Design Science

The neural correlates of ideation in product design engineering practitioners

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Abstract

In product design engineering (PDE), ideation involves the generation of technical behaviours and physical structures to address specific functional requirements. This differs from generic creative ideation tasks, which emphasise functional and technical considerations less. To advance knowledge about the neural basis of PDE ideation, we present the first fMRI study on professional product design engineers practising in industry. We aimed to explore brain activation during ideation, and compare activation in open-ended and constrained tasks. Imagery manipulation tasks were contrasted with ideation tasks in a sample of 29 PDE professionals. The key findings were: (1) PDE ideation is associated with greater activity in left cingulate gyrus; (2) there were no significant differences between open-ended and constrained tasks; and (3) a preliminary association with activity in the right superior temporal gyrus was also observed. The results are consistent with existing fMRI work on generic creative ideation, suggesting that PDE ideation may share a number of similarities at the neural level. Future work includes: functional connectivity analysis of open-ended and constrained ideation to further investigate potential differences; investigating the effects of aspects of design expertise/training on processing; and the use of novelty measures directly linked to the designer's internal processing in fMRI analysis.

Key words: creative design, design cognition, fMRI, ideation, neuroimaging

Received 9 May 2019
Revised 7 November 2019
Accepted 12 November 2019

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Published by Cambridge University Press

Des. Sci., vol. 5, e29
journals.cambridge.org/dsj
DOI: 10.1017/dsj.2019.27

1. Introduction

Product design engineering (PDE) refers to the set of tasks involved in conceptualising, developing, and realising functional products (Pugh 1991). It may be viewed as a key domain of human creative activity, and is critical for meeting human needs and advancing technology across numerous sectors of society (Sosa & Gero 2005). Fundamental to the PDE process is creative ideation, which may be generally defined as the generation of ideas to address a given brief or problem. Numerous studies of creative ideation in the general population have been conducted in cognitive neuroscience, typically employing generic divergent thinking tasks such as the Alternative Uses Task (Benedek *et al.* 2018).

This predominant approach has been critiqued by Dietrich (2019), who highlights several issues. Firstly, it has been demonstrated that other kinds of thought process – e.g. convergent thinking – can be creative. Thus, studying divergent thinking alone is unlikely to provide a comprehensive view on the neural basis of creative ideation. Secondly, there is a tendency to view creativity as a distinct trait or ability that can be uniquely located in the brains of 'creative people'. However, Dietrich (2019, p. 38) suggests that what 'scientists, entrepreneurs, designers, or ballet dancers must do to be creative in their respective domains' is too different for this to be a foregone conclusion. The findings emerging from recent neuroimaging studies suggest that creative ideation is likely to be a complex, higher-order phenomenon that may potentially involve a multitude of interacting processes and neural regions at different scales (Liu *et al.* 2018*b*). There is a need for studies in areas such as PDE to explore whether these vary across domains, or if there is some common neural basis underpinning different creative ideation tasks.

The need for neuroimaging work on PDE ideation is further supported by differences between PDE tasks and widely studied generic divergent thinking tasks. In both, the production of novel ideas is a key goal (Shah, Smith & Vargas-Hernandez 2003; Benedek *et al.* 2013). However, in the former, the designer must also address specific functional requirements (e.g. 'transfer ink to paper') derived from a technical problem (e.g. 'enable person to write'), and the ideas must have some potential for further development into manufacturable products (Shah *et al.* 2003). This requires the designer to think about what kinds of behaviours could achieve the function (behaviour in the technical systems sense (Hubka & Eder 1988), e.g. 'ink flows under gravity'), and what kinds of physical structures and mechanisms could provide this behaviour (e.g. 'ink reservoir connected sufficient height above rollerball'). Whilst divergent thinking tasks may also involve consideration of functional aspects, these tend to be more abstract (e.g. uses of a given object) and less constrained by technical considerations. Furthermore, as discussed in Section 1.2 below, designers frequently deal with both open-ended and constrained problems. Studies of divergent thinking deal almost exclusively with the former, whilst the latter is more closely associated with convergent thinking. Given these differences, it is not clear to what extent knowledge about neural activation in divergent thinking tasks is applicable to PDE ideation. In this respect, Abraham (2013) highlights the need to investigate brain activity associated with tasks particular to specific domains of creativity, and reflect on how the findings fit into the broader creativity research landscape.

Whilst there have been studies of creative ideation in artistic domains, including drawing (Kottlow *et al.* 2011), musical composition (Lu *et al.* 2015), and story generation (Howard-Jones *et al.* 2005), there have thus far been few in design and engineering. In the field of design science, researchers have been studying the cognition of designers and engineers for over 60 years (Hay *et al.* 2017*a*). However, neuroimaging research is only just beginning to emerge in this area, with a limited number of studies applying functional near-infrared spectroscopy (Shealy & Gero 2019), electroencephalography (Liu *et al.* 2018*a*; Nguyen, Nguyen & Zeng 2018; Vieira *et al.* 2019), and functional magnetic resonance imaging (Alexiou *et al.* 2009; Sylcott, Cagan & Tabibnia 2013; Goucher-Lambert, Moss & Cagan 2017, 2019). To advance knowledge about the neural basis of PDE ideation, in this paper we present results from a functional magnetic resonance imaging (fMRI) study of ideation in professional product design engineers. We investigated ideation in response to both open-ended and constrained problems. To our knowledge, this is the first fMRI study on professional designers working full time in industry after completing their degree-level education (as opposed to design students). Given that brain activity and performance during creative tasks may be affected by contextual factors such as expertise (Beaty *et al.* 2016; Kleinmintz, Ivancovsky & Shamay-Tsoory 2019), investigations of professionals are important for building a comprehensive understanding. We discuss how our findings compare with the existing body of neuroimaging work on creative ideation, and outline future avenues for investigation at the intersection of cognitive neuroscience, design science, and PDE.

To provide further background to the work, existing research on ideation and constrained versus open-ended problems is briefly reviewed in Sections 1.1 and 1.2 below, before details on the reported study are provided in Section 1.3.

