Functional activity and connectivity during ideation in professional product design engineers

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In product design engineering, ideation involves producing ideas for new products that fulfil functional requirements. Ideation is associated with activity in multiple regions across the brain. However, knowledge about how these regions interact is limited. In an fMRI study of professional product design engineers ($n = 30$), we examined neural regions activated during ideation compared with three control conditions (rest, working memory and visuospatial processing). Using Psychophysiological Interactions analysis, we identified increased functional connectivity between five regions of interest and other areas. This included functional coupling between regions of the executive control and salience networks, and the default mode and visual networks. Connectivity between the lingual gyrus and cerebellum also suggests an interplay of visual and motor imagery during ideation.

Keywords: design cognition, creative ideation, fMRI, functional connectivity, neuroimaging

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Knowledge about the neural basis of design ideation has the potential to inform the development of cognitive theories and brain-computer-interface (BCI) tools to support product design engineering practice, but little is presently known about how this process occurs in the brain. Product design engineers (designers) create products that solve problems and fulfil human desires. To arrive at a final design that can be manufactured, designers produce increasingly detailed candidate ideas for physical products that satisfy functional requirements. Design ideation is the process of producing these candidate ideas. Neuroscientific research methods such as functional Magnetic Resonance Imaging (fMRI) can reveal the neural activity that occurs during design ideation, providing insights that may contribute to explanations and predictions of designer behaviour (Balters et al., 2023). Future BCI technologies could benefit from this knowledge to support design ideation by for example, providing neurofeedback to allow designers to sustain effective ideation performance (Hu, Shealy, Milovanovic, & Gero, 2022; Shealy, Gero, Milovanovic, & Hu, 2020) or allowing them to realise their imagination seamlessly in digital environments (Duffy, Hay, Grealy, & Vuletic, 2019; Korik et al., 2018). To date, studies investigating the neural basis of design ideation have focused on identifying the associated brain regions, but they have yet to fully address the important larger question of how these regions functionally interact. This study addresses this gap.

The production of new ideas is thought to be dependent on interaction between cortical networks that are distributed throughout the brain (Beaty, Benedek, Silvia, & Schacter, 2016; Ovando-Tellez et al., 2022). Creative cognition refers to the cognitive processes associated with the production of novel and useful ideas (Beaty et al., 2016; Ward, 2007). Studies on both domain-general (Beaty, Kenett, et al., 2018; Shi et al., 2018) and domain-specific (Liu et al., 2015; Pinho, Ullen, Castelo-Branco, Fransson, & de Manzano, 2016) creative cognition have found increasing evidence for the involvement of three large-scale brain networks: the default mode network (DMN), executive control network (ECN) and the salience network (SN). Interaction between these networks is thought to reflect dynamic switching between bottom-up, generative processing and more top-down evaluative cognition (Beaty et al., 2016; Beaty, Kenett, et al., 2018).

Design ideation is a domain-specific form of creative cognition and shares many of the same cognitive processes, but it is not yet known to what extent the two engage the same neural networks. To produce candidate ideas, designers engage in iterative generative and evaluative processing (Liikkanen & Perttula, 2010). Such processing is argued to involve dynamic interaction between the DMN and ECN in creative cognition (Beaty et al., 2016), and so these same networks may be involved in design ideation. However, designers also engage in processing that has no clear parallels in the creative cognition literature, raising the need for design-focused neurocognitive studies. These include the decomposition of problems into functional requirements and reasoning about physical systems that can achieve those functions and be manufactured (Hay et al., 2019a). As we outline in Section [1], existing neurocognitive studies of design ideation have examined the cortical regions contributing to design ideation, without shedding light on larger-scale interactions between brain networks during this process (Fu, Sylcott, & Das, 2019; Goucher-Lambert, Moss, & Cagan, 2019; Hay et al., 2019a). There are a few exceptions, where studies have directly explored functional connectivity between brain regions during ideation (Gilbert, Zamenopoulos, Alexiou, & Johnson, 2010; Milovanovic, Hu, Shealy, & Gero, 2021; Shealy et al., 2020), but as described below (Section 1.1), only limited conclusions can be drawn from this initial work.

To advance knowledge of the complex nature of neural activity during design ideation in product design engineering (PDE), we used fMRI to explore task-related functional activity and connectivity. Consistent with an existing fMRI paradigm (Hay et al., 2019a), we recruited professional product design engineers and used a design ideation task that reflects naturalistic ideation in early-stage conceptual PDE. These study characteristics provide improved ecological validity with respect to PDE practice, compared with the use of students (Fu et al., 2019; Goucher-Lambert et al., 2019; Milovanovic et al., 2021; Shealy et al., 2020) or room layout tasks (Gilbert et al., 2010). The use of professionals is important given that in PDE, experienced designers differ from novices in how they: frame and form initial mental representations of design problems (Björklund, 2013; Kim & Ryu, 2014), decompose problems (Ho, 2001), connect problem representations with prior knowledge (Björklund, 2013), and use activities and strategies to solve design problems (Ahmed, Wallace, & Blessing, 2003; Kim, Kim, Lee, & Park, 2007). Unique to the present research, we also examined control tasks involving working memory and visuospatial processing. Research indicates that these processes are involved during design ideation (see Section 1.1), so removing them (by subtraction) from our ideation condition provides new insights into the neural activation during design ideation. To do this we conducted standard comparisons between ideation and control conditions to reveal regions showing higher activity during ideation. Importantly, we also used Psychophysiological Interactions (PPI) analysis to uncover regions showing increased functional connectivity during ideation.

1 *Functional connectivity in design ideation*

Functional connectivity refers to the strength of the relationship between the activity of distinct brain regions (Babaeeghazvini, Rueda-Delgado, Gooijers, Swinnen, & Daffertshofer, 2021). Even at rest, particular regions of the brain show strong and reliable correlations with one another in terms of their activity, indicating that such regions are part of a larger, interconnected brain network

(Rosazza & Minati, 2011). A well-known example is the visual network, which comprises regions principally involved in visual processing such as the occipital lobe and fusiform gyrus (van den Heuvel & Hulshoff Pol, 2010).

In the creative cognition literature, there is now considerable evidence for the interaction of three large-scale brain networks during creative thought (Beaty et al., 2016, 2018): the default mode network (DMN), the executive control network (ECN) and the salience network (SN). The DMN consists of regions such as the precuneus and posterior cingulate cortex and tends to be active during spontaneous, self-generated thought (Andrews-Hanna et al., 2014) involving mental simulation, the use of episodic memory, perspective-taking and the imagination of future scenarios (Buckner, Andrews-Hanna, & Schacter, 2008). This is consistent with the production of design ideas through the use of semantic and experiential knowledge either retrieved from memory or perceived from external sources (Hay et al., 2017). The ECN, by contrast, comprises frontoparietal regions involved in cognitive control and is held to support the more top-down, analytical aspects of creative cognition such as idea evaluation and decision-making. Design ideation involves similar evaluative processing to evaluate the efficacy of ideas and make decisions about whether to commit to an idea or reject or modify it (Liikkanen & Perttula, 2010; Vargas Hernandez, Shah, & Smith, 2007). Finally, the SN includes regions such as the anterior cingulate cortex and insula, and it has been documented for its role in the detection of task-relevant stimuli as well as in transferring information between other networks (Uddin, 2015). Accordingly, this region is held to function as a gating/switching mechanism between the other two networks, identifying potentially task-relevant ideas initiated by the DMN and relaying these onto the ECN for further evaluation and development (Beaty et al., 2016, 2018).

To date, only two studies have addressed the role of functional connectivity specifically in a design context (Gilbert et al., 2010; Milovanovic et al., 2021). Using fMRI, Gilbert et al. (2010) compared an ill-structured room layout task with a matched well-structured problem-solving task. A direct comparison between the two conditions revealed that the ill-structured design task was associated with greater activity in the right dorsolateral prefrontal cortex (DL-PFC). Furthermore, using PPI analysis, the authors found that this region showed higher functional connectivity with the precuneus during the ill-structured task relative to the control task. Since the DL-PFC and precuneus are key hubs of the ECN and DMN respectively, the results indicate a pattern that has been observed in the wider creative cognition literature. However, as this result did not meet a statistically corrected threshold, the findings remain exploratory.

The more recent study used fNIRS to compare brain activity specifically within the frontal lobes during three ideation methods (Milovanovic et al., 2021). These were brainstorming (the spontaneous generation of ideas) and two structured ideation methods, morphological analysis (the combination of sub-functions into wholes) and TRIZ (a set of design principles and a matrix-based method for assessing design tradeoffs). Using temporal connectivity analysis, the authors observed consistent functional interaction between the right and left PFC across the different ideation methods, which was taken to reflect dynamic switching between divergent (right PFC) and convergent (left PFC) modes of thought during ideation (Milovanovic et al., 2021). These results highlight the importance of functional interaction and knowledge transfer between hemispheres during ideation. However, as the analysis was restricted to frontal regions, they do not give insight into the larger-scale interactions between multiple distributed networks that may be occurring during design ideation.

