Unsuccessful External Search: Using Neuroimaging to Understand Fruitless Periods of Design Ideation Involving Inspirational Stimuli

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This paper uses neuroimaging to provide insight into specific cognitive processes involved in design conceptualization with and without the support of inspirational stimuli. In particular, this work focuses on neural activity during unsuccessful search for a design solution. Twenty-one participants completed a brainstorming task while undergoing functional magnetic resonance imaging (fMRI). Participants were asked to think of concepts with and without the support of inspirational stimuli for 12 design problems. Behavioral results indicated that inspirational stimuli were most impactful after participants had time to begin developing solutions for a design problem. fMRI results during periods without inspirational stimuli indicated brain regions indicative of an impasse-based search strategy. This work elucidates cognitive mechanisms of continued search for insight into a design problem before a solution has been obtained. Furthermore, this work explores the meaning of distance for inspirational stimuli and what happens when stimuli are too far from the problem domain.

Introduction

Analogical reasoning and related processes have been formally investigated as a tool to support design ideation for over 30 years [1–9]. However, there is still a significant amount to learn regarding the cognitive processes that underpin design ideation involving inspirational stimuli (e.g., analogies). The overarching goal of this work is to understand unique brain networks that are activated during concept generation with and without the support of inspirational stimuli. Gathering insights into the neural

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activity during design ideation will allow for a more holistic understanding of how inspirational stimuli affect cognitive strategies undertaken by design practitioners. Uncovering this information will help design researchers to create more effective design theories, methods, and tools.

The research presented in this paper examines a piece of this overall goal. Broadly speaking, the analysis of neuroimaging data can be examined using either response models or block models. Response models focus on specific moments in time around a participant response (e.g., the few seconds surrounding when a design solution is indicated as being generated). Block models average neural activity over longer periods of time (e.g., overall activity during a multiple minute design conceptualization session). Examining the data in terms of each of these two mechanisms answers fundamentally different questions. The focus of this work is investigating brain activity using block models over longer periods of time. Again, the task involves generating design concepts with and without the support of inspirational stimuli. Averaging brain activity over the entire problem-solving block (in which multiple solution concepts may be generated) is truly capturing the "unsuccessful" search for design solutions. This is because there is proportionally more time spent being stuck searching for solutions than actually finding a solution for a given design problem. As discussed within the methods section of this paper, an approach was taken to filter out times in which ideas were successfully generated, therefore isolating the brain activity associated with unsuccessful search.

Background

This section provides a background of important prior research findings at the intersection of both the design research and neuroimaging literature, with a particular emphasis on analogical reasoning.

Design researchers have applied several neuroimaging techniques, including electroencephalography (EEG) [10, 11] and functional magnetic resonance imaging (fMRI) [12–14]. fMRI, the method of choice in this paper, is a brain imaging modality that measures changes in blood oxygen levels in short (~1 s) intervals of time. This change in blood flow gives an indication of brain activity and allows researchers to determine changes in activity due to specific experimental task conditions. Using fMRI, it is possible to gain an understanding of the cognitive processes involved during specific design related tasks beyond what could be determined from a traditional behavioral study. Neuroimaging techniques, such as fMRI, provide insight into what participants are truly thinking, feeling, and desiring at the time of mental judgments.

A few examples of prior investigations at the intersection of neuroimaging and design research include product preference judgments and design creativity. Sylcott et al. used fMRI to investigate tradeoffs between form and function preference decisions [14]. More recently, work by Goucher-Lambert et al. examined the neural signatures of product preference judgments involving sustainable design attributes [15]. Using fMRI, the presence of a network of brain regions associated with moral reasoning and theory of mind (i.e., "what will other people think of my actions and behavior") was present during sustainable product preference decisions. In a separate study from Alexiou and colleagues, the neural correlates of creativity in design during an apartment layout task were examined [12, 16]. This study indicated that the dorsolateral prefrontal cortex, a region of the brain critical to cognitive executive functions, including working memory and cognitive flexibility, was highly involved in design cognition during ill-structured design tasks. Finally, a study by Saggar et al. [18] used fMRI to study creativity during concept generation using a Pictionary-like game. Researchers found increased activation in several brain regions during concept generation compared to control, including the left parietal, right superior frontal, left prefrontal, and cingulate regions [17, 18]. Together, these prior works indicate that fMRI is most effective by providing links between specific features of design decisions to brain activation associated with separate cognitive tasks.

