Functional magnetic resonance imaging (fMRI) in design studies: methodological considerations, challenges, and recommendations

Highlights

- Methodological guidance on fMRI for design researchers is lacking.
- We outline the activities involved in developing and executing fMRI design studies.
- Both methodological and conceptual decisions have implications fMRI results quality.
- Protocols, ontology, and foundation knowledge need developed for fMRI design studies.
- Balancing fMRI constraints and ecological validity is also a key challenge.

Abstract

Functional magnetic resonance imaging (fMRI) enables identification of the brain regions and networks underpinning cognitive tasks. It has the potential to significantly advance cognitive design science, but is challenging to apply in design studies and methodological guidance for design researchers is lacking. In this Research Note, we reflect on our experiences and other work to outline the activities involved in developing and executing fMRI design studies. The implications for research quality at each stage are highlighted. We then consider the challenges for fMRI research on design and make recommendations for addressing them. Four critical areas are identified: establishing experimental protocols; establishing a cognitive design ontology; generating foundational knowledge about brain activation; and balancing fMRI constraints against ecological validity.

Functional magnetic resonance imaging (fMRI) is a method for recording brain activity based on changes in cerebral blood oxygenation. Due to its comparatively high spatial resolution, it is effective for localising the brain regions involved in cognitive tasks. Since its emergence in the early 1990s, it has been extensively applied by cognitive neuroscientists aiming to understand the neural basis of cognition (Bandettini, 2012). More recently, design researchers have begun to use fMRI to explore the neural mechanisms underpinning design activities. Whilst this work is still relatively limited, a steadily expanding corpus of journal articles suggests that fMRI is an important emerging approach for empirical studies on designing.

fMRI has the potential to significantly advance our understanding of designing as a mental activity mediated by the brain. However, studying design with fMRI is challenging. The method requires a high degree of empirical control, involving constraints that clash with some of the inherent characteristics of designing. Whilst existing studies outline methods and key parameters, there is little guidance available regarding how to apply fMRI as a design research method. There is an extensive body of literature on fMRI methodology in neuroscience (Soares et al., 2016), but this can be highly technical and inaccessible for design researchers. It also does not discuss issues specific to design studies.

A broad range of fMRI paradigms and techniques have been developed in cognitive neuroscience, suitable for different kinds of investigations (Glover, 2011; Soares et al., 2016). As such, there is no singular 'fMRI methodology' for design research. However, there is a need for a general framework to provide guidance on the key activities involved and how they can impact the quality of results. This would provide a starting point for study development, help to maintain rigour and consistency across the field as it advances, and provide a common conceptual basis to support collaboration with cognitive neuroscientists. In this Research Note, we aim to provide the initial underpinnings for such a framework and initiate a dialogue on the topic. Reflecting on our own experiences and the work of others, we outline the activities involved in developing and executing fMRI design studies, and the implications for research quality. We then consider the major challenges for fMRI research on design, and propose some recommendations for addressing these.

1 Existing fMRI design studies

Table 1 provides an overview of all six fMRI studies published in design journals (Design Science (2), Design Studies (2), and Journal of Mechanical Design (2)) as of April 2021. Conference papers reporting further analysis of data gathered in these studies (e.g. Goucher-Lambert & McComb, 2019) have been excluded to avoid duplication. fMRI research on design remains in its infancy, and is thus far limited to a relatively narrow range of domains. Alexiou et al. (2009), who report what is likely the first fMRI study on designing, focused on architectural design, whilst the other five studies in Table 1 focus on product design and development. Study samples range in size from 11 to 29 participants, and include practising designers and design/engineering students.

fMRI is one of several neuroimaging methods currently applied in design research, along with electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS). These methods differ in their spatial and temporal resolution, which makes them better suited for answering different types of question. fMRI has higher spatial resolution, and is most appropriate for questions about *where* activation occurs in the brain during tasks. fNIRS can answer similar questions, but is more suitable for naturalistic settings due to its higher portability and tolerance to body movements. EEG has higher temporal resolution, making it well suited to questions about the brain activity associated with specific *events in time* or *neural oscillations* in mental tasks/states. There is a fairly extensive body of EEG studies on design (e.g. Jia & Zeng, 2021; Nguyen et al., 2018; Vieira et al., 2020; Vieira et al., 2019; Zhao et al., 2020), and a growing number of fNIRS studies (Hu et al., 2021; Shealy, Gero, Hu, et al., 2020).

fMRI builds on our understanding of design cognition (i.e. the mental processes and representations involved