Finally, a recent study by Hu, McComb, and Goucher-Lambert (2023) did not assess functional connectivity, but used hidden Markov modelling (HMM) to uncover dynamic patterns of neural activity during design ideation. This approach uses unsupervised machine learning to decompose fMRI data into distinct states i.e., spatially and temporally independent patterns of neural activity. The authors found that certain states showed a higher probability of activation than other states during a design ideation task, including states mapping onto the executive control network (ECN) and semantic network. This suggested the involvement of processes such as working memory (ECN), semantic association and analogical reasoning (semantic network) during design ideation. Moreover, HMM was able to reveal information on dynamic transitions between states. For instance, the authors found a relatively high probability of shifts between a state involved in internal memory search, to one linked with external, visual processing, possibly indicating a tendency to orient towards external stimuli when an impasse is reached. Overall, the use of HMM in this study provided a novel insight into dynamic patterns of neural activity during ideation. However, it should be noted that the study did not involve comparison with a non-ideation control task, thus it is difficult to determine to what extent the patterns of activity observed here are uniquely associated with design ideation.

1.1 The present study

We examined functional activity and connectivity involved in design ideation using fMRI. We used a similar experimental design to an existing fMRI study in which participants were asked to generate ideas for products in response to design briefs that outlined a broad societal problem to be addressed (Hay et al., 2019a). Importantly, we recruited a new sample of participants with the same level of experience and built on and extended this prior work by taking three key approaches. First, we used standard t-contrast analyses to compare brain activity during design ideation versus control conditions but also included Psychophysiological Interaction (PPI) analysis to explore regions showing increased functional connectivity during ideation. PPI analysis involves specifying a region of interest (ROI) and examining whether any other brain regions show increased co-activity with this ROI during a particular behavioural task (Friston et al., 1997; O'Reilly, Woolrich, Behrens, Smith, & Johansen-Berg, 2012) – in this case, during design ideation.

Secondly, we used three distinct control tasks, including a standard baseline (rest) task, a working memory task (2-back task) and a visuospatial processing task (mental rotation). We used a standard baseline condition to examine the regions activated during ideation as compared with rest. Additionally, we included a working memory and visual-spatial control task on the basis that these processes are important for design ideation. Working memory is thought to allow designers to observe failures and evaluate the novelty of prior ideas (Liikkanen & Perttula, 2010) and is a core component of cognitive models of design ideation (Vargas Hernandez et al., 2007). Visuospatial processing refers to the manipulation of visual and spatial imagery. Product design engineers reason about how physical artefacts will interact spatially with human users and with the physical environment. Since designers communicate these ideas visually during the design process (Purcell & Gero, 1998; Stauffer & Ullman, 1991) and since design ideation can be carried out in the mind's eye without the aid of sketching (Athavankar, 1997; Bilda, Gero, & Purcell, 2006; Verstijnen et al., 2000; Verstijnen, van Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998), we assume that design ideation involves the manipulation of visuospatial imagery. Our study, therefore, aimed to contrast design ideation with both of these fundamental processes and provide insights into the remaining neural processes involved in ideation.

A final change was made to the instructions on the design ideation tasks. Rather than simply tasking the designers with generating concepts in response to a design brief (Hay et al., 2019a), we amended the task instructions to include performance goals by specifying that concepts should be 'as novel and feasible as possible'. The aim of this was to induce periods of design ideation that included the mental development of ideas (rather than the immediate externalization of an initial idea) and thus took longer than they would have without the performance goals. This was done to provide longer blocks of data for the design ideation condition and reduce the likelihood that the blocks failed to capture rapid instances of ideation.

2 Methods

2.1 Participants

There were 32 participants (29 males, 3 females) aged 23–59 years (mean = 34.43, SD = 10.45) who were right-handed and had no history of neurological impairment. They were all practising product design engineers with at least 2 years of professional experience (mean = 9.95, SD = 10.15, range = 2.08−36.83). Product design engineers were defined as designers who: (i) apply both creative and analytical thought processes during design, and (ii) have a general understanding of the design process that encompasses technical aspects, aesthetics, ergonomics, materials, manufacturing, marketing and commercial aspects. 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

The study consisted of a structural MRI, a functional MRI, and a post-scan sketching session. The functional scanning run used an event-related design with four different conditions: 1) design ideation, 2) working memory, 3) visuospatial processing and 4) baseline (rest). There were 20 trials per condition, which were presented in a pseudo-randomised order.

2.3 Materials

2.3.1 Design ideation

The design ideation condition consisted of a series of ideation tasks requiring participants to generate novel and feasible concepts in response to problem-oriented design briefs (e.g., *Domestic food waste is a serious problem due to global food shortages and socio-economic imbalances. Generate novel and feasible concepts for products that may reduce unnecessary food wastage in the home*). The importance of the novel and feasible task requirements was emphasised to participants before the experiment via both verbal and written instructions from the researchers. Ten design briefs were used (Table 1), nine of which were taken from Hay et al. (2019a).

Each design brief was presented twice, with participants being required to generate a different concept each time. In the first presentation, the design brief remained on the screen for up to 18 s, or until the participant pressed the left response button. A row of shapes then appeared on the screen signalling that the participant should begin generating a concept in their mind. Participants were instructed to press the right response button when they had generated a concept they deemed to be novel and feasible. The purpose of the shapes was to control for the visual processing of on-screen stimuli across conditions and participants were instructed to ignore the shapes and focus on generating a concept. The ideation phase lasted up to 40s. At the end of the 40s, or when the participant had pressed the response button (whichever was first), they were given 20 s to provide a brief verbal summary of the concept they had just generated which was recorded.

Table 1 Design briefs used in the design ideation task

#	*Design brief*
1	The use of mains water in gardening is often limited in summer due to low rainfall and droughts. Generate concepts for novel and feasible products that may reduce the mains water consumption associated with gardening.
2	Domestic food waste is a serious problem due to global food shortages and socio-economic imbalances. Generate concepts for novel and feasible products that may reduce unnecessary food wastage in the home.
3	Pets can become lonely or stressed when left alone for extended periods of time. Generate concepts for novel and feasible products that can improve the quality of life for pets who are left home alone for extended periods
4	Camping is a popular activity but can have negative environmental impacts through disruption to wildlife; litter and pollution of water sources. Generate concepts for novel and feasible products that reduce the negative impacts of camping.
5	Chores such as cooking and cleaning may be difficult for wheelchair users due to space and height limitations. Generate concepts for novel and feasible products that may facilitate domestic chores for wheelchair users.
6	Rain and wind make it difficult for pedestrians to keep dry and pose dangers e.g. slipping; falling trees. Generate concepts for novel and feasible products to reduce the discomfort and danger of poor weather for pedestrians.
7	Leaving personal belongings unattended while working in cafes may expose them to the risk of theft. Generate concepts for novel and feasible products that allow belongings to be secured in a public workspace for short periods.
8	Sitting in the same position for long periods may be harmful to health. Generate concepts for novel and feasible products that may facilitate physical exercise whilst completing activities in a seated position in the home and office.
9	Working while travelling may be noisy; full of distractions; and physically uncomfortable. Generate concepts for novel and feasible products that may reduce the difficulties associated with on the go working.
10	Dog excrement on pavements is unsightly and unhygienic but its disposal may be unpleasant and unhygienic for dog owners. Generate concepts for novel and feasible products that may improve dog excrement disposal for dog owners.

∗Design briefs were adapted from Hay et al. (2019a) by adding 'novel and feasible' except for task 3 which is new.

The second presentation of each ideation task was the same in all respects except that only the last sentence of the design brief was presented during the instructions phase (e.g., *Generate novel and feasible concepts for products that may reduce unnecessary food wastage in the home)*, and that this remained on the screen for 7s. It was emphasised to participants that the second concept they generated for a given task should be distinct from the first concept generated.

2.3.2 Working memory task (2-back)

A series of shapes appeared on the screen one at a time and participants were required to press the right response button if they judged the shape on the screen to be the same as the one presented two trials previously (match) and to not respond to indicate they were different. Each shape was presented on the screen for 1000 ms, followed by a fixation cross for 2000 ms. The task was programmed to have either 1 or 2 'match' trials per block of 10 trials. There were 20 blocks of trials in total and before every block, a preparatory message was presented for 5s.

2.3.3 Visuospatial task (mental rotation)

This task was a computerised version of Ekstrom's mental rotation task (Ekstrom & Harman, 1976 [modified with permission]) in which participants were presented with a series of shape pairs and asked to judge whether the two shapes were the same or different. Throughout each block of trials, the shape on the left remained constant whereas the shape on the right was either rotated so that it could be made to match the one on the left by changing its orientation (match) or rotated and flipped/mirrored, such that it did not match the shape on the left regardless of orientation (no match). Each shape pair was presented on the screen for 2500 ms followed by a fixation cross for 500 ms. If participants judged the two shapes to be the same, they pressed the right response button and if they judged them to be different no response was required. There were 20 blocks and each was preceded by a 5s preparation message.

2.4 Procedure

Prior to the scanning session participants were screened for MRI compatibility and performed the tasks to familiarise themselves with the procedure. On the day of scanning, participants performed additional practice trials before entering the scanner. The scanning session consisted of a structural scan followed by a functional scanning run.

The ideation, working memory and visuospatial tasks were presented in a pseudo-randomised order such that no task of the same type was presented back-to-back, and that the first presentation of any ideation task was always followed by the second presentation of that same task on the next ideation trial. In addition, 20 baseline rest periods (8s each) were presented after every three main task trials. An illustration of the study design is presented in Figure 1.