1.1. Existing work on ideation

As noted above, research on creative ideation in cognitive neuroscience has been dominated by the study of divergent thinking tasks. In this context, dual process theories have been influential in shaping the prevailing two-fold model: creative ideation involves both lower-order generative processes, and higher-order evaluative processes (Beaty *et al.* 2018; Kleinmintz *et al.* 2019). Current research suggests that three interacting brain networks may be involved in supporting these processes during generic creative ideation tasks (Beaty *et al.* 2015, 2016, 2018): (1) the default mode network, supporting idea generation through spontaneous memory retrieval and self-generated thought processes; (2) the executive control network, supporting the higher-order evaluation and modification of ideas to meet the goals and constraints of the task; and (3) the salience network, involved in identifying candidate ideas from generative processes and transferring these to the executive control network for higher-order processing. Recent fMRI work by Beaty *et al.* (2018) suggests that higher creative ability may be associated with simultaneous engagement of these networks, which ordinarily work in competition with one another. Results from a technique called connectome-based predictive modelling suggest that the core hubs of the three networks form important connectivity points during ideation. These include the left posterior cingulate cortex (default mode network), the left anterior insula (salience network), and the right dorsolateral pre-frontal cortex (executive control network).

It is difficult to directly map the above work to existing knowledge on design cognition, due to ontological differences between the fields (Hay *et al.* 2017*b*) and the lack of neuroimaging work conducted in the latter to date. However, the dual process view of creative ideation is also reflected in research on ideation in PDE. For instance, a recent systematic review of protocol studies on creative design cognition (Hay *et al.* 2017*a*,*b*) suggests that higher-order executive processes – such as evaluation and decision making – are involved alongside the generation and synthesis of ideas. The Geneplore model of creativity (Smith, Ward & Finke 1995), which formalises creative thinking in terms of generative and evaluative phases, has also been applied to model design ideation processes (e.g. Chusilp & Jin 2006). As such, it is possible that despite the perceived differences between PDE ideation and divergent thinking tasks, they could be underpinned by similar brain regions and networks. The systematic review by Hay *et al.* (2017*a*,*b*) also suggests that visual perception and visual mental imagery feature prominently in PDE ideation. A meta-analysis of fMRI studies on visual creativity by Pidgeon *et al.* (2016) found that the right pre-frontal cortex, thalamocortical nucleus and left middle frontal gyrus may be associated with ideation in this context. Again, it is possible that similar brain regions are activated during the generation of ideas in PDE ideation, although the studies in the meta-analysis employed tasks focusing on relatively simple visual forms as opposed to functional products.

In addition to the broad range of studies on divergent thinking, there have been a limited number of fMRI studies focusing specifically on design ideation tasks. The focus of these tasks varies considerably, e.g.: Ellamil *et al.* (2012) compared the generation of book cover designs with evaluation of the designs; Alexiou *et al.* (2009)/Gilbert *et al.* (2010) compared an ill-structured room layout task with a well-structured problem solving task; and Kowatari *et al.* (2009) compared an aesthetic pen design task with a counting task across experienced and novice designers. Although these tasks fall within the design domain, they differ from the ideation tasks tackled by product design engineers specifically. As noted in the introduction, the latter require consideration of what (technical) behaviours could fulfil functional requirements derived from a technical problem, and what physical structures/mechanisms/relationships could provide these behaviours to form a product. The tasks used in the three studies above do not seem to involve the same kind of thought processes: generating book cover designs is a primarily visual aesthetics task that does not involve consideration of product function, behaviour, or structure; generating room layouts involves configuring given structural elements in space rather than generating new ones in a product context; and aesthetic pen design focuses on changing the visual appearance of a given structure. Few commonalities may be identified in the results of these studies, other than the general involvement of various regions of the pre-frontal cortex.

Finally, one paper in the design literature reports an fMRI study employing design ideation tasks more reflective of PDE. Goucher-Lambert *et al.* (2019, p. 1) found that the use of 'inspirational stimuli' during ideation activated several regions in the temporal cortex, including middle and superior temporal gyri. However, the study was limited to students from mixed design backgrounds rather than a consistent sample of product design engineers. That is, designers concerned primarily with the function, behaviour, and structure of physical products as opposed to entities such as services, experiences, interfaces, etc. Furthermore, to gain insights into the effects of stimuli on brain activation, they contrasted an ideation task with another ideation task as the control condition (i.e. the same task, with and without inspirational stimuli). This limits the conclusions that can be drawn about the brain regions fundamentally associated with PDE ideation.

1.2. Constrained and open-ended problems in PDE ideation

As conveyed in the introduction, the technical problems encountered by product design engineers vary in terms of how constrained they are (Silk *et al.* 2014; Sosa 2018). More constrained problems may specify a desired solution type (e.g. a particular kind of product) and specific functional requirements to be addressed, as well as targets for product characteristics such as cost, size, weight, and so on (Jin & Chusilp 2006). More open-ended problems do not specify a solution, and may convey ambiguous information on functional requirements that stimulates the exploration of different interpretations and associated solutions (Sosa 2018). Constrained problems have fewer possible solutions, and solving them may centre on finding which version of a particular idea best satisfies the set of constraints. In contrast, open-ended problems have a broad range of possible solutions that may differ considerably depending on how the requirements are interpreted. In the course of finding an appropriate interpretation of the problem, the designer may explore a larger solution space than in the case of constrained problems.

In the literature, constrained problems have been associated with convergent thought processes, where the goal is to find a 'correct' or 'optimal' solution that satisfies the constraints. Open-ended problems are frequently associated with divergent thinking, where the goal is to explore different possible solutions deriving from different problem interpretations (Goel 2014; Liu *et al.* 2018*a*). Proficient designers are adept at dealing with both constrained and open-ended problems (and degrees in between); however, it is not clear whether generating solutions to these different types of problem during ideation should be expected to differ at the neural level. As discussed above, the majority of the research on creative ideation in cognitive neuroscience focuses on open-ended tasks and divergent thinking. Comparing brain activity associated with ideation in response to constrained and open-ended problems could provide deeper insights into the neural basis of PDE ideation, given the importance of each in this context.

