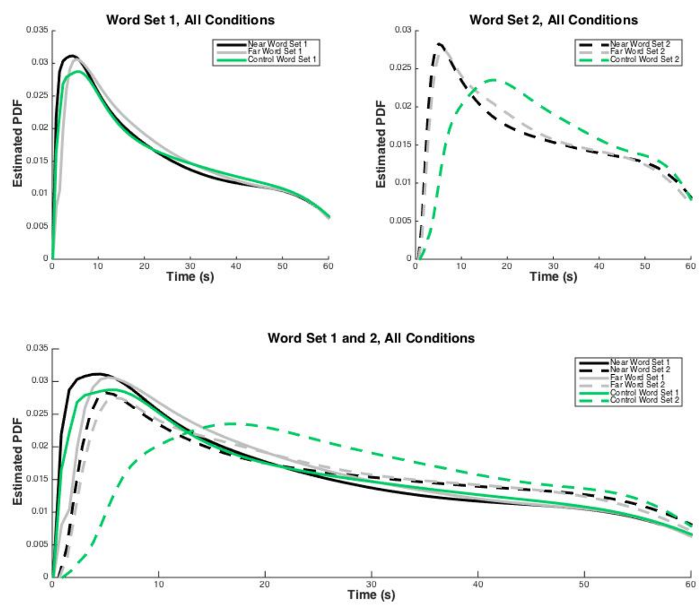

FIGURE 3: KERNEL SMOOTHING FUNCTION ESTIMATES FOR SOLUTIONS GENERATED IN EACH CONDITION WORD SET. PROBABILITY OF SOLUTION GENERATION TIMING IS INCONSISTENT IN SECOND BLOCK OF THE CONTROL CONDITION.

The bottom graph in Figure 3 superimposes all Condition-WordSet combinations onto the same plot. The outlier effect of

Control-WordSet2 is apparent against all of the conditions. The WordSet1 and WordSet2 PDFs for the other conditions are similar in their distribution shape. Together, this indicates that the impact of inspirational stimuli on problem solving is most apparent in the second problem-solving block. If not given stimuli (i.e. Control WordSet2), idea generation is reduced, and shifted out in time relative to the block onset.

4.2 fMRI Data Results

To examine differences in brain activity specifically associated with reasoning using 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 inspiration conditions added together (Near+Far) against the control. To maintain parity between the two contrasted elements (Inspiration and Control), brain activation for the Control condition was multiplied by two (Inspiration – 2*Control). AFNI's TENT model (piecewise-linear) was used; specifically modeling time points 7 to 5 seconds prior to participants' response indications. As previously mentioned, these time points were shown to produce the peak hemodynamic response based on pilot subjects.

A contrast between the Inspiration 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 2. A visual representation of these activation clusters is shown in Figure 4 by mapping the clusters onto a 3D template brain rendering.

Brain activation from this contrast (Inspiration – 2*Control, WordSet2) shows robust 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 compared to the Inspiration condition). Therefore, the resulting brain activity from the condition contrast can be positively associated with the inspirational stimuli. Previous research has shown that bilateral temporal lobe activation precedes moments of insight [45]. Temporal lobe activation is generally consistent with word representation and meaning, and has been shown to be a key driver in memory retrieval [46]. Furthermore, the right lateralized temporal-parietal activation is consistent with prior research which shows the parietal lobe directs attention to memory retrieval of concepts [47]. Together this presents strong evidence of increased semantic processing, word-meaning/retrieval, word representation, directing attention to memory, and moments of insight when participants are generating concepts with the assistance of inspirational stimuli. Due to the null results during WordSet1 when comparing the brain activation data from Inspiration vs. Control, it is also likely that the impact of the inspirational stimuli on ideation is most salient after other means of idea generation have been exhausted by the participant.