After the scanning session participants were asked to sketch the design ideas they had generated using their audio recordings as a memory aid. It was emphasised that the sketch should reflect the idea as it was generated in the scanner as much as possible and that they should not add any additional features or details. An example is shown in Figure 2, where the participant was asked to *"Generate concepts for novel and feasible products that can improve the quality of life for pets who are left home alone for extended periods"*. When they had sketched all their concepts participants were asked to go back through all their sketches in the order of production and rate each one in terms of creativity, novelty, and feasibility on a scale of 1 (low) to 7 (high). Note that participants' self-ratings are not a focus of the current paper and further analyses including them will be reported in a separate publication (see section 4.4 for further discussion).

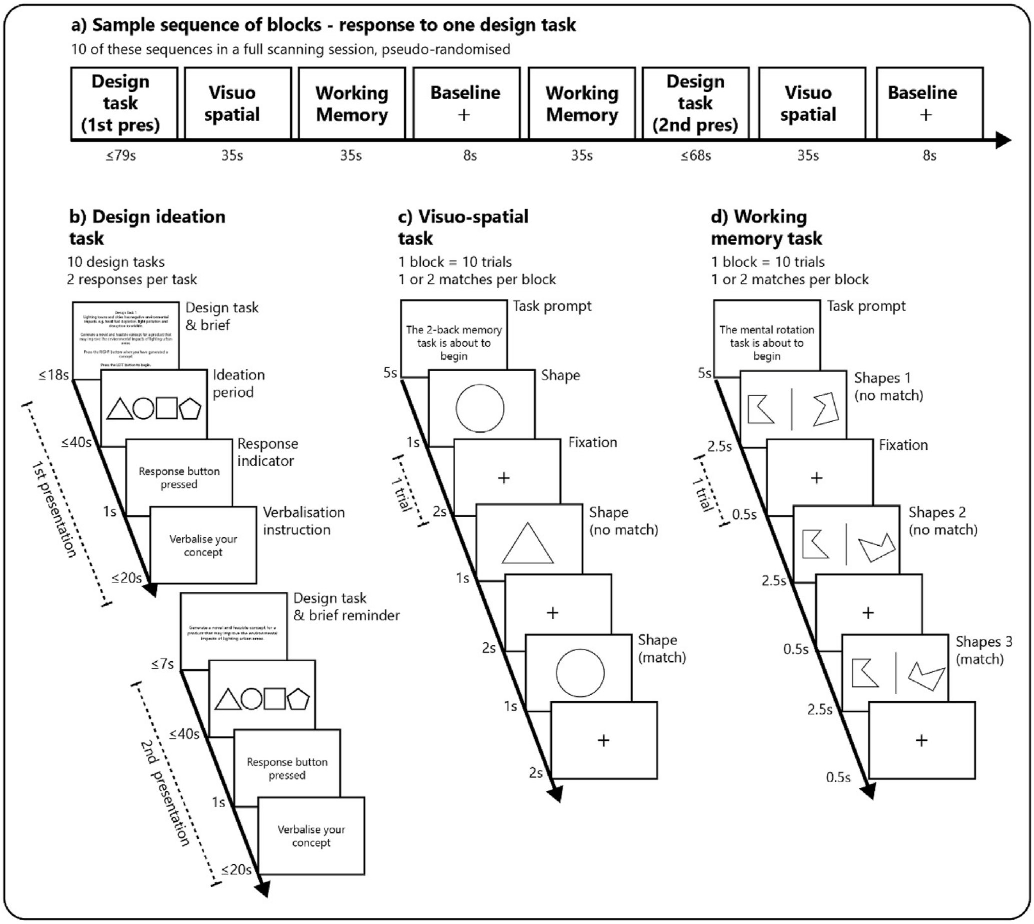


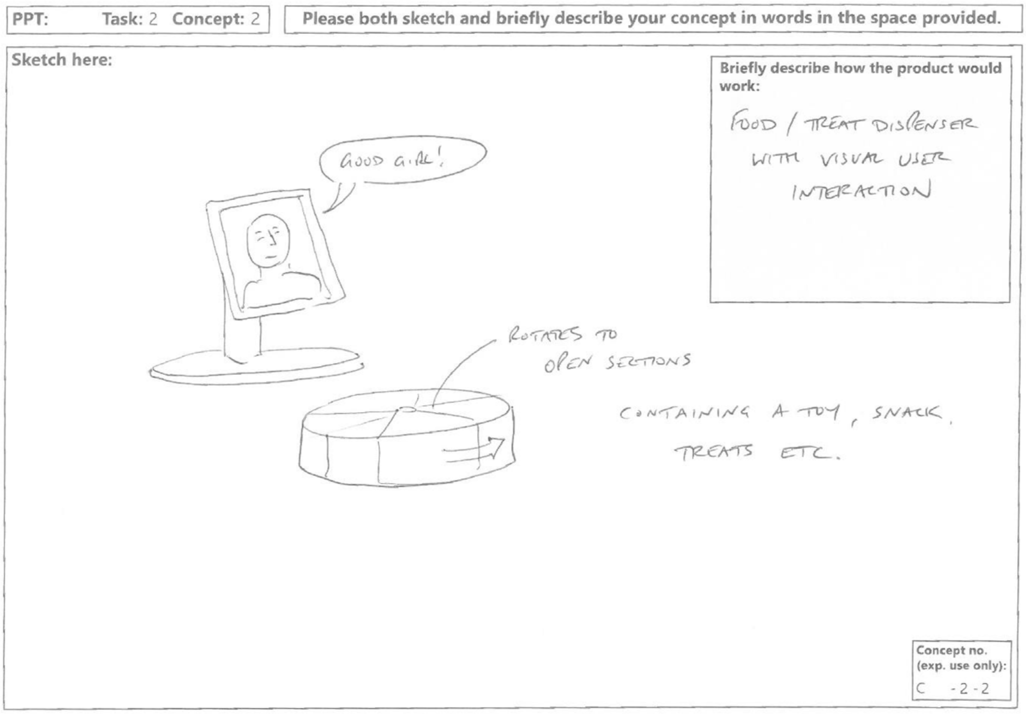
Figure 1 Illustrated procedures for each of the four tasks

2.5 fMRI data acquisition and analysis

Functional and structural imaging was carried out using a Siemens 3T scanner with a standard head coil. T2∗ weighted image volumes with BOLD contrast were acquired parallel to the anterior commissure/posterior commissure (AC/PC line) using an echo-planar sequence (repetition time [TR] = 2.39 s, echo time [TE] = 26 ms). Each volume comprised 35 axial slices (3 mm thick) covering the whole brain excluding the ventral parts of the cerebellum. Anatomical T1 weighted images were collected during the structural scanning session.

2.5.1 Preprocessing

Data were analysed using Statistical Parametric Mapping 12 with MATLAB (version 2021b). Pre-processing steps included spatial realignment, slice timing



PPT: Task: 2 Concept: 2

Please both sketch and briefly describe your concept in words in the space provided.

Sketch here:

Briefly describe how the product would work:

FOOD / TREAT DISPENSER WITH VISUAL USER INTERACTION

Concept no. (exp. use only): C -2 -2

*Figure 2 An example of a design concept produced by one of the designers. Participants were asked to "*Generate concepts for novel and feasible products that can improve the quality of life for pets who are left home alone for extended periods"

correction, co-registration, spatial normalisation to standard Montreal Neurological Institute (MNI) space and spatial smoothing using an isotropic Gaussian kernel (8 mm^3 full-width at half maximum). The data were high-pass filtered to a cut-off of 128s to remove low-frequency noise.

2.5.2 *First- and second-level analyses*

A standard two-stage hierarchical approach was adopted for the fMRI analysis, consisting of a first level (i.e., individual analysis of each participant's data) and a second level (i.e., group-level analysis). At the first level, effects were estimated with a GLM-based design matrix comprising separate box car regressors for the main tasks: design ideation, working memory and visuo-spatial. Note that ideation was split into two regressors coding separately for the 1st and 2nd ideation phases. The ideation phases were modelled as the entire time period between the start of the ideation phase (i.e., shapes appear on screen) until the participant pressed the response button, or the 40s time-limit was reached. An additional 6 regressors accounting for movement were added to the model. T contrasts were then used to generate contrast images for each participant across the main contrasts of interest: a) ideation (collapsing over 1st and 2nd presentation) > baseline, b) the conjunction of ideation > working memory & ideation > visuo-spatial. The former contrast was conducted to reveal brain regions significantly activated during ideation as compared to rest. The latter was conducted to reveal regions significantly activated when subtracting out both working memory and visuospatial processing. Finally, t-contrasts were conducted for the above contrasts at the second level using a threshold of $p < 0.05$ family-wise error corrected for multiple comparisons across the whole brain volume. With regards to the conjunction contrast, the threshold of $FW < 0.05$ was applied to both contrasts individually.

2.5.3 PPI analysis

To examine functional connectivity, we used PPI analysis. PPI analysis involves specifying a region of interest (ROI) and examining which regions show increased functional connectivity with this ROI in a given context, such as during the performance of a cognitive task (Friston et al., 1997; O'Reilly et al., 2012). In this study, we used PPI to examine regions showing higher connectivity with specified ROIs during design ideation as compared with the two main control conditions (working memory and visuospatial processing). The ROIs explored were identified based on the results of the main second-level analysis i.e., they were among regions showing significantly higher activation during ideation as compared to control (working memory and visuospatial activation).