1.3. The present study

The study reported herein aimed to examine the brain regions activated during ideation in professional product design engineers, and to compare brain activation patterns for open-ended and constrained PDE ideation tasks. This was an exploratory study, seeking to gain initial insights into the neural basis of ideation in an under-researched area. In Section 4, we discuss opportunities to build upon this by studying brain networks, which are increasingly considered to be fundamental to creative thinking.

In the study, a sample of professionals were asked to generate product concepts in response to a series of PDE problems while undergoing fMRI scanning. Of these problems, half were open-ended and the other half constrained. To identify the brain regions associated with PDE ideation, it was necessary to compare activity during the ideation tasks with activity during an appropriate control task. The control task must be similar to PDE ideation, minus the process of interest – in this case, the generation of novel ideas for functional products. As discussed in Section 1.1, existing literature suggests that this may involve the retrieval of information from memory, some form of spontaneous generative processing, higher-order evaluation and modification processes, and visual mental imagery processing. A similar task that does not involve the generation of new ideas is imagery manipulation. That is, retrieving a known product from memory, forming a visual mental image of it, and performing a requested manipulation on the image (e.g. rotation or resizing). We contrasted activity elicited during the ideation conditions with activity during imagery manipulation tasks, with the aim of isolating cortical regions uniquely engaged by PDE ideation. We also examined whether brain regions activated when solving open-ended problems were different to those activated when solving constrained problems.

2. Method

2.1. Participants

There were 32 participants (27 males, 5 females), aged 24–56 years (mean = 31.63, SD = 8.15). They were all practising product design engineers with at least 2 years professional experience (mean = 7.75 years, SD = 7.51, range = 2–34). Ethical approval for the study was granted by the University of Strathclyde Ethics Committee and approved by the NHS Lothian Research and Development Office. All participants gave written informed consent and were reimbursed £30 per hour for their participation.

2.2. Design tasks

Participants were presented with three types of task: open-ended ideation, constrained ideation, and imagery manipulation. The first type of ideation task focused on open-ended problems (e.g. '*Lighting towns and cities at night has negative environmental impacts e.g. fossil fuel depletion; light pollution; and disruption to wildlife. Generate concepts for products that may improve the environmental impacts of lighting urban areas*'.). The second type focused on more constrained problems, where a desired product type was specified (e.g. '*Street lighting powered through the National Grid creates high annual running costs and negative environmental impacts for local authorities. Generate concepts for a self-powered street light that does not use mains electricity*'.). During the manipulate tasks, participants were asked to form a detailed mental image of a type of existing product described in the task instructions, and to mentally rotate or resize a selected feature of the image. For example: '*Many types and brands of personal beauty and grooming devices are available. Produce detailed mental images of electrical personal beauty and grooming devices in which selected features are rotated*'. Everyday commonly encountered products were selected for the manipulate tasks to try to ensure that participants engaged in the visualisation of known products rather than the generation of new ideas.

An unrelated task was used as a baseline. During this task, participants responded each time a fixation cross presented on a black background changed from white to purple. The cross was presented for 30 s in total, and changed colour for 200 ms at least three times. Colour changes were separated by intervals of 1–10 s.

The ideation tasks were based on a variety of sources, including student design projects in the authors' university department and publicly available information on design competitions. A range of different tasks were employed to avoid effects of task focus on the fMRI results, and instructions were matched in structure and word count to avoid effects of reading time. Designing the fMRI study involved a trade-off between the number of concepts generated in each condition, and the overall length of the scan: there must be enough of the former to achieve sufficient statistical power, but the scan cannot be so long that participants become fatigued and uncomfortable within the constrained scanning environment (Henson 2007). To optimise these parameters and test whether the ideation and manipulate tasks could be completed by designers, we carried out behavioural pilot studies with 35 designers (24 professionals and 11 students). The designers completed the tasks on a laptop in an office environment, and were able to provide a variety of appropriate responses to all. We analysed the average response times and number of concepts/mental images generated, to determine the maximum task durations that would minimise overall scan length whilst maintaining a sufficient number of concepts per condition for the analysis (see Section 2.3). Finally, to ensure that the ideation tasks were matched in difficulty, we asked designers to rate the perceived difficulty of each one on a scale from 1 (very easy) to 7 (very difficult). On average, the tasks were rated as moderately difficult, with a mean rating of 3.76 ($SD = 1.08$) for professionals and 3.80 ($SD = 0.74$) for students (Hay *et al.* 2019*b*).

2.3. Procedure

All participants were assessed for MRI compatibility, and prior to scanning their average rate of concept generation was assessed to ensure compatibility with the timing and number of tasks presented during the fMRI scan. Based on the pilot studies, participants were required to have an average concept generation rate of $\leqslant$35s and to be able to generate at least 12 concepts across a set of 5 tasks. The 32 participants in the study had a mean concept generation rate of 7.46 s (range = 2.60–21.08, $SD = 3.81$) and on average generated 14.7 concepts (range = 12–15, $SD = 0.82$). Prior to scanning, participants were not informed that there would be two types of ideate task.

During the scan, open-ended, constrained, and manipulate task instructions in the form of two sentence descriptions were presented on the screen (viewed through Nordic Neurolab MRI-compatible goggles) for up to 18 s, or until the participant pressed a button on the handheld response box. A black fixation cross then appeared, signalling that the participant should commence generation of the concepts/mental images indicated by the task description. Participants were asked to generate up to three distinct concepts/mental images in each task, and to press a button on the response box as soon as they had generated each individual concept/image. Participants were given 85 s to complete open-ended and constrained tasks, and 30 s to complete manipulate tasks. In total, each participant completed 10 open-ended, 10 constrained, 10 manipulate, and 20 baseline tasks, and these were presented in a random order. Thus, participants generated a maximum of 30 concepts/mental images per condition.

At the end of each open-ended and constrained task, participants were immediately given 25 s to provide a brief verbal summary of all concepts they had just generated (i.e. up to 3 for each task), which was recorded. This was done to act as a reminder of the concepts when the participant was later asked to sketch them on paper. Participants were not permitted to sketch during scanning to avoid negative effects on the data due to motor actions.