TABLE 2: INSPIRATION – 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, angular, inferior parietal gyri	39, 19	-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

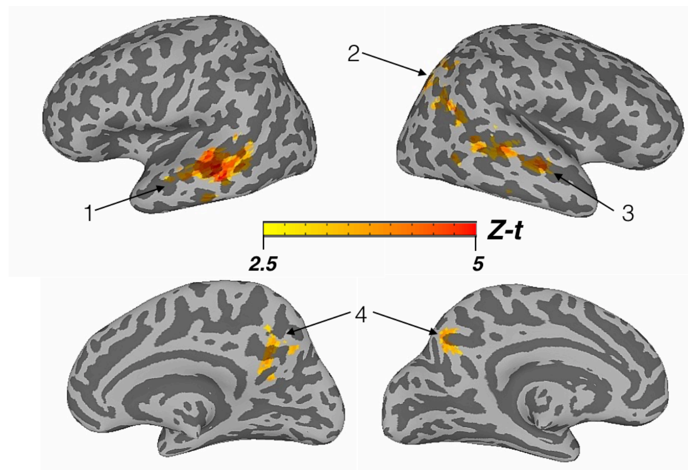

FIGURE 4: INSPIRATION – CONTROL CONTRAST BRAIN ACTIVATION CLUSTERS— FOR TIME LOCKED RESPONSE MODEL. CLUSTER NUMBERING CORRESPONDS TO TABLE 2

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 stimuli distances. Finally, the near and far stimuli were contrasted against each other to see if there were any specialized differences between the two inspirational conditions. For these analyses, the SPM 2-Gamma model was used with times 7 seconds 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 with the behavioral results, 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 inspirational stimuli to help promote ideation.

TABLE 3: 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	13, 21	34.5	-4.5	-0.05	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

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 3. There are some similarities to be drawn between both condition contrasts here, and the Inspiration vs. Control contrast shown in Figure 4. Mainly, ideating with both near and far stimuli 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 applying the usage of those words in new ways. Activation in the near condition is much more robust and widespread than the far condition. There are more positive regions of activation associated with the near vs. control, compared to the far vs. control. Furthermore, activation from the near condition more closely resembles the overall effect of inspirational stimuli vs. control discussed previously (Figure 4).

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 Inspiration 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 activation network to the Near – Control contrast, however only one cluster of activation survived statistical thresholding (L middle temporal gyrus). This indicates that the effect of the inspirational stimuli is weaker in the far condition compared to the near condition.

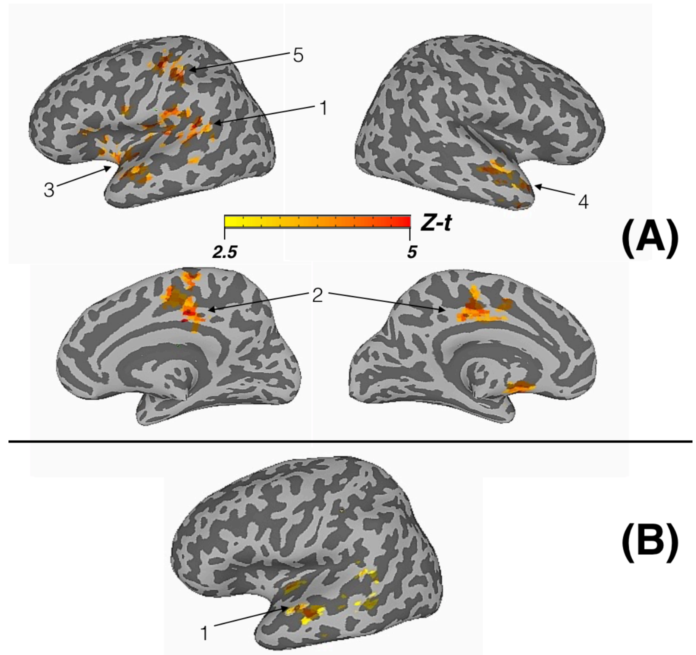

FIGURE 5: NEAR – CONTROL (A) AND FAR – CONTROL (B) CONTRASTS FOR WORDSET 2 RESPONSES. CLUSTER NUMBERING CORRESPONDS TO TABLE 3

5. DISCUSSION

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 compared to a control. Within the inspirational stimuli conditions (near and far), participants generate more concepts with near stimuli compared to far stimuli. Additionally, behavioral results clearly show that inspirational stimuli have a greater impact on idea fluency in the second block of problem solving compared to the first. This is consistent with prior research regarding open goals, where analogies are more helpful only after time is spent searching for a solution for the design problem [10,48].