In this work, design ideation supported by "inspirational stimuli" is investigated, which is hypothesized to encourage cognitive processes closely related to analogical reasoning. Broadly speaking, the engineering design literature typically refers to analogical reasoning as a process by which information from a source domain or area is applied to a target through the connection of relationships and representations between the two [4, 19]. In this work, inspirational stimuli are provided to designers (participants) and then the relational mapping from the stimuli (source) to the problems (target) is left to the designer. Because of this key distinction, the stimuli provided in this work are not described as analogies themselves, and instead termed "inspirational stimuli." However, if designers are able to construct the relational mapping from the stimuli to the problem, they are likely engaging in what is typically considered analogical reasoning.

Analogical reasoning has been intensely studied because analogies can serve as a powerful mechanism to assist designers in stimulating ideas more fluently, and/or ideas that embody positive characteristics (e.g., increased novelty, quality) [2–6, 8, 20–23]. In addition to the aforementioned areas of research regarding analogical reasoning, an additional body of prior work has centered on two fundamental features of utilizing analogies to inspire design activity. These are *when* an analogy should be presented and *what* analogy should be provided. In answering the when part of this question, research has identified that analogical stimuli are most impactful when presented after the development of an open goal (problem-solving has commenced, but the problem remain unsolved). Research from Tseng et al. found that when distant analogies were given after the development of an open goal, more novel and diverse solutions were produced [8].

Research answering what analogies are most effective has focused on understanding 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, 24]. A near analogy implies that the analogy comes from the same (or closely related) domain, where a far analogy comes from a distant domain. Prior work has demonstrated differing results as to whether near or far analogies are more beneficial. For example, far analogies are usually considered to yield more novel solutions [25], yet they have also been found to cause to increase design fixation

[26]. In reality, it appears that the most impactful and effective analogies may reside between being too near and too far. Work by Fu et al. converged on this idea, by identifying the existence of a “sweet spot” of analogical distance; where analogies were most helpful to designers [5].

From a cognitive neuroscience perspective, analogical reasoning is a relevant and active area of research, as it is representative of some of the most unique characteristics of human logic, creativity, and thinking [27]. Neuroimaging studies in this area attempt to map the neural processes involved in analogical reasoning by breaking the process into separate component parts and studying them one at a time. Prior work has identified key component parts including 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 [27]. Encoding and retrieval primarily depend on the type and complexity of the analogy being studied. The study presented here uses word-based inspirational stimuli. Prior 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 the words associated with the task [28]. Typically, the complexity of analogical stimuli has been controlled using text-based semantic approaches, such as latent semantic analysis [29]. The retrieval of the analogy from memory calls upon anterior parts of the prefrontal cortex (PFC) [29–32]. In addition, the rostrolateral prefrontal cortex (RLPFC) has been identified as brain region, which supports higher level cognitive functions including analogical reasoning and episodic memory retrieval [33]. Wharton et al. implicated the left prefrontal and inferior parietal cortices as playing an important role in mediating analogical mapping [34]. These prior studies provide insights into the brain activation networks that may be observed in this work.