After exiting the scanner, participants were given the audio recordings of their verbal summaries and asked to use these as a memory prompt to recall each concept they had generated. The concepts were sketched using a pencil/pen and paper (an example of a sketch produced for the 'lighting cities' task outlined in Section 2.2 is presented in Figure 1). Participants were instructed that their sketches should be as representative of the generated idea as possible, and that they should not add additional features. They were asked to sketch in enough detail for the concept to be understandable to an observer. In addition, given the typically rough and abstract nature of design ideation sketches, they were asked to briefly describe in words how the product would work to reduce ambiguity. An example of a sketch from a design task not used in the study was shown to all participants.

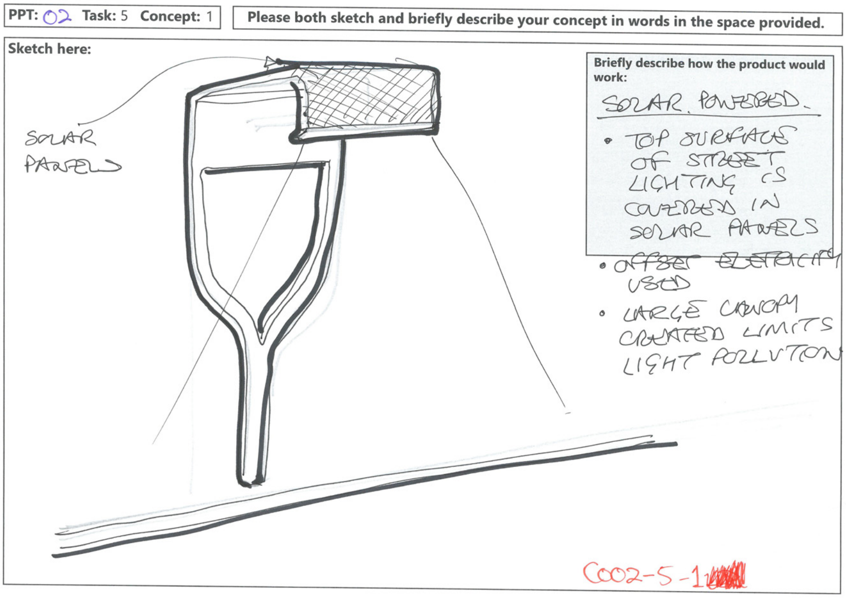

Figure 1. Example of a concept sketch produced by a participant.

2.4. fMRI data acquisition and analysis

A Siemens 3T MRI scanner with a standard head coil was used to record both T1-weighted anatomical and echoplanar T2*-weighted image volumes with BOLD contrast. The structural T1-weighted images were collected in a 10–15 min session at the start of the study. T2*-scanning parameters were set such that each volume comprised 35 axial slices (3.3 mm thick, oriented approximately to the AC–PC plane), covering the whole brain (excluding the ventral parts of the cerebellum) with echo time (TE) set at 26 ms and repetition time (TR) set at 2.39 s.

Data were analysed using Statistical Parametric Mapping 12 (SPM12) running on MATLAB (version R2016b). The volumes were realigned to correct for movement, slice-time corrected using the middle slice (23rd) as a reference slice, normalised to standard anatomical space (based on Montreal Neurological Institute [MNI] template) and spatially smoothed using an isotropic Gaussian kernel (8 mm^3 full-width at half-maximum). The data were high-pass filtered to a cutoff of 128 s to remove low-frequency signal changes in the blood oxygen level dependent (BOLD) signal. Onset times and durations were defined separately for each individual concept/image generated using participants' response button data. fMRI data were then analysed using a standard general linear model (GLM) approach. The design matrix was generated with separate box-car regressors (convolved with the haemodynamic response function) coding for neural activity across the different trial types. Six additional regressors accounting for movement-related artefacts were also included in the model. At the participant level, t-contrasts were used to generate contrast images for the main contrasts of interest: (1) ideate (collapsing over open-ended and constrained) > manipulate; and (2) open-ended > constrained. Participant-level contrast images were then entered into GLMs at the group level and further explored, again using *t*-contrasts.

Contrast 1 was additionally run including two variables as covariates to assess any relationships with brain activation:

(i) each participant's years of professional experience in PDE, given that expertise may have an effect on brain activation during creative ideation (Beaty *et al.* 2016; Kleinmintz *et al.* 2019); and

(ii) each participant's average concept novelty score (see Section 2.5 for calculation procedure), given that a relationship may be expected with brain activation during the creation of ideas.

Further details on the analysis procedure are provided in supplementary material that can be downloaded from the journal website.

2.5. Analysis of concept sketches

The soundness of the results obtained from the above contrasts is at least partly dependent on the extent to which the participants were actually engaged in ideation during the open-ended and constrained tasks. That is, generating solutions to the design problems presented as opposed to some off-task activity. Ordinarily, the sketches produced by a designer during ideation indicate the solutions they were working on. However, as noted in Section 2.3, sketching was not permitted inside the scanner to maintain fMRI data quality. As such, we assessed engagement in the ideation tasks by analysing the sketches participants produced after exiting the scanner. Whilst there are questions regarding how reflective these sketches are of the ideas actually generated during the tasks (discussed in Section 4), they at least provide an indication in a context where it is difficult to gather more conventional evidence.

Sketches were interpreted to determine whether they conveyed solutions to the open-ended and constrained problems presented during the study through a qualitative coding process described in detail in Hay *et al.* (2019*b*). Coding was completed using the NVivo software package (QSR International 2018). To qualify as a solution, a sketched concept had to be: (1) recognisable as a functional product, as opposed to e.g. a service or process; and (2) a product that is relevant to the open-ended/constrained design problem tackled. Each sketch determined to be a solution was coded with the type of product proposed. A separate coding scheme of product types was developed for each ideation task in the study. When determining how a particular sketch should be coded, the interpreted product type was compared against others already existing in the relevant coding scheme. One of three actions was then taken:

(i) If distinct from existing codes, the product was added to the coding scheme and applied to label the sketch.

(ii) If the same as existing codes, the matching code was selected and applied to label the sketch.

(iii) If similar to and/or overlapping several existing codes, the latter were adapted and/or merged to create new codes that more accurately describe the full set of sketches concerned.