A separate PPI was conducted for each of the specified ROIs. As with the main analysis, a conjunction approach was used for each PPI such that the following process was carried out for both the ideation > working memory and ideation > visuospatial contrasts: For each participant, volumes-of-interest (VOIs) were extracted at each ROI in the form of a sphere (6 mm radius). A separate model was generated for each participant consisting of 3 regressors: a) the physiological variable (the time-series data of the VOI); b) the psychological variable (i.e., a regressor coding for the contrast of interest); c) the interaction term of a) and b). Additional regressors accounting for movement were also added to the model.

Once this process had been conducted for each participant, a conjunction analysis was then conducted at the second level using t-tests i.e., ideation > working memory & ideation > visuo-spatial.

3 Results

Two participants' data were removed due to poor quality fMRI data, resulting in a final sample of $n = 30$. Across all 20 ideation trials, participants were found to generate an average of 18.03 concepts (SD = 2.92). On the working memory and visuospatial processing task, participants' mean accuracy ratings were 94.76% (SD = 4.41) and 92.83% (SD = 4.29), respectively. Thus, the behavioural data indicate that participants were fully engaged in all of the tasks.

3.1 Functional activity during design ideation

3.1.1 Ideation > Baseline

To assess brain regions showing significantly more activation during ideation as compared with baseline, an ideation > baseline t-contrast was conducted. This revealed significant activity predominantly in the left hemisphere including several pre-frontal regions (the middle, superior and inferior frontal gyrus), as well as in the left supplementary motor area, postcentral gyrus, insula, precuneus and fusiform gyrus. Significant activity was also found in the right lingual gyrus and cerebellum. These activations are visualised in Figure 3, and a full list of activated clusters is presented in Table 2. This contrast was also examined with participants' years of professional design experience (2.08−36.83, mean = 9.95, SD = 10.15) included as a covariate. This was not found to be significantly associated with the contrast at a statistically corrected threshold, suggesting that participants' level of design experience was not related to the activations observed.

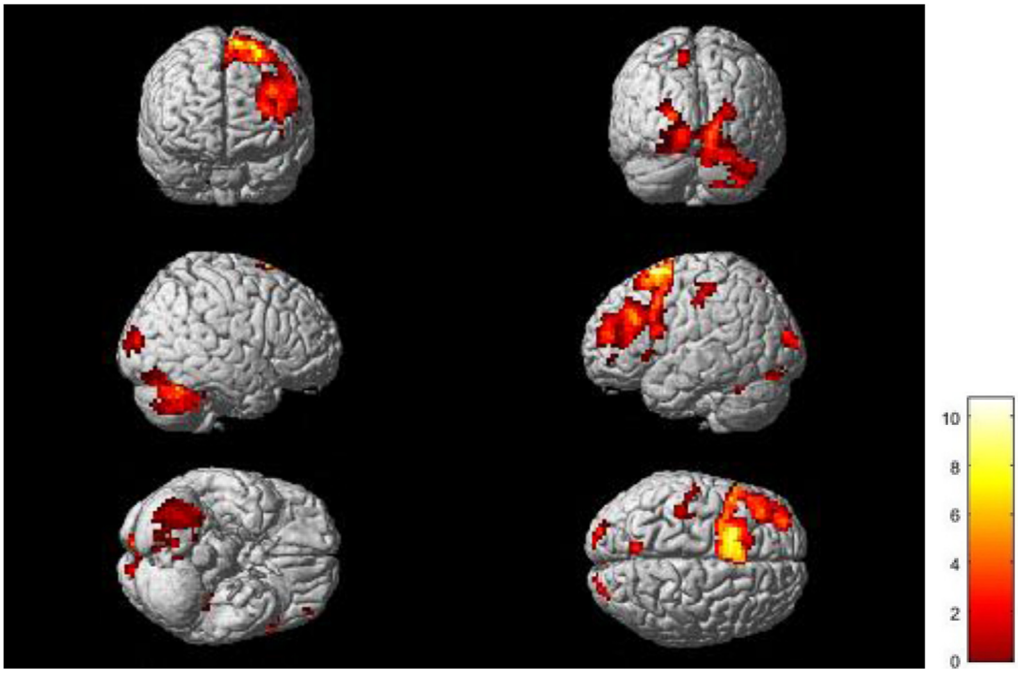


Figure 3 Regions showing significantly higher activation during ideation compared with baseline. Colours indicate effect size (t-value).

Table 2 Regions showing significant activation during ideation versus baseline (MNI coordinates)

Cluster size	*P value (FWE corrected)*	*P Value (uncorrected)*	*SPM(Z)*	*x*	*y*	*z (mm)*	*Area*
1410	<0.001	<0.001	6.76	−54	17	32	Left inferior frontal gyrus
			6.55	−21	11	68	Left superior frontal gyrus
			6.37	−9	5	65	Left supplementary motor area
1883	<0.001	<0.001	6.71	33	−55	−28	Right cerebellum
			6.64	15	−85	−10	Right lingual gyrus
			6.55	15	−97	2	Right calcarine
79	<0.001	<0.001	5.61	18	2	23	Right caudate
67	<0.001	<0.001	5.53	33	−55	8	
			5.3	36	−40	−1	
			5.06	30	−64	2	Right lingual gyrus
90	<0.001	<0.001	5.52	−39	−31	53	Left postcentral gyrus
			5.2	−57	−19	41	Left supramarginal gyrus
			4.86	−42	−25	41	Left inferior parietal lobule
14	0.001	0.028	5.47	−27	−25	−4	
41	<0.001	0.001	5.36	−9	−67	53	Left precuneus
15	0.001	0.023	5.2	−54	17	2	Left inferior frontal gyrus
49	<0.001	<0.001	5.1	−18	5	20	Left caudate
			4.97	−18	−1	5	Left pallidum
			4.91	−18	11	5	Left putamen
10	0.003	0.057	5.07	−42	−37	−7	
16	0.001	0.02	5.05	27	−37	20	
			4.83	30	−34	5	
20	0.001	0.011	5.05	−33	−52	−28	Left cerebellum
7	0.005	0.104	5.01	−33	−34	−22	Left fusiform
23	<0.001	0.007	4.98	−30	−58	26	
			4.91	−33	−52	20	
6	0.007	0.13	4.81	−45	50	−7	Left middle frontal gyrus
7	0.005	0.104	4.76	−24	−64	8	Left calcarine
3	0.014	0.277	4.68	−3	−34	−4	
1	0.027	0.539	4.67	15	2	5	
1	0.027	0.539	4.67	24	−28	−1	
1	0.027	0.539	4.64	30	−43	14	
3	0.014	0.277	4.63	15	−4	2	
1	0.027	0.539	4.63	−18	−49	11	Left precuneus
2	0.019	0.375	4.63	12	−61	5	Right lingual gyrus
1	0.027	0.539	4.62	24	−70	11	Right calcarine
1	0.027	0.539	4.61	−30	26	−1	Left insula

3.1.2 Ideation > Working memory & Ideation > Visuo-spatial

To assess the neural regions showing significantly higher activation during ideation as compared with the two main control conditions, the conjunction contrast of ideation > working memory and ideation > visuo-spatial processing was conducted. This revealed significant activity in the bilateral prefrontal

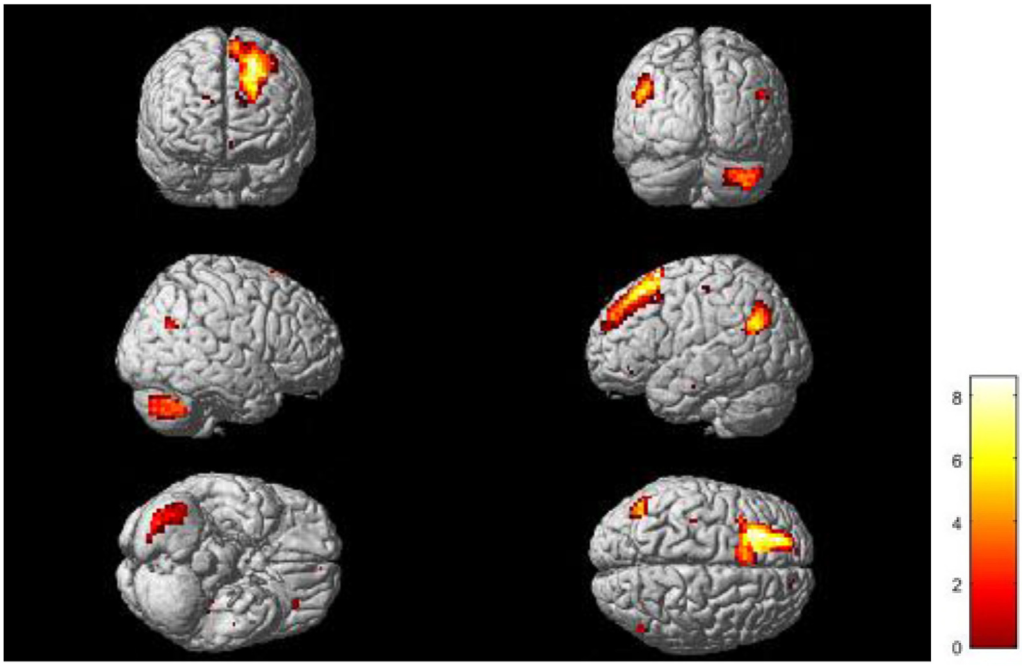


Figure 4 Regions showing significantly higher activity during ideation compared with both working memory and visuospatial processing

cortex, although the strongest activations were primarily left-lateralised including the left superior, inferior and middle frontal gyrus. In addition, significant activity was observed in the middle temporal gyrus, postcentral gyrus, precuneus, parahippocampal gyrus and lingual gyrus (all left) and in the bilateral angular gyrus and cerebellum. See Figure 4 for a visualisation of these results and Table 3 for the full list of significant activations.