Neuroimaging results added significant insight into the mental processes that underpin design ideation and concept generation. A key result from the neuroimaging analyses in this work is greater involvement of several temporal brain regions in the inspirational stimuli (near and far) conditions compared to the control condition (see Figure 4 and Table 2). Temporal brain areas are well established as being integral for semantic memory and knowledge of objects, words, and facts [46]. A review of semantic processing by Binder and Desai showed the middle temporal gyrus to be one of the most reliably activated brain regions across a range of semantic processing and memory experiments [49]. Furthermore, the current work identified left lateralized activation in the parietal and temporal lobes that was positively associated with ideating while given inspirational stimuli. An additional study on analogical reasoning and memory linked similar areas in the middle temporal gyrus extending into the inferior parietal region as being associated with memory retrieval [50]. Prior work has also established that interactions between the parietal and temporal lobes are linked to directing attention to the products of memory retrieval [47].

In the present study, 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 stimuli helps participants generate new ideas. A recent review of the cognitive neuroscience of insight during problem-solving suggests that activation of the right anterior and superior temporal gyrus (similar to the activation found in the Inspiration vs. Control contrast in this study) is indicative of insight during problem solving [51]. A separate study found support for activation in the right temporal gyrus related to insight in a combined EEG and fMRI experiment (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 in an analogy.

5.1 Inspired Internal Search

When given inspirational stimuli, neuroimaging data help to uncover what we term *inspired internal search*. During this time, participants actively recognize meaning in the stimuli, and make 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 [45,53]. In the present task, the successful use of these stimuli allows participants to be more successful at generating design concepts to multiple open-ended problems. Prior research from the authors identified an impasse-based activation network termed "unsuccessful external search".

When examining differences between near and far inspirational stimuli during design conceptualization, there were unexpected findings. While the near stimuli seem to activate a robust brain network consistent with the positive qualities of inspired internal search (Figure 5—B), the far stimuli do not. At times, far 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 stimulus is too far, then it is ignored (e.g., similar to the control condition). If the stimulus is useful (i.e., not too far), the brain activity mirrors the activation in inspired internal search (Figure 4). Both behavioral and neuroimaging data support this duality of far 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. One explanation for this is that the near stimuli from the present work might actually occupy a space similar to the "sweet spot" proposed by Fu et al. [5]. A more accurate description of the near and far conditions from this work may be "closer" and "further". The origin of the stimuli is based upon a large population (~N=1000) of crowdsourced workers [20]. Collecting data from a wide variety of people likely led to pushing all inspirational stimuli further away in distance for individual participants (e.g, a near stimulus to me is not necessarily a near stimulus to you). Due to the fact that detailed participant concepts were not recorded, one limitation of the current work is that there is no way to definitively link whether a newly generated concept incorporates a given stimulus. Future work should examine whether other mechanisms (besides the presented words) led to idea generation in either of the inspirational stimuli conditions.

6. CONCLUSION

The work presented in this paper used an fMRI (neuroimaging) experiment to investigate the neural activity underlying design ideation and concept generation with and without the use of inspirational stimuli. Inspirational stimuli at varying distances (near and far) 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 (e.g., an open goal has been established). fMRI data suggest that there is a unique brain activation network involved in the successful moments of idea generation involving inspirational stimuli, which we term *inspired internal search*. 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. Less distant inspirational stimuli trigger activation consistent with inspired internal search more frequently than more distant stimuli. Additional work is needed to further classify inspirational stimuli into an ideal distance to promote inspired internal search for specific problem classes. This work demonstrates why inspirational stimuli are effective during design ideation on a neural level and adds critical information regarding the best timing to interject with supportive stimuli.

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