In cases where a sketch could not be coded as a solution, one of four alternative classifications was applied:

(i) Insufficient information to interpret concept: the sketch did not provide sufficient detail for interpretation.
(ii) Multiple concepts: the participant had recorded multiple concepts on a single sheet and the sketch could not be uniquely categorised.
(iii) Inappropriate task response: the concept was interpreted as unrelated to the task description.

The full sample of sketches was initially coded by a single researcher with 10 years of experience in product design engineering (education and research). To mitigate the risk of bias towards one perspective, the coding schemes developed for each task were reviewed and discussed regularly by the full research team (design and psychology academics/researchers) and alterations made where required. A reliability sample consisting of $\sim$16% of the sketch sample was then independently coded by a design professional with over 30 years of industrial experience, and a PhD student with 1.5 years of experience in design cognition. Krippendorff's alpha of 0.79 was achieved, indicating acceptable inter-coder reliability (Krippendorff 2004). The full coding scheme of product types developed for each task, plus the codes applied to all sketches analysed, can be accessed in the supporting dataset linked at the end of this paper.

To enable the inclusion of concept novelty as a covariate in the fMRI analysis, the novelty of sketched solutions was also rated. Non-solutions were firstly denoted N/S. Each solution was then assigned a novelty rating depending on the frequency of its coded product type (Mouchiroud & Lubart 2001; Shah *et al.* 2003; Chou & Tversky 2017). Concepts were rated 2 if the coded type of product was identified in $\leqslant$2% of the concept sketches produced by participants (most novel), rated 1 if identified in 3%–5% of sketches (moderately novel), and 0 if identified in $>$5% of sketches (least novel). This method is based on the observation that statistically infrequent responses in creative generation tasks tend to be the most unique, and common responses tend to be more routine ideas (Goff & Torrance 2002; Barto, Mirolli & Baldassarre 2013). For example, in the open-ended task focusing on reducing negative impacts of lighting cities (Section 2.2):

(i) infrequent responses (scoring 2) included infrared lighting with specialised glasses and light-filtering goggles for wildlife, which are dissimilar to existing products in this area; and
(ii) common responses (scoring 0) included solar powered street lighting and lighting operated by motion sensors, which are similar to existing products.

3. Results

Three participants were excluded from the analysis due to poor quality fMRI data, resulting in a final sample size of $n = 29$.

3.1. Concept ratings

Table 1 provides a summary of the concept coding and rating results for the open-ended and constrained ideation conditions. A total of 836 concepts were generated in the open-ended condition, and 845 in the constrained condition. Overall, participants were able to recall and sketch 95.1% and 94.6% of these concepts, respectively. The majority of the sketches were coded as solutions for the ideation tasks completed in the study, with only 3.6% denoted N/S

Table 1. Summary of concept rating results

Measure	Open-ended	Constrained
Total number of concepts generated	836	845
Percentage of concepts that were recalled and sketched	95.1	94.6
Percentage of sketches denoted N/S (not a solution)	3.6	2.3
Percentage of sketches rated 0 (least novel solution)	59.2	71.7
Percentage of sketches rated 1 (moderately novel solution)	21.9	15.3
Percentage of sketches rated 2 (most novel solution)	15.2	10.8

(i.e. not a solution) in the open-ended condition and 2.3% in the constrained condition. This suggests that in the majority of tasks, participants engaged in generating solutions to the design problems presented to them rather than off-task activity. In both conditions, the majority of sketched solutions were rated 0 (least novel): 59.2% in open-ended, and 71.7% in constrained. As shown in Table 1, a higher percentage of solutions were rated 1 (moderately novel) and 2 (most novel) in the open-ended condition than the constrained condition.

3.2. fMRI results

In order to identify the regions associated with design ideation, we first collapsed across the open-ended and constrained tasks to give an ideation condition and compared this to the manipulate condition. Concept generation during ideation tasks was associated with greater activity in the left cingulate gyrus (Table 2, Figure 2), right medial frontal gyrus and right superior temporal gyrus (Table 2, Figure 2). However, as the latter two activations were non-significant at a corrected threshold they remain preliminary findings. Several other activations were also found in white matter (see supplementary material for coordinates, and Section 4 for discussion). In addition, this contrast was conducted including each participant's years of professional design experience (2–34 years, mean $= 7.86$, SD $= 7.55$) and average concept novelty score (0.1–0.7, mean $= 0.5$, SD $= 0.1$) as covariates. Neither covariate was found to be significantly associated (positively or negatively) with the contrast at a statistically corrected threshold.

To examine differences in neural activity between open-ended and constrained tasks, direct comparisons were made between these two conditions. The t-contrasts revealed no significant differences at a whole-brain FWE corrected threshold. We further examined this contrast within a pre-frontal region of interest (ROI) identified by the ideate > manipulate contrast (see Table 2), but this also revealed no significant differences suggesting that similar brain regions were recruited during performance of both the open-ended and constrained tasks.

Table 2. Ideate > Manipulate brain activation clusters (MNI coordinates)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	Y	z (mm)	Area
138	0.016	0.003	4.03	−15	17	32	Left anterior cingulate cortex
55	0.198	0.047	3.97	63	−13	2	Right posterior superior temporal gyrus
59	0.173	0.040	3.41	18	38	23	Right medial frontal gyrus

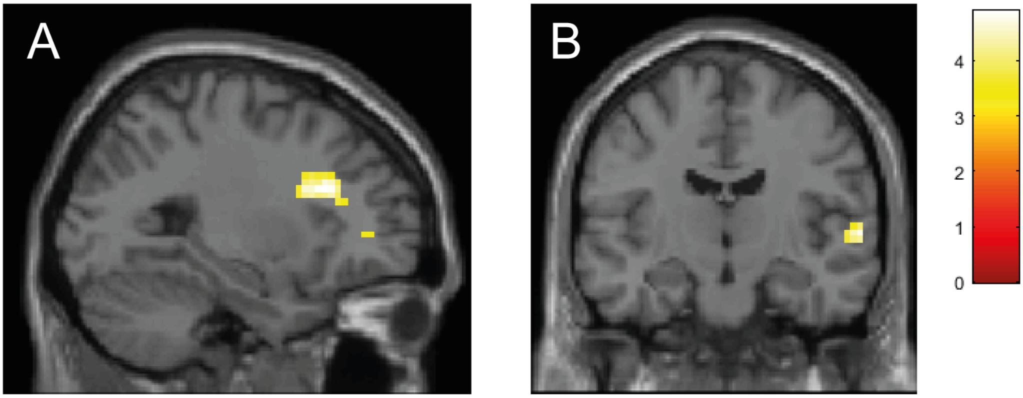

Figure 2. Ideate > manipulate contrasts revealed significant activations in the left anterior cingulate cortex (A) and right superior temporal gyrus (B). Colour indicates *t*-value.