Methodology

An open-ended concept generation task using crowdsourced inspirational stimuli was used to investigate the cognitive processes involved in design ideation. While inside of an MRI machine, participants were asked to freely generate concepts for twelve different design problems from the literature. During problem-solving blocks, participants were presented with additional inspirational stimuli at varying distances (e.g., near vs. far). Using a combination of behavioral and neuroimaging data, an understanding of the ways in which inspirational stimuli impact design cognition was able to be determined. Of particular interest here was the overall neural activation patterns occurring over longer time periods, which was hypothesized to be consistent with the unsuccessful search for design solutions.

Participants

Twenty-one participants (13 male/8 female, mean = 27 yrs, SD = 5.4 yrs) were recruited to complete the fMRI study. Each of the participants provided informed consent in accordance with protocol approved by the Institutional Review Board at Carnegie Mellon University. In addition, all participants had design domain knowledge and experience as demonstrated by being an upper division student in Mechanical Engineering, or a Master's level student focusing on Design, Human–Computer Interaction, or Product Development. For their time, all participants were compensated monetarily and received a digital image of their brain.

Session Overview

The concept generation experiment that participants completed within the MRI machine was partitioned into three separate experimental conditions. Two of these conditions utilized inspirational stimuli at varying distances ("Near" or "Far"), and the third was a control condition in which words were reused from the problem statement. Each participant saw one condition per problem, and a total of twelve problems in the 1-hr session. The orders of these problem-condition pairs were presented in three separate counterbalanced groups.

The problems, as well as the inspirational stimuli used in this experiment, were identified in prior research from the authors, where a method was introduced to obtain useful inspirational stimuli with a crowdsourcing approach [35]. The motivation of this prior work was in part to address the difficulty in obtaining relevant and useful inspirational stimuli for wide varieties of design problems. The results of this work yielded an agnostic approach that utilized the naïve crowd to identify words, assessed analytically for their "distance", as inspirational stimuli for designers. Over 1300 crowd workers generated solutions. Near inspirational stimuli represented roughly the top 25% most used words, while the far stimuli sets were words that were only used once. The inspirational stimuli in this experiment were a subset of the extracted words from that prior experiment. The specific problems and words (inspirational stimuli) used for the fMRI experiment presented here are shown in Table 1.

The experiment consisted of a 1-hr brain scan, where participants generated ideas to various conceptual design problems. All experimental stimuli were presented in the MRI using the E-Prime Software package [44]. Subjects lay supine in the scanner, and viewed stimuli displayed using a monitor with a mirror fixed to the head mounted coil. Using a response glove strapped to their right hand, participants indicated a new response (including each time they had thought of a new idea) by pressing a button.

The timing of each trial is described in Fig. 1. For each problem, participants first read the problem statement for the given trial. Next, they began conceptualizing ideas for a 1-minute continuous block. During this period (WordSet1), participants were given a random subset of three words from the specific condition associated

Table 1 Problem statements and examples of inspirational stimuli from each experimental condition

Problem	Near words	Far words	Control words
1. A lightweight exercise device that can be used while traveling [36]	Pull, push, band, resist, bar	Roll, tie, sphere, exert, convert	Lightweight, exercise, device, while, traveling
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 [8]	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 [37]	Extend, clamp, pole, hook, reel	Pulley, hover, sticky, voice, angle	Device, allows, people, book, reach
6. An innovative product to froth milk [38]	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 [39]	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 [40]	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 [41]	Adjust, lift, hose, step, nozzle	Shrink, catch, attach hydraulic, telescopic	Way, drinking, fountains, accessible, people
10. A measuring cup for the blind [26, 42]	Braille, touch, beep, sound, sensor	Preprogram, recognize, pressure, holes, cover	Measuring, cup, for, the, blind
11. A device to immobilize a human joint [25]	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 [43]	Crack, crank, blade, squeeze, conveyor	Melt, circular, wedge, chute, wrap	Device, remove, shell, peanut, areas

Fig. 1 Trial timing outline

with that problem (near, far, or control). A simple 1-back memory task was used to break up periods of concept generation, as prior research has determined that tasks lasting longer than approximately 1 min can have temporal frequencies that overlap with typical MRI signal drift [45]. After the 1-back task, participants continued generating design concepts for another 1-minute block (WordSet2). During this time, participants were shown the original set of three words (WordSet1), as well as an additional set of two new words (WordSet2). Following concept generation, participants provided ratings on a scale from 1 (low) to 5 (high) for four questions regarding the (1) usefulness and (2) relevancy of the inspirational stimuli, as well as (3) the novelty and (4) quality of their design solutions.