3.2 Functional connectivity during design ideation

PPI analysis was used to examine regions showing higher connectivity with specified ROIs during ideation as compared to the two main control conditions (i.e., ideation > working memory & ideation > visuo-spatial). A total of 7 ROIs were explored including the left middle frontal gyrus (−27,20,62) left superior frontal gyrus (−21,44,23), left angular gyrus (−42,-61,26), right angular gyrus (48,-64,29), left parahippocampal gyrus (−27,-34,-13), left lingual gyrus (−15,-43,-10) and right cerebellum (42, −67, −37). A summary of the main activations for each ROI is provided below, and a full list is given in Table 4. For ROIs showing significant functional connectivity with other regions, visualisations of the significant activations are presented in Figures 5 and 6.

Table 3 Regions showing significant activation during ideation versus working memory and visuospatial processing (MNI coordinates)

Cluster size	*P value (FWE corrected)*	*P Value (uncorrected)*	*SPM(Z)*	*x*	*y*	*z (mm)*	*Area*
401	<0.001	<0.001	6.86	−42	−61	26	Left angular gyrus
			6.8	−45	−67	35	Left angular gyrus
			6.24	−18	−49	11	Left precuneus
689	<0.001	<0.001	6.79	−27	20	62	Left middle frontal gyrus
			6.54	−24	29	53	Left middle frontal gyrus
			6.43	−21	44	32	Left superior frontal gyrus
239	<0.001	<0.001	6.59	42	−67	−37	Right cerebellum
			6.56	33	−76	−37	Right cerebellum
21	0.001	0.019	5.77	48	−64	29	Right angular gyrus
38	<0.001	0.003	5.75	27	−52	14	
15	0.002	0.042	5.48	−39	−34	−7	
46	<0.001	0.001	5.41	−12	−58	−13	Left cerebellum
			4.64	−15	−43	−10	Left lingual gyrus
8	0.006	0.123	5.22	−33	35	−7	Left inferior frontal gyrus
17	0.002	0.031	5.08	−27	−34	−13	Left parahippocampal gyrus
2	0.022	0.436	4.99	−3	56	−13	Left medial frontal gyrus
1	0.03	0.593	4.75	45	−10	17	Right rolandic operculum
4	0.014	0.268	4.65	−36	−22	53	Left postcentral gyrus
1	0.03	0.593	4.56	12	56	23	Right superior frontal gyrus
2	0.022	0.436	4.56	18	53	26	Right superior frontal gyrus
1	0.03	0.593	4.56	−48	−13	−22	Left middle temporal gyrus
2	0.022	0.436	4.55	15	11	20	Right caudate

3.2.1 Middle and superior frontal gyrus

The left middle frontal gyrus ROI (−27,20,62) showed significantly increased connectivity with another cluster in the middle frontal gyrus during ideation. In addition, the left superior frontal gyrus (−21,44,23) ROI showed significant ideation-related co-activity with clusters in the bilateral superior and middle frontal gyrus as well as with the right caudate and right insula.

3.2.2 Angular gyrus

The left angular gyrus ROI (−42,-61,26) was found to show significant ideation-related connectivity with the left fusiform gyrus and lingual gyrus,

Table 4 Results of PPI analysis: regions showing significantly greater functional connectivity with ROI during ideation, as compared with working memory and visuospatial processing (MNI coordinates)

ROI: Left middle frontal gyrus (L.MFG, −27, 20,62)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
1	0.028	0.548	4.64	−27	20	62	Left middle frontal gyrus

ROI: Left superior frontal gyrus (L.SFG, -21, 44, 23)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
282	<0.001	<0.001	5.77	−36	35	32	Left middle frontal gyrus
			5.44	−15	32	26	
			5.34	−24	35	26	Left superior frontal gyrus
8	0.005	0.098	5.36	12	5	20	Right caudate
77	<0.001	<0.001	5.22	33	41	20	Right middle frontal gyrus
			4.88	36	35	32	Right middle frontal gyrus
			4.64	30	53	8	Right superior frontal gyrus
39	<0.001	0.001	5.18	18	38	29	
			4.74	15	29	23	
5	0.009	0.183	4.94	−27	11	14	
1	0.028	0.559	4.65	9	20	20	
2	0.02	0.398	4.62	−6	11	14	
1	0.028	0.559	4.55	36	23	2	Right insula

ROI: Left angular gyrus (L.AG, -42, -61, 26)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
20	0.001	0.016	5.18	−24	−40	−13	Left fusiform gyrus
			5.38	−18	−46	−4	Left lingual gyrus

ROI: Left parahippocampal gyrus (L.PHG, -27, -34, -13)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
33	<0.001	0.004	5.38	−21	−43	−13	Left fusiform gyrus
			4.82	−27	−49	−7	Left lingual gyrus
16	0.002	0.034	5.15	−45	−52	−13	Left inferior temporal gyrus
24	0.001	0.012	5.02	39	−61	−40	Right cerebellum
			4.81	30	−61	−34	Right cerebellum
2	0.022	0.428	4.74	24	−34	−13	Right parahippocampal gyrus
2	0.022	0.428	4.6	42	−67	−34	Right cerebellum
1	0.03	0.586	4.54	−33	−37	−19	Left fusiform gyrus

Functional activity and connectivity during design ideation

ROI: Left lingual gyrus (L.LG, -15, -43, -10)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
852	<0.001	<0.001	5.67	24	−58	−7	Right lingual gyrus
			5.6	15	−61	2	Right lingual gyrus
			5.6	21	−49	−10	Right lingual gyrus
57	<0.001	0.001	5.29	−27	−55	−46	Left cerebellum
			5.27	−48	−61	−37	Left cerebellum
			4.82	−36	−64	−40	Left cerebellum
19	0.002	0.034	5.08	3	−70	−25	Vermis
48	<0.001	0.002	4.99	39	−64	−43	Right cerebellum
			4.87	27	−61	−40	
2	0.024	0.47	4.85	15	−58	−49	Right cerebellum
3	0.019	0.372	4.63	−12	17	41	Left superior frontal gyrus
5	0.013	0.249	4.6	−36	−46	−37	Left cerebellum
1	0.031	0.621	4.57	0	−67	−46	
1	0.031	0.621	4.55	−45	−49	−31	Left cerebellum
1	0.031	0.621	4.53	30	−46	−28	Right cerebellum
1	0.031	0.621	4.51	30	29	−4	
1	0.031	0.621	4.5	−33	−40	−31	Left cerebellum

ROI: Right cerebellum (42, -67, -37)

Cluster size	P value (FWE corrected)	P Value (uncorrected)	SPM(Z)	x	y	z (mm)	Area
3	0.017	0.339	4.83	39	−64	−46	Right cerebellum
3	0.017	0.339	4.64	39	−58	−40	Right cerebellum

whereas the right angular gyrus ROI (48,-64,29) did not reveal any significant effects.

3.2.3 Parahippocampal gyrus

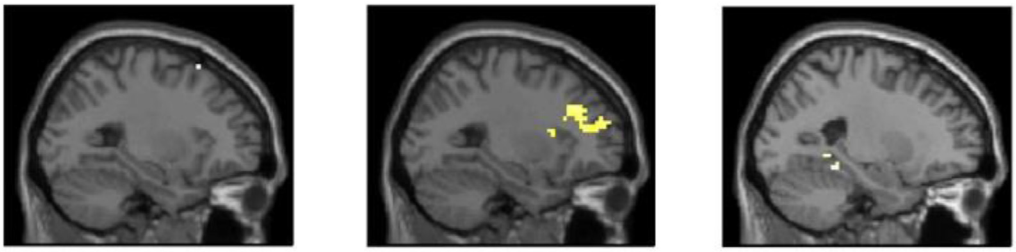
The ROI in the parahippocampal gyrus (−27,-34,-13) revealed significant ideation-related co-activations with the left fusiform gyrus, lingual gyrus, inferior temporal gyrus and right cerebellum.

3.2.4 Lingual gyrus

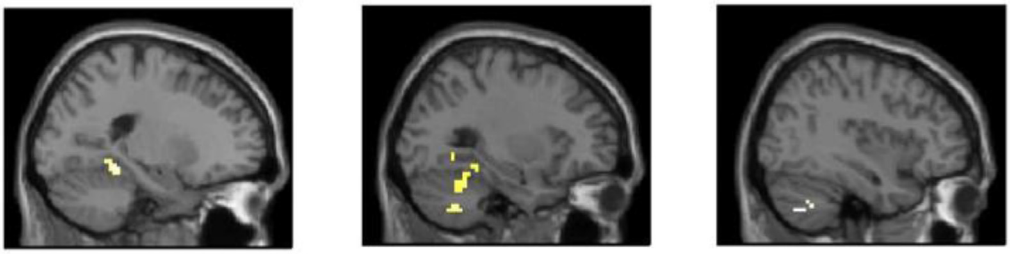
The left lingual gyrus ROI (−15,-43,-10) was found to have significant ideation-related functional connectivity with clusters in the right lingual gyrus, as well as in the left superior frontal gyrus and bilateral cerebellum.