4. Discussion

The aim of this study was to examine the brain regions involved in ideation in professional product design engineers using fMRI, and to compare brain activation patterns for concept generation during open-ended and constrained ideation tasks. Compared with manipulate tasks, design ideation was found to be associated with activations in several regions of the pre-frontal cortex. This is consistent with previous neuroimaging investigations of creative ideation (Boccia *et al.* 2015; Pidgeon *et al.* 2016), as well as theoretical accounts of creativity emphasising the importance of executive functioning during creative idea generation (Dietrich 2004; Mumford, Medeiros & Partlow 2012). A preliminary observation from the study suggests that ideation is also associated with activity in the superior temporal gyrus, which aligns with previous studies indicating that this region contributes to the spontaneous realisation of solutions during creative problem solving (Jung-Beeman *et al.* 2004; Shen *et al.* 2017). We found no significant differences in neural activity during concept generation between the two types of ideation task, suggesting that these engaged similar regions of the brain.

The following sub-sections provide a discussion on the work. In Section 4.1, we consider how the results fit into the broader body of knowledge on creative ideation, what the findings mean for design cognition research, and avenues for future work. In Section 4.2, we reflect on the methodological limitations of the study and how these may be addressed in future fMRI studies of design ideation.

4.1. Theoretical interpretation

With regards to the pre-frontal cortex, our ideation tasks were found to be associated with activity in the left anterior cingulate cortex and right medial frontal gyrus, although the latter activation did not meet a corrected statistical threshold. The anterior cingulate cortex has been highlighted in previous investigations of creativity (Abraham *et al.* 2012; Pidgeon *et al.* 2016) and it also appears to play a key role in several aspects of executive functioning such as error detection (Amiez, Joseph & Procyk 2005), decision making (Kennerley *et al.* 2006) and the controlled monitoring and evaluation of responses (Botvinick, Cohen & Carter 2004). Furthermore, it is commonly activated during tasks that measure the ability to suppress irrelevant or incorrect responses, such as the Stroop task (Matthews *et al.* 2004) and Flanker task (Brown 2009). In the context of PDE, this region may therefore support ideation via the suppression of highly obvious or common but unoriginal product concepts, facilitating the generation of more unique solutions.

The observed activations in the anterior cingulate cortex and medial pre-frontal cortex may also indicate the engagement of distinct functional networks during our ideation tasks. The anterior cingulate cortex is a key hub of the salience network, a collection of regions contributing to the detection and filtering of behaviourally relevant stimuli in accordance with experience, task goals or current psychological state (Uddin 2015). During design ideation, it may serve as a gating mechanism, identifying candidate ideas originating from bottom-up, associative processing in the default mode network and forwarding them to pre-frontal regions involved in higher-order processing (e.g. error detection mediated by the medial pre-frontal cortex (Mayer *et al.* 2012)). This interpretation is supported by evidence from functional connectivity studies introduced in Section 1.1, which demonstrate that creativity is characterised by dynamic engagement of functionally distinct brain networks including the default mode network, salience network and executive network (Beaty *et al.* 2015, 2018). Furthermore, this interpretation is consistent with the prominent two-fold model of creative ideation, which suggests that interacting generative and evaluative processes are involved (Finke, Ward & Smith 1992; Kleinmintz *et al.* 2019).

We also found an activation during ideation in the superior temporal gyrus. This region is often associated with creative insight, i.e. the sudden and unexpected realisation of problem solutions (Shen *et al.* 2017). Whilst this finding can only be considered preliminary, as it did not reach a corrected statistical threshold, it is of theoretical significance given that insight is a widely reported phenomenon during design ideation (Dorst & Cross 2001; Chandrasekera, Vo & D'Souza 2013). Several previous studies have found superior temporal gyrus activity during creative insight tasks (Bechtereva *et al.* 2004; Jung-Beeman *et al.* 2004; Sandkühler & Bhattacharya 2008), and a recent fMRI investigation of design also reported activity in this region during ideation (Goucher-Lambert *et al.* 2019). It should be noted that activity in our study appeared to be centred in the posterior superior temporal gyrus, a region that has previously been associated with the 'preparation' stage of insight problem solving, rather than the discovery of the solution itself (Kounios *et al.* 2006; Tian *et al.* 2011). Suggestions have been made that activity in the posterior superior temporal gyrus may reflect an initial readiness to activate semantic search processes, which may then be further guided by executive processes, such as those linked with the anterior cingulate cortex (Kounios *et al.* 2006; Tian *et al.* 2011).

Direct comparisons of neural activity in the open-ended and constrained conditions revealed no significant differences, even when being compared within an ROI restricted to pre-frontal regions. This suggests that while the tasks differed in terms of the novelty of solutions generated (Table 1), they engaged overlapping neural processes. There are three potential interpretations of this finding. Firstly, it is possible that there is truly no difference between ideation in response to open-ended and constrained design problems at the neural level. This would seem to counter existing positions in design and creativity research – for instance, the view that more constrained problems are associated with convergent thinking, and more open-ended problems are associated with divergent thinking (Section 1.2). Is this really the case, or are both kinds of processing involved in both types of problem (perhaps to different extents, or cooperating in different ways)? Secondly, it is possible that there are differences, but our approach was not suitable for detecting them. As previously noted, functional connectivity analysis has revealed that creative cognition involves a dynamic interplay of cognitive control (centred in the pre-frontal cortex) and more automatic, spontaneous processes based in the default mode network (Beaty *et al.* 2016). Moreover, there is increasing evidence that the extent of cooperation between these two networks depends on the level of task constraints involved, with greater executive-default coupling being observed on tasks with more goal-specific requirements (Liu *et al.* 2015; Beaty *et al.* 2016; Pinho *et al.* 2016). Thus, future research could investigate the possibility that greater functional coupling is observed during more constrained ideation tasks. Finally, it is also possible that the constrained tasks we employed in our study were not constrained enough to elicit differences compared with the open-ended tasks. Designers were constrained to producing a specific type of functional product – however, in design practice, problems may involve a plethora of constraints on different properties and attributes of the product and how it is to be used. Thus, any future studies employing functional connectivity analysis should also consider how constrained design problems are defined, drawing from existing work on design problem/task definition (e.g. Silk *et al.* 2014; Sosa 2018).