Data Analysis

fMRI Data Preprocessing

The raw neuroimaging data collected during the experiment were preprocessed and analyzed using the Analysis of Functional NeuroImages (AFNI) software package (March 1, 2017 version 17.0.11) [46]. A custom automated Nipype (Python language) preprocessing script was used to complete the preprocessing of the neuroimaging data into a form suitable for data analysis [47]. Preprocessing steps within this pipeline 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 (7 mm FWHM). Smoothing reduces the impact of high-frequency signal and enhances low-frequency signal. This causes more pronounced spatial correlation in the dataset. 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.

fMRI Data Analysis

In this work, the brain activity present during design ideation over long time scales is of interest. Here, the brain activity is averaged over the entire problem-solving period (WordSet1 and WordSet2). To do this, a mixed block model was utilized, which combined response regressors and the block regressors. The process of using response regressors (around the time of idea generation) in the block-level model has shown to be an effective way to measure sustained activity during task-level processing [48]. This allowed for an examination of widespread brain activity that is active across the whole concept generation period, while simultaneously filtering brain activity during idea generation.

At a block level, the resulting activity between contrasts is representative of the unsuccessful search for a design solution. By removing periods of productive idea generation captured in the response models, the block-level analysis captures brain activity representative of searching for a solution and not finding one. Neural activity at the block level was explored using the brain activation data from both WordSet1 and WordSet2 combined (2 × 60 s), as well as separately (60 s). The GLM block regressors were 1-parameter models with fixed shapes constructed using the AFNI BLOCK hemodynamic response type. The response regressors utilized the AFNI TENT (piecewise linear) and SPMG 2-parameter gamma variate models. The details of the implementation of how these models were executed can be found in companion work from the authors [49].

Behavioral Data Analysis

As mentioned previously, participants provided ratings across four metrics: the (1) usefulness and (2) relevancy of the inspirational stimuli being presented to them, as well as the (self-rated), (3) novelty and (4) quality of their design solutions. These scores were collected from participants after each problem during the fMRI experiment using the response glove provided to them. Repeated measures ANOVAs were used to determine whether there was a significant effect across the three experimental conditions (near or far inspirational stimuli, control) for any of these four rating areas.

Results and Discussion

This section introduces and discusses the behavioral and neuroimaging results from the fMRI design ideation experiment discussed previously. First, behavioral results are presented, as they help to better frame and interpret the results from the neuroimaging analyses. Results from a block-level fMRI analysis are presented, where brain activation from within an entire problem-solving period (i.e., Near Condition, WordSet2) is averaged. Together, behavioral and neuroimaging analyses help to uncover the characteristics of design ideation involving inspirational stimuli, and in particular, periods of unsuccessful search during problem-solving.

Behavioral Results: Participants' Self-Rating Metrics

Mean values from participant self-reported ratings are shown in Fig. 2. Each value in the figure represents the mean rating (scale from 1–5) 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 (participants rated measures from each problem as a set). Using a repeated measures ANOVA, it was determined that there was no effect between conditions seen for how novel participants felt their solutions were ($F(2, 40) = 0.43$, $p = 0.43$), or the overall self-rated quality of their solutions ($F(2, 40) = 0.46$, $p = 0.63$). Prior work from the authors using these inspirational stimuli found that while participants did not self-report a difference in the novelty and quality of their design solutions, expert evaluators did perceive a statistically significant difference between the various conditions [35].