3.2.5 Cerebellum

The ROI examined within the right cerebellum (42,-67,-37) only showed significant ideation-related co-activity with other clusters in the right cerebellum.



a) Left Middle Frontal Gyrus b) Left Superior Frontal Gyrus c) Left Angular Gyrus



d) Left Parahippocampal Gyrus e) Left Lingual Gyrus f) Right Cerebellum

Figure 5 Regions showing significantly greater coactivation with the specified ROIs during ideation as compared with the working memory and visuospatial processing conditions. Note that the results for the right Angular Gyrus PPI are not shown here as no regions were found to significantly increase their activity with this ROI during ideation

4 *Discussion*

The aim of this fMRI study was to examine the neural regions activated during design ideation in professional product design engineers, as well as to assess functional connectivity during ideation using Psychophysiological Interaction (PPI) analysis.

We found that design ideation, as compared with baseline, was associated with predominantly left-lateralised activity in several regions across the brain, including pre-frontal regions involved in executive control (e.g., middle, inferior & superior frontal gyrus), as well as regions involved in visual (e.g., lingual gyrus) and motor imagery processing (e.g., supplementary motor area). A conjunction contrast comparing design ideation with both a working memory and visual imagery processing task also revealed activations similar to the above. However, this contrast was also uniquely associated with activity across several nodes within the default mode network (DMN) including the bilateral angular gyrus, precuneus, parahippocampal gyrus and middle temporal gyrus (all left).

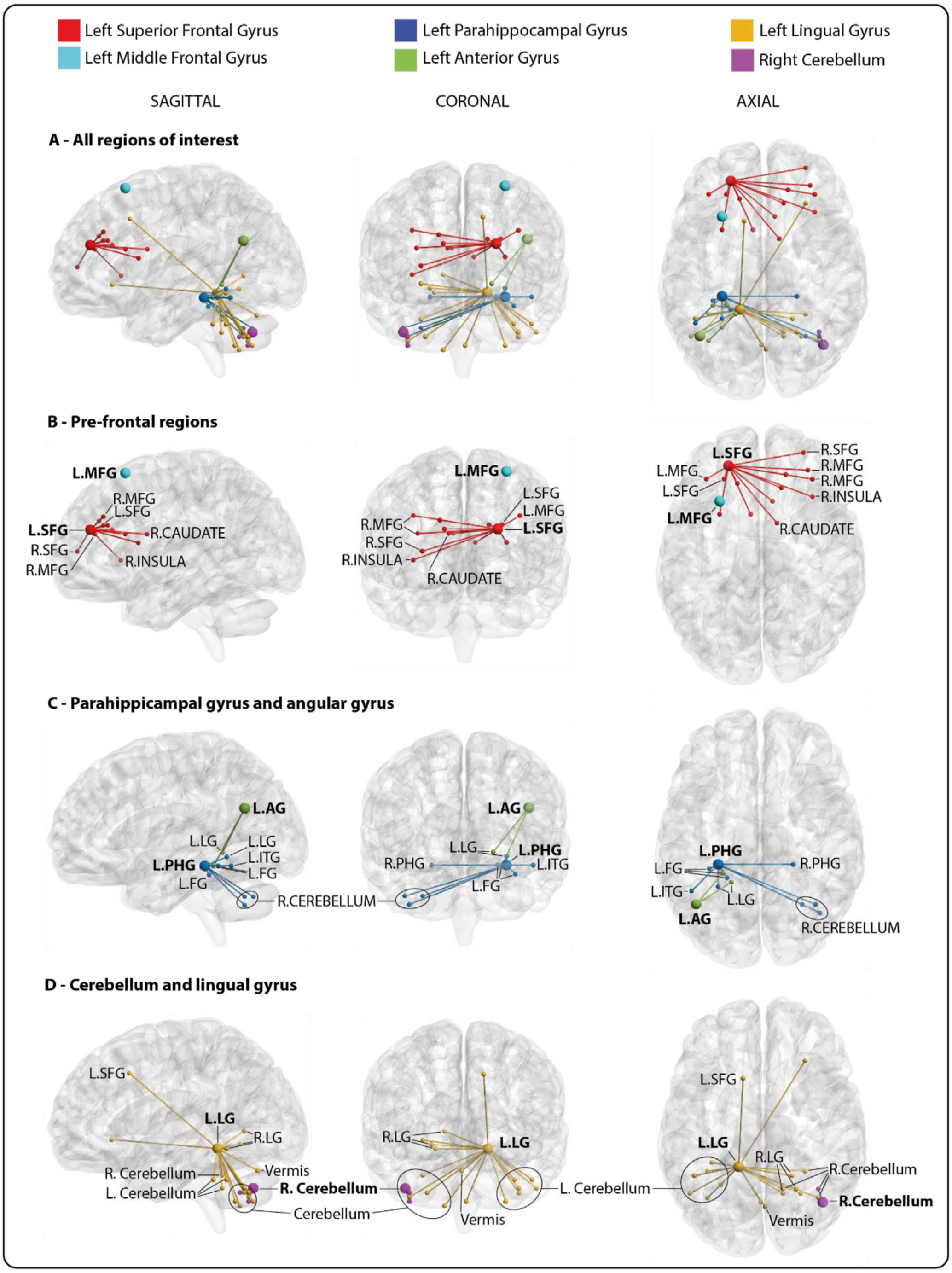


Figure 6 Results of the PPI analysis, showing: A — All regions of interest, B Pre-frontal regions, C — Parahippocampal gyrus and angular gyrus, D — Cerebellum and lingual gyrus. Seed regions are shown by the largest circles and bold labels. Abbreviations are listed in Table 4

PPI analysis was then used to examine regions showing significant functional connectivity with seven specified ROIs, which were identified based on the results of the above contrast analyses. Two ROIs (left middle frontal gyrus and superior frontal gyrus) within the executive control network (ECN) were found to show significant connectivity with other prefrontal regions. The superior frontal gyrus ROI also showed significant co-activity with the insula (part of the salience network [SN]), showing evidence of functional coupling between the ECN and SN.

A further two ROIs within the DMN (left angular gyrus and parahippocampal gyrus) both showed significant connectivity with visual processing regions (lingual gyrus and fusiform gyrus), possibly reflecting an interplay between long-term memory processes and mental imagery. Two final ROIs were explored within the right cerebellum and left lingual gyrus. The right cerebellum was found to show significant associations with other regions within the cerebellum, and the left lingual gyrus ROI showed significant functional coupling with the bilateral cerebellum.

In the remaining sections, we discuss the results in more detail, firstly, with a focus on the key regions activated during design ideation, as revealed by the main contrast analysis, followed by a discussion of the functional connectivity analysis results. We then briefly reflect on the issue of hemispheric lateralisation in the context of the existing literature on neuroimaging during creative cognition. Finally, limitations are discussed as well as suggestions for future work.

4.1 *Neural regions activated during ideation*

4.1.1 *Ideation compared with baseline*

Design ideation as compared with baseline was associated with activity in several left pre-frontal regions including the superior, middle and inferior frontal gyrus. These regions are part of the ECN and contribute to a range of cognitive control functions including attention (Andersson, Ystad, Lundervold, & Lundervold, 2009), planning (Kaller, Rahm, Spreer, Weiller, & Unterrainer, 2011) and working memory (Yee, Roe, & Courtney, 2010). As such, the left PFC may support the top-down, analytical aspects of design ideation, such as evaluation, decision making and logical reasoning (Hay et al., 2017). It may additionally facilitate problem structuring or decomposition, where the designer decomposes an open-ended, ill-structured problem into a more manageable sub-problem (Kim & Ryu, 2014; Liikkanen & Perttula, 2010). This is argued to be an executively demanding aspect of design ideation (Ball & Christensen, 2019), and is likely to have been important in the current study given that the problem-orientated design briefs used in the ideation task (see Hay et al. (2020) for an analysis of responses to an equivalent set of briefs). Finally, in a broader sense, the activation of the left PFC is consistent with a vast body of theoretical (Dietrich, 2004; Mumford, Giorgini, Gibson, & Mecca, 2013) and empirical (Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Zabelina, Friedman, & Andrews-Hanna, 2019) studies emphasising the importance of top-down, executive cognition during creative thought.

Comparing design ideation with baseline also revealed activity in regions of the visual cortex, including the left fusiform gyrus, and right lingual gyrus. This supports the widely held view that design ideation is a highly visual activity involving mental imagery (Goldschmidt, 1991; Park & Kim, 2007). The fusiform gyrus is known to be involved in the processing of objects and features (Sigurdardottir & Gauthier, 2015) and thus may support the mental visualisation and transformation of products and their features during ideation. The lingual gyrus has similarly been implicated in vivid mental imagery (Belardinelli et al., 2009) and visual memory (Bogousslavsky, Miklossy, Deruaz, Assal, & Regli, 1987; Postle, Stern, Rosen, & Corkin, 2000), processes which are held to play a key role during creative thought. For instance, Hart & Hay (2022) recently observed a positive association between the self-reported vividness of visual imagery and creativity ratings on a design ideation task. Bilda and Gero (2006) also emphasise the importance of visual working memory in supporting imagery processes during design ideation, particularly in the absence of sketching.