Finally, it should be noted that several of the activations detected were observed in white matter. Whilst a number of studies have also reported white matter activations (see Gawryluk *et al.* (2014*a*) for a review) the consensus is that fMRI is not sufficiently sensitive to capture white matter signal, owing to the lower levels of cerebral blood flow in white matter as compared with grey matter (Rostrup *et al.* 2000). However, several authors have noted that various physiological properties of white matter, such as the presence of nitric oxide producing neurons that yield a haemodynamic response, may indeed render white matter activity detectable via standard fMRI techniques (Barbaresi, Fabri & Mensà 2014; Gawryluk, Mazerolle & D'Arcy 2014*b*). In any case, whether our results do reflect genuine white matter activity, or conversely, an analysis-related artefact (e.g. from pre-processing measures), we were nonetheless still able to detect grey matter activations that were both consistent with previous research and theoretically informative.

As conveyed above, work in cognitive neuroscience is beginning to show that creative ideation is likely a complex, higher-order phenomenon that involves a multitude of interacting brain processes, regions, and networks (Liu *et al.* 2018*b*). Owing in part to a lack of domain-specific studies, it is not clear if the processes involved vary across different creative domains or if there is some common neural basis that is fundamental to creative ideation in everyone. Our results suggest that PDE ideation may have a number of similarities with generic creative ideation tasks, as outlined above. Thus, it is possible that there is at least a shared subset of processes underpinning ideation in professional designers and the general population. Future studies are needed to build upon this work and further explore this possibility (addressing some of the methodological issues discussed in Section 4.2). However, if this is indeed the case, it raises questions about what enables designers to create solutions to design problems that non-designers may struggle to solve. Weisberg (1993, p. 262) has proposed that human thought is fundamentally creative in nature, and it is the development of 'deep expertise in a particular domain' that enables higher creative performance in a specific area. In this respect, it could be that designers' education and training equips them with particular expertise in some of the fundamental processes of ideation. For instance, designers are trained to suppress evaluation during brainstorming-type ideation sessions (Boeijen *et al.* 2013), which may prevent the premature dismissal of novel ideas. They are also trained to use analogies as a strategy for idea generation (Chan *et al.* 2011), which may enable them to form more novel associations and to avoid fixation on known products. Investigating the effects of different components of design expertise on cognitive and neural processing during creative ideation could therefore be a fruitful avenue for future research. In this work, we studied product design engineers alone; future investigations could build upon this by exploring the potential differences between designers from different domains, e.g. product design, engineering design, and architecture.

4.2. Methodological considerations

In addition to the above theoretical implications, the work also highlights several methodological considerations for future studies in this area. As discussed in Section 2.5, it was important for the soundness of the fMRI analysis to obtain evidence that the designers actually generated concepts during the ideation conditions. Sketching inside the scanner was avoided as extensive motion disrupts the signal being measured and negatively affects data quality. Instead, we used sketches produced after the end of the scanning session, which were based on short verbal summaries gathered from the participants immediately after each ideation task. Although this provides an indication that the participants engaged in ideation, a limitation is that we cannot be sure that the concepts recalled and sketched accurately match the concepts generated during the tasks. Furthermore, although we assessed the reliability with which solutions were coded from these sketches, we cannot be sure of the validity of the coding. That is, the extent to which the solution codes reflect the solution intended by the designer. In turn, it is not clear to what degree the novelty scores calculated based on the coding reflect the participants' ideation processes versus the coders' interpretations (Hay *et al.* 2019*b*). As noted in Section 3.2, we did not observe a relationship between concept novelty and brain activation during ideation, which seems counterintuitive given that a key goal of ideation is to generate new ideas (Benedek *et al.* 2013). However, it is of course possible that the absence of an effect reflects limited statistical power to detect brain-behaviour correlations of this type.

In terms of increasing confidence in the correspondence between sketches and concepts generated during the tasks, one potential solution is to use an MRI-compatible drawing tablet. These have been utilised in previous investigations of visual creativity striving for more naturalistic settings (Ellamil *et al.* 2012; Saggar *et al.* 2015). However, this is not necessarily a straightforward solution. The participant must still lie down and keep their body as still as possible (particularly the head); as such, considerable participant training would likely be required to obtain sketches that can be interpreted during analysis. In addition, the motor actions involved in sketching also have their own associated neural activity. Thus, it would be necessary to find a control task that is well-matched to the design tasks in terms of sketching-related motor activity as well as cognitive complexity. Nonetheless, given the important role that sketching potentially plays in ideation (see below), it is worth exploring this option for future studies.

Addressing the validity of coding and novelty metrics is a more conceptual challenge. In this study, the novelty of a solution was computed based on how infrequently it appeared within the set of solutions generated by all participants in the study (for a given task). This approach is widely applied in research on design ideation (e.g. Shah *et al.* 2003; Nelson *et al.* 2009; Peeters *et al.* 2010; Verhaegen *et al.* 2013; Sluis-Thiescheffer *et al.* 2016; Fiorineschi, Frillici & Rotini 2018*a*,*b*); however, fundamentally, it may not be appropriate for cognitive and neural studies. Hay, Duffy & Grealy (2019*a*) present a framework conceptualising two perspectives on novelty evaluation. They propose that a designer's assessment of the novelty of their own concepts directly relates to their cognitive processing during an ideation task: if the concept has some degree of novelty to the designer, they must have created an idea (or parts thereof) that was previously unknown to them. If the concept has no novelty, it must already be known to them and they likely engaged in memory recall rather than creative ideation. In contrast, the novelty metric applied in our study does not have any relationship to the designer's internal processing during ideation. It is based on a comparison between the designer's concept and ideas generated by other participants in the sample. This may be misleading in terms of cognitive and neural processing – for instance, a concept that is not novel based on infrequency (i.e. the same as other participants' concepts) could be novel to the designer (i.e. unknown to them before they created it). Relying on the former metric, we would incorrectly conclude that no creative processing had taken place. From this perspective, it is perhaps unsurprising that we did not observe a correlation between brain activation during ideation and infrequency-based novelty. Designers' self-assessments of novelty and creativity may be a more valid metric for future fMRI studies of design ideation, and would reduce the issues with coding validity discussed above. As discussed in more detail by Hay *et al.* (2019*a*), work is needed to develop such metrics and address issues including reliability.