In addition to questions about their developed solutions, participants also provided ratings for the relevancy and usefulness of the inspirational stimuli. For each of these metrics, a highly significant effect was observed. For example, there was a strong correlation between participant ratings for the relatedness of the inspirational stimuli and its distance from the design problem. For this metric, participants rated all conditions to be significantly different from one another ($F(2, 40) = 9.37$, $p \ll 0.01$). 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 ($F(1, 20) = 25.22$, $p \ll 0.01$). Similarly, there was a significant trend for participant judgments of the usefulness of the inspirational stimuli. The mean usefulness of the three conditions was different with a high degree of statistical significance ($F(2, 40) = 76.73$, $p \ll 0.01$). Not surprisingly, participants rated the control stimuli (reused words from the design problem statement) as not useful (mean = 1.56, SD = 0.84). In addition, participants rated near stimuli (mean = 3.68, SD = 0.87) as being more useful than far stimuli (mean = 3.13, SD = 1.10). Finally, a separate contrast between the near and far conditions for the usefulness metric confirmed the significance of this difference ($F(1, 20) = 11.12$, $p \ll 0.01$).

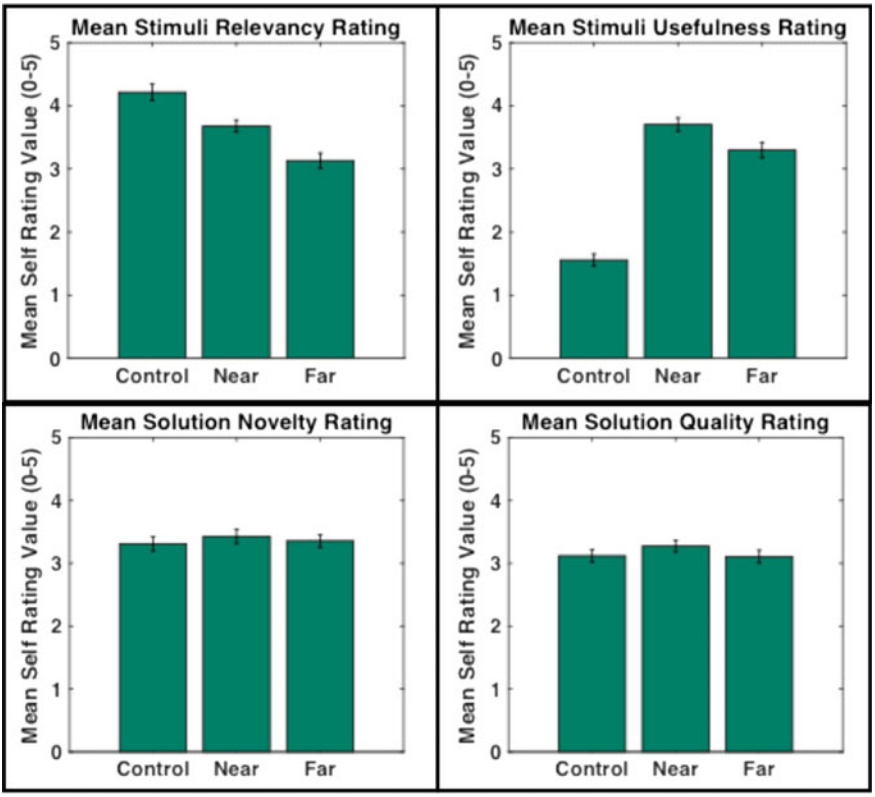

Fig. 2 Mean ± 1 S.E participant self-ratings for relevance and usefulness of inspirational stimuli, and novelty and quality of design solutions ($N = 84$ per bar—21 participants * four samples of each condition)

Neuroimaging Results

Block Models: Brain Activation Patterns During the Unsuccessful Search for Design Solutions

Behavioral data provides insight into aspects of how design ideation is impacted by inspirational stimuli, but not *why*. This level of depth can be obtained using neuroimaging methods. 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 are 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 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 (Near, Far, Control) and WordSet (WordSet1, WordSet2) combinations. From this analysis, only one contrast yielded significant group-level results: the Near–Control WordSet2 contrast. There is 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 consistent with prior research regarding open goals [50]. Research from Tseng et al. found that analogies were more helpful after an open goal already existed for the problem [8]. Therefore, one explanation for inspirational stimuli only having an impact during the second block of problem-solving is that the first block was needed to develop open goals for the problem, and having versus not having inspirational stimuli did not make a difference. 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 the unsuccessful search for a design solution during concept generation. From this analysis, it appears that this is occurring most when inspirational stimuli are not present and after an open goal has been established for a given problem (Control WordSet2 block).

All significant clusters of activation from this contrast are shown in Table 2 and Fig. 3. 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 people are engaged in unsuccessful search. 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 [51]. In addition to 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 [52] (though to be fair, not much is generally known about switching between internal and external attention [53]). This type of activity makes sense, as switching between attention states would be necessary for participants as they continue to search for inspiration.

One explanation for the activation network established here (centered on the unsuccessful search for design solutions) is that participants are experiencing design fixation. Here, design fixation is defined as the impasse or mental block that occurs during the search for insight during a design problem, based upon the counterproductive impact of prior knowledge [54, 55]. Prior research demonstrates fixation is

Table 2 Near–control contrast for WordSet2 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

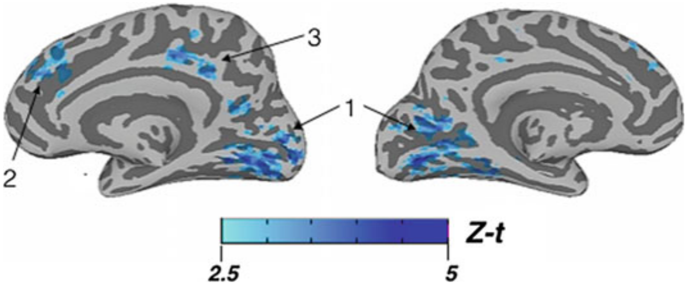

Fig. 3 Near–control contrast for WordSet2 block. Cluster numbering corresponds to Table 2

inversely related to the quantity of ideas being generated [54]. As the only significant brain activation occurred during WordSet2, it is possible that participants remain fixated on the initial ideas that they generated. Furthermore, not having additional inspirational stimuli in the control condition prevents participants from having a starting point to generate new insights into the problem space.

Further Identification of Brain Regions Indicative of Unsuccessful Search Using an Ancillary Block Modulation Analysis

The key result from the neuroimaging analyses was that there appeared to be a consistent network of brain regions (most notably areas in the occipital lobe including the lingual gyrus, cuneus, and calcarine gyrus) that seem to be linked to the unsuccessful search for a design solution. This was evident at the block level when contrasting Near WordSet2–Control WordSet2. To 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.

This analysis indicated that unsuccessful search was present in all three of the experimental conditions. This in and of itself is not particularly surprising, due to the fact that unsuccessful periods are reasonably expected to occur when attempting 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. Following this, the mean brain activity for each condition during WordSet2 was sampled within each ROI to see whether there was a statistically significant difference between the conditions.[1]

The extracted ROIs are listed in Table 3 and displayed in Fig. 4. The mean activity values from these ROIs were not statistically different, except for ROI 2. For this ROI, the mean activation was highest in the control condition ($F(2, 62) = 3.10$, $p = 0.052$). When comparing the mean activation for the near and control conditions within the extracted ROIs, the difference is highly significant ($F(1, 41) = 6.23$, $p = 0.017$). 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 as being related to unsuccessful search 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 contrasts, lend strong support for the presence of an unsuccessful search region in these brain areas. This unsuccessful search region is most strongly correlated with the control condition, implying that solution search is more difficult in the absence of inspirational stimuli.

Put together with the previously presented results, in the absence of inspirational stimuli, participants engage in a unique search strategy. This strategy is represented by a specific brain activation network and is also present in the far condition (compared to the near condition). We call this network of brain regions and resulting solution search strategy *unsuccessful external search*. An increase in activity in primary visual processing-related brain regions, which make up the center of an identified unsuccessful search brain network, indicates that participants continue to explore

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[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 et al. using the external neuroimaging database—Neurosynth. However, here the ROI mask was created based on a specialized analysis of the empirical data [56].

Table 3 Regions of interest for unsuccessful search modulation 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 postcentral gyrus, paracentral lobule	5, 6	−10.5	−46.5	50.5	154
6	L angular gyrus, middle occipital gyrus	39, 40	34.5	67.5	11.5	129

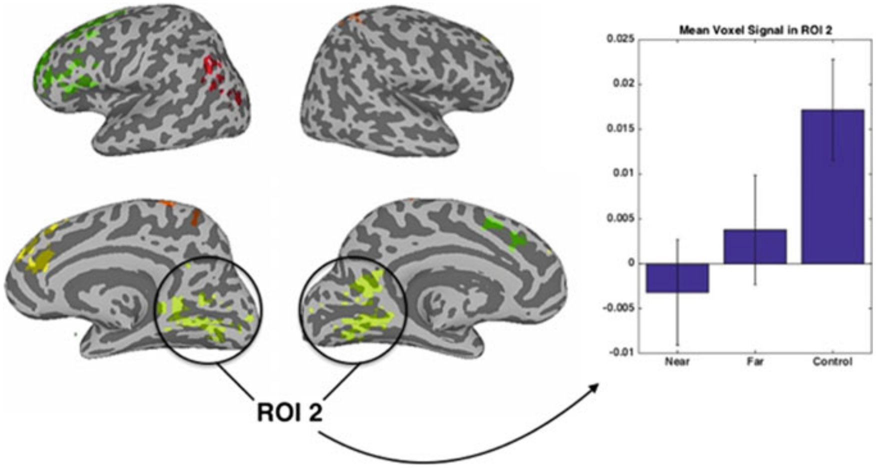

Fig. 4 Unsuccessful search ROI from modulation analysis—control condition shows highest level of activity

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 [51]. Furthermore, behavioral data from this experiment support the notion that individuals are less successful at generating ideas without inspirational stimuli.

Conclusion

The work presented in this paper used a neuroimaging experiment to investigate the neural correlates of the unsuccessful search for solutions during design problem-solving. Of particular interest were the impacts of design ideation with and without inspirational stimuli over longer time periods (minutes, compared to instances when participants generated new solution concepts). Investigating behavioral data and neural activity at this level provides insight into characteristics of unsuccessful search, which may be representative of design fixation. Inspirational stimuli at varying distances were compared against a control condition in which words were reused from the problem statement. Behavioral data gathered from participants self-reported ratings revealed that near-field inspirational stimuli are more useful and relevant compared to more distant stimuli. However, there was no significant difference in how participants rated the novelty and quality of their design solutions. Neuroimaging analyses provide insights into the mental processes during design ideation that participants are unable to verbalize. Mainly, fMRI data suggest that participants are more unsuccessful when not provided inspirational stimuli, or provided stimuli that are too distant. This leads to a specific brain activation network, which we term *unsuccessful external search*. Unsuccessful external search shows increased activation in brain regions associated with visual processing and directing attention outward. While the highest level of unsuccessful search was found in the absence of inspirational stimuli (control condition), distant stimuli show features of this search strategy. This suggests that when inspirational 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 accurately characterize when a far inspirational stimuli (e.g., analogies) become too far and exhibit characteristics of unsuccessful external search. Taken together, this work demonstrates the effectiveness of inspirational stimuli on a neural level, opening the door for further advancements in the development of new design theory and methods.

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