Finally, design ideation compared with baseline was found to engage several regions involved in motor control and imagery, such as the left supplementary motor area, left post-central gyrus, and bilateral cerebellum. Engagement of motor regions has been observed across a wide range of creative cognition tasks (Aziz-Zadeh, Liew, & Dandekar, 2013; Benedek, Jauk, Fink, et al., 2014; Matheson, Buxbaum, & Thompson-Schill, 2017) and it has been proposed that the simulation of motor activity and imagined interaction with physical objects is fundamental to creative cognition (Matheson & Kenett, 2020). In the context of design ideation, motor regions may support several processes including imagined interaction with products (e.g., from a user perspective) as well as simulated sketching activity during ideation. In support of the latter point, the post-central gyrus has been highlighted for its involvement in coordinating limb movement (Matheson & Kenett, 2020). In addition, a previous study on visual creativity by Aziz-Zadeh et al. (2013) suggested that left supplementary motor activity reflected the simulated motor activity of the dominant right hand during creative thought.

4.1.2 Ideation compared with working memory and visuospatial processing

We also compared ideation with a working memory and visuospatial processing task to reveal the neural regions associated with design ideation after controlling for these processes. Ideation was found to engage several regions within the DMN including the bilateral angular gyrus, precuneus, parahippocampal gyrus and middle temporal gyrus (all left). Apart from the precuneus, these regions were not significantly activated in the design ideation versus baseline contrast. As discussed in the introduction, the DMN has been implicated in self-generated thought such as mental simulation, the use of episodic memory, and the imagination of future scenarios, as well as internally directed cognitive states such as mind-wandering (Kucyi, Esterman, Riley, & Valera, 2016) and meditation (Jang et al., 2011), and it is argued to underlie more spontaneous, associative cognition during creative cognition (Beaty et al., 2016; Kleinmintz, Ivancovsky, & Shamay-Tsoory, 2019). Importantly, the DMN has also been widely observed to be active during non-task, resting states (Gusnard & Raichle, 2001; Raichle et al., 2001). As such, it makes sense that most of the above DMN regions were not significantly activated when comparing design ideation with a baseline resting task.

Regarding the specific role of the above regions, the angular gyrus and middle temporal gyrus may support semantic processing during design ideation. It has been proposed that design ideation involves the retrieval of semantically clustered ideas via a search through associative memory (Liikkanen & Perttula, 2010), and it has been shown that designers can create design concepts by combining concept categories (Jang, Oh, Hong, & Kim, 2019; Nagai, Taura, & Mukai, 2009; Taura & Nagai, 2013). The angular gyrus and middle temporal gyrus both have a well-documented role in relevant processes such as retrieving concepts from long-term memory (Davey et al., 2015, 2016), forming associations between concepts (Price, Bonner, Peelle, & Grossman, 2015; Zhang et al., 2020) as well as generating new concepts and categories (Ren et al., 2020). The middle temporal gyrus has also been highlighted for its role in semantic search during design ideation. Goucher-Lambert et al. (2019) found activation of this region when participants addressed solution-oriented design briefs with single-word inspirational stimuli as compared with a no-stimuli control. The authors suggested that the middle temporal gyrus facilitated the semantic search of concepts related to the cues. It may also be the case that this region is activated during self-initiated semantic search processes in the absence of external cues, as in the present study.

With regards to the parahippocampal gyrus, this DMN region is known to play a fundamental role in episodic memory i.e., the storage and retrieval of autobiographical information (Aminoff, Kveraga, & Bar, 2013). Thus, the observed activation of the parahippocampal gyrus may reflect the engagement of episodic memory processes during design ideation. This explanation is supported by a wealth of evidence linking the parahippocampal gyrus and other medial temporal lobe structures to the retrieval and re-combination of episodic information during creative thought (Beaty et al., 2020; Beaty, Thakral, Madore, Benedek, & Schacter, 2018; Madore, Thakral, Beaty, Addis, &

Schacter, 2019). It is also consistent with findings from a systematic review of protocol studies on conceptual design, which identified episodic memory retrieval as a key cognitive process in early-stage conceptual design cognition (Hay et al., 2017). One empirical example of this is case-based reasoning i.e., the process of retrieving information relating to a previously encountered design problem and mapping it onto the problem at hand (Ball, Ormerod, & Morley, 2004).

An alternative explanation for the involvement of the parahippocampal gyrus stems from its documented role in scene processing and spatial navigation (Bastin et al., 2013). When communicating design ideas through sketches, designers naturally situate their products in scenes that show how they interact with human users and existing products, and reasoning about scenarios is one method through which designers can produce new product ideas (Georgiev, Sumitani, & Taura, 2017; Nagai et al., 2009; Taura & Nagai, 2013). However, it has to be acknowledged that the significant visuospatial processing demands of the mental rotation control task make this interpretation less likely.

Finally, it is worth noting that the conjunction contrast also revealed some activations similar to those observed when comparing design ideation with baseline. For instance, activation of the prefrontal cortex was also found in the conjunction contrast, although this activity appeared to be less widespread and with reduced effect sizes. Such activations might reflect involvement of executive processes that were not engaged by the 2-back working memory task, such as response inhibition i.e., the suppression of goal-irrelevant information (Mostofsky & Simmonds, 2008). This process is known to engage the middle and inferior frontal gyrus (Fonken et al., 2016; Swick & Ashley, 2008), and is argued to be required for the suppression of inappropriate or unoriginal ideas during creative thought (Benedek, Jauk, Sommer, et al., 2014; Camarda et al., 2018). In addition to the prefrontal cortex, we also observed activity in motor regions on this contrast, which would be expected since neither of the two comparison tasks controlled for motor imagery processing.

4.2 *Functional connectivity during ideation*

PPI analysis was used to examine regions showing higher connectivity with specified ROIs during design ideation as compared with the working memory and visuospatial processing tasks. The ROIs explored were identified based on the results of the second level conjunction contrast of ideation > working memory and ideation > visuospatial processing.

4.2.1 *Pre-frontal regions*

Firstly, we examined two ROIs within the pre-frontal cortex (left middle frontal gyrus and left superior frontal gyrus). These regions tended to show increased connectivity with other regions across the bilateral pre-frontal cortex. For example, the ROI within the left superior frontal gyrus showed greater connectivity with clusters in the right superior frontal gyrus and bilateral middle frontal gyrus. These findings suggest cooperation between nodes of the ECN to support the top-down and analytical aspects of the ideation task. These findings are consistent with other recent neuroimaging studies showing bilateral activation of prefrontal ECN regions during design ideation (Hu et al., 2023; Milovanovic et al., 2021).

It is of further interest that the left superior frontal gyrus ROI also had significant co-activity with the right insula, which is a key hub of the SN. The SN is involved in the detection of task-relevant stimuli (Uddin, 2015) and commonly shows functional connectivity with the ECN during creativity tasks (Beaty et al., 2016). It has been argued that the SN is responsible for identifying candidate ideas stemming from default-mode regions and passing these on to executive control regions for further processing and evaluation (Beaty, Kenett, et al., 2018). Overall, functional coupling of the ECN and SN appears to be a robust pattern of activity across different forms of creative cognition including design ideation.

4.2.2 *Parahippocampal gyrus and angular gyrus*

We also examined three ROIs within the DMN, including one in the left parahippocampal gyrus, and two within the angular gyrus (left and right). While no regions were found to significantly co-activate with the right angular gyrus, the left parahippocampal gyrus and left angular gyrus ROIs both showed significant ideation-related connectivity with visual processing regions, including the left fusiform gyrus and lingual gyrus. These DMN regions showed significantly increased functional connectivity with the visual cortex during design ideation as compared to both the working memory and mental rotation task.

This may suggest that semantic (angular gyrus) and episodic memory (parahippocampal gyrus) processes within the DMN are supported by mental imagery during design ideation. In general, mental imagery has been identified as a fundamental aspect of episodic memory processing (Dawes, Keogh, Andrillon, & Pearson, 2020), and numerous studies have found activation of the visual cortex during episodic memory retrieval (Bone, Ahmad, & Buchsbaum, 2020; St-Laurent, Abdi, Bondad, & Buchsbaum, 2014). Mental imagery has also been implicated in a range of semantic memory processing tasks (Kan, Barsalou, Olseth Solomon, Minor, & Thompson-Schill, 2003; Kosslyn, 1976) including semantic association (Kim, Karunanayaka, Privitera, Holland, & Szaflarski, 2011; Zhang, Liu, & Zhang, 2014). Of relevance, Zhang et al. (2014) found activation of the visual cortex during a ‘functional feature association’ task – a creative analogical reasoning task in which participants are given specific cues (e.g., tree’s root) and asked to generate a corresponding novel invention inspired by the cue. Due to activations being observed in both a key semantic processing region (inferior frontal gyrus) as well as the visual cortex (lingual gyrus) during the task, the authors concluded that mental imagery plays a key role in forming novel semantic associations during the creative process.

Considering the above, it is certainly plausible that the observed functional coupling between DMN regions and the visual cortex reflects the interplay of semantic/episodic memory and mental imagery during design ideation. While the precise nature of this relationship requires further investigation, it is possible that mental imagery facilitates the vivid visualisation of retrieved conceptual knowledge (semantic) and autobiographical information (episodic), allowing such information to be synthesised in novel ways and merged to accomplish design ideation tasks.

4.2.3 Cerebellum and lingual gyrus

Finally, our functional connectivity analysis revealed a relationship between the cerebellum and lingual gyrus. The ROI within the right cerebellum was only found to show significant connectivity with other clusters within the cerebellum. However, the ROI within the lingual gyrus was found to have significant connections with several clusters within the bilateral cerebellum. As discussed in section 4.1.1, the cerebellum may contribute to a range of motor imagery processes during design ideation, such as imagined sketching activity and imagined interactions with the product. These processes could also involve a degree of visual imagery, and so the observed functional coupling between the cerebellum and lingual gyrus may reflect the interplay of motor and visual imagery processes during design ideation.

4.3 Issue of hemispheric lateralisation

A general finding in the current study was that overall, the activations tended to be left-lateralised. As with several other findings (see Dietrich & Kanso (2010) for review), these results directly contradict theories emphasising the predominance of the right hemisphere in creative cognition (Goel, 2014; Jung-Beeman et al., 2004). For example, Goel's (2014) Frontal Lobe Lateralisation Hypothesis argues that the right PFC "supports abstract, vague, ambiguous, indeterminate representations of the world" (p.8), and that a level of right over left PFC dominance aids in solving ill-structured, ambiguous design problems.

With regards to why the current findings show evidence for left-lateralisation, a likely explanation relates to the higher verbal processing demands in the design ideation condition. Although language-related processes involve both hemispheres, the predominance of the left hemisphere is well-established in the literature (Vigneau et al., 2006). Thus, a level of left-hemispheric dominance would be expected in the ideation condition relative to the control tasks.

Consistent with this explanation, Abraham et al. (2012) previously observed greater left-hemispheric response during a divergent thinking task as compared with a 2-back task, and similarly attributed this finding to the more verbal nature of the divergent thinking task.

4.4 Limitations

There are some limitations of the current study to be highlighted. Firstly, while the study sheds light on the key regions and functional interactions supporting ideation, it does not provide insight into how activity may differ according to the creative value of the idea being generated. As noted in section 2.4, we have collected participants' self-ratings of creativity, novelty and feasibility for all concepts generated. We chose to collect self-ratings rather than external ratings as the former can give a more direct insight into the neural processes specifically associated with the generation of creative ideas as opposed to those simply retrieved from memory (Hay, Duffy, & Grealy, 2019b). While an examination of how neural activity varies according to these measures is beyond the scope of the current study, we are planning to assess in future work using parametric modulation, an analysis technique which can reveal how brain activity changes on a trial-by-trial basis about a given variable (in this case, the self-rated creativity of the generated idea).

A second limitation of the study relates to the control tasks employed in the current study. As discussed by Hay et al. (2022), selecting an appropriate control task is complicated because design ideation involves multiple interacting processes, and it can be challenging to determine which process(es) should be subtracted out. Here, we decided to control for working memory and visuospatial processing, given that there is already substantial literature to indicate that these processes contribute to design ideation. However, it is acknowledged that there are several other cognitive processes which may be useful to subtract out, either in addition to or instead of working memory and visuospatial processing. For example, future research may wish to include a cognitive task that controls for long-term memory retrieval, which could better isolate processes involved in creative idea generation as opposed to retrieval of pre-formed solutions held in long-term memory.

4.5 Implications for design and future work

Knowledge of the brain regions and networks involved in design ideation can support the development of new methods and tools for design practice by providing targets for behavioural and neural interventions that enhance ideation performance. For example, design-specific training exercises (Shah et al., 2012, 2013) could be developed to target cognitive processes that are typically associated with the regions of the brain that were highlighted in this study (e.g., Fink et al., 2015; Fink et al., 2018; Saggar et al., 2017). Likewise, neurofeedback methods could be used to make designers aware of their brain activity in those same brain networks and allow them to self-regulate their ideation process (Hu et al., 2022). Finally, neural stimulation methods such as transcranial direct current stimulation (tDCS) could enhance creative performance by stimulating brain activity within regions most associated with effective ideation (Hertenstein et al., 2019) [see Section 4.3].

To translate neuroimaging findings into practical applications, there is a need for further research. In addition to examining the neural correlates of effective ideation performance [section 4.4], there is a need to determine the precise role that certain regions play during design ideation, such as regions within the motor cortex. The current study shows that motor regions are engaged during ideation, but there are several possible explanations for this, including imagined sketching behaviour and simulated interactions with the product. To shed light on this, future research could allow designers to sketch while undergoing fMRI using a scanner-compatible tablet computer. If there is a significant difference in motor regions in design ideation *without* sketching compared to design ideation *with* sketching (and thus movement-related motor activation), this may suggest that the motor regions engaged during no-sketch ideation are contributing to imagery processes beyond imagined sketching activity. It has been quantitatively established that the spatial distribution of local neuronal population activity during motor imagery mimics the spatial distribution of activity during actual motor movement but the level of activation differs significantly (Miller et al., 2010). Therefore, additional or different spatial activation during ideation could be linked to simulated interactions.

Secondly, to develop interventions that work for a broad range of design practitioners, it would be beneficial to establish the predictive power of brain-behaviour correlations. For example, functional connectivity is a robust predictor of creative performance in domain-general creative cognitive tasks (Beaty, Thakral, et al., 2018; Ovando-Tellez et al., 2022), but this has yet to be tested in design. Although our study has suggested the involvement of key functional networks in design ideation, the correlational approach means that we cannot make any predictive claims and the generalizability of the findings to other participants is unknown. Techniques such as connectome-based predictive modelling (Shen et al. 2017) could be used to test whether functional connectivity can predict creative outcomes in a novel sample of participants, thereby building confidence in the generalizability of the results.

4.6 Conclusions

An understanding of the brain regions and functional networks involved in design ideation is essential for the development of neurocognitive theories of product design engineering, as well as the realisation of BCI technologies that can radically enhance ideation performance. As a complex form of creative cognition, design ideation likely depends on multiple, interacting cortical networks that are spatially distributed throughout the brain. However, existing research on the neural basis of design ideation has tended to focus on the contribution of isolated brain regions, with limited focus on interactions between larger-scale functional networks (Fu et al., 2019; Goucher-Lambert et al., 2019; Hay et al., 2019a).

To address this issue, the current study examined functional activity and connectivity during ideation in professional product design engineers. To identify the regions of the brain that are associated with design ideation, we contrasted ideation with a set of novel tasks designed to control for different cognitive processes, including a baseline (rest) task, a working memory task and a visual-spatial processing task. Importantly, we also used Psychophysiological Interactions (PPI) analysis to reveal regions showing higher functional connectivity during design ideation as compared with the control tasks. To the best of our knowledge, this is the first fMRI study of design neurocognition to reveal interaction effects between brain regions across the cortex during design ideation.

Ideation compared to baseline (rest) was found to be associated with widespread and mainly left lateralised activations across the brain, including prefrontal regions involved in executive control, as well as regions involved in visual and motor imagery. Furthermore, a conjunction contrast between ideation and working memory/visuospatial processing revealed activation within several nodes of the DMN, which we propose underlie relatively diffuse, associative processes, such as the retrieval and combination of information stored in semantic and episodic memory.

Using PPI analysis, we found that several regions of interest (ROIs) within the prefrontal cortex showed significant coactivation with other prefrontal regions, suggesting engagement of the executive control network (ECN) during design ideation. Moreover, the left superior frontal gyrus ROI showed significant connectivity with a region within the salience network (SN), thus displaying a pattern of ECN-SN coupling that has been widely observed in other forms of creative cognition. In addition, two ROIs within the DMN (left angular gyrus, parahippocampal gyrus) were found to show significant connectivity with the visual cortex during ideation, suggesting that semantic and episodic memory processes may be supported by visual imagery. Similarly, we observed significant connectivity between an ROI within the left lingual gyrus and the bilateral cerebellum, which may reflect an interplay of visual and motor imagery during ideation. Overall, these results show that the visual cortex is functionally interlinked with several distinct networks during design ideation, supporting the notion that visual imagery plays a critical role in many aspects of the design ideation process.

The findings provide fundamental knowledge about the individual brain regions and functional networks involved in design ideation. This knowledge could be used to provide targets for behavioural and neural interventions that can support design practice by enhancing designer ideation performance. To translate neurocognitive findings into practical applications, we outline three directions for future research. First, further research is required to clarify the nature of specific cognitive processes highlighted by the current study. This includes but is not limited to, examining the role of motor imagery in a design context as well as clarifying the relationship between long-term memory processes (stemming from the DMN) and mental imagery during design ideation. Second, to support effective ideation performance, there is a need to identify how neural activity and connectivity vary according to the creative value of the design ideas. Finally, to demonstrate the generalisability of findings to other designers, it would be beneficial to establish the predictive power of brain-behaviour associations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data underpinning this publication are openly available from the University of Strathclyde KnowledgeBase at https://doi.org/10.15129/ebb043dd-9463-42f9-8954-5b23e98c244e.

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Notes

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