Finally, a more general challenge is how to increase ecological validity in future fMRI studies. That is, the extent to which the tasks and experimental procedure reflect everyday design practice. fMRI has several constraints that make it challenging to apply in this context. Designing is a temporal activity, that can unfold over hours, days, months, and even years. In contrast, fMRI captures brain activity over short periods of seconds or minutes. It is unclear, for instance, how reflective the brain activity during our short ideation tasks (85 s) is of activation during a typical design ideation session of 30 min to an hour or more. As discussed above, there are constraints on physical movement that make sketching during tasks difficult. The MRI scanning environment can also be uncomfortable and claustrophobic to participants, which is likely to have a negative impact on their ability to be creative (Dietrich 2019). Furthermore, Abraham (2013) highlights that creative processes are highly variable in general, and it is difficult to 'turn on' creative thinking when prompted during a controlled experiment. It is not immediately clear how we can overcome all of these challenges Duffy *et al.* (2019), but we must at least be aware of the limitations when designing studies and interpreting results.

5. Conclusion

Creative ideation is increasingly viewed as a complex, higher-order phenomenon that involves a multitude of interacting processes and neural regions at different scales (Liu *et al.* 2018*b*). However, it is not clear from existing cognitive neuroscience work whether these vary across domains, or if there is some common neural basis underpinning different creative ideation tasks. Product design engineering (PDE) is an important creative domain, focusing on the development of functional products for society. There are considerable differences between PDE ideation and the generic divergent thinking tasks typically studied in cognitive neuroscience. Whilst both involve the generation of novel ideas, the former additionally requires the designer to address specific functional requirements by generating appropriate technical behaviours and physical structures/mechanisms. PDE ideation may also involve both open-ended and constrained tasks, whilst studies of divergent thinking deal primarily with the former. Although there have been neuroimaging studies on creative ideation in artistic domains (e.g. drawing (Kottlow *et al.* 2011), musical composition (Lu *et al.* 2015), and story generation (Howard-Jones *et al.* 2005)), there have been few in design and engineering and only one examining ideation tasks reflective of PDE (Goucher-Lambert *et al.* 2019).

To advance knowledge about the neural basis of PDE ideation, this paper has presented results from a functional magnetic resonance imaging (fMRI) study of ideation in professional product design engineers practising in industry. The study aimed to examine the brain regions activated during ideation, and to compare brain activation in open-ended and constrained PDE tasks. The results suggest that ideation in PDE draws on pre-frontal regions (left anterior cingulate cortex and right medial frontal gyrus). These regions may contribute to the monitoring and evaluation of design concepts generated, and may also indicate the engagement of distinct functional networks during PDE ideation (salience, default mode, and executive) in line with existing cognitive neuroscience research (Beaty *et al.* 2018). A preliminary activation was also observed in the superior temporal gyrus, which has been linked to creative insight in existing studies on both generic and design ideation (Bechtereva *et al.* 2004; Jung-Beeman *et al.* 2004; Sandkühler & Bhattacharya 2008; Goucher-Lambert *et al.* 2019). No differences in neural activation were observed between open-ended and constrained tasks, which could suggest that overlapping brain regions are involved. However, it is possible that functional connectivity analysis may be more suited to detect differences between the tasks, and that more of a distinction may be required between the tasks in terms of level of constraint. Future work is required to explore both of these areas. Lastly, fMRI analysis including participants' years of design experience and average concept novelty scores as covariates did not reveal any associations with brain activation during ideation.

Overall, the results align with several existing fMRI studies of generic creative ideation tasks, suggesting that PDE ideation may share a number of similarities at the neural level. Thus, it is possible that there is at least a shared subset of processes underpinning ideation in professional designers and the general population. This raises questions about what enables designers to create solutions to design problems that non-designers may struggle to solve. It could be that certain aspects of design education and training equip designers with expertise in some of the fundamental processes of ideation (e.g. evaluation suppression and analogising/association). Investigating the effects of different components of design expertise on cognitive and neural processing during creative ideation could therefore be a fruitful avenue for future research.

The work also highlights methodological considerations to be addressed by future fMRI research on design ideation. Firstly, the use of MRI-compatible drawing tablets could facilitate sketching during ideation (subject to the identification of control tasks matched in motor activity). This could increase confidence in the degree of correspondence between sketches and the ideas actually generated during MRI scanning. Secondly, it seems that the type of metric predominantly used to assess concept novelty in design (sample infrequency) may not be directly related to cognitive and neural processing during ideation (Hay *et al.* 2019*a*). This could explain why no relationship was observed between concept novelty and brain activity during ideation in our study. Drawing on the conceptual framework outlined by Hay *et al.* (2019*a*), designers' self-assessments of novelty could be a more appropriate metric for future studies, although work is needed to develop reliable approaches in this area.

Acknowledgments

This research was supported by the United Kingdom's Engineering and Physical Sciences Research Council (EPSRC) (grant number EP/M012123/1 – LH, AD, LL, MG; and EP/M01214X/1 – DC), and an EPSRC/University of Strathclyde Research Studentship (EP/M508159/1 – GC). The authors would like to thank Pei Ling Choo, Attila Korik, Christopher McTeague, Mina Tahsiri, and Tijana Vuletic for their input into the work.

Data statement

All data underpinning this publication are openly available from the University of Strathclyde KnowledgeBase at https://doi.org/10.15129/a82c32a8-689a-4be5-a61f-17d60eaad10c.

Supplementary material

Supplementary material is available at https://doi.org/10.1017/dsj.2019.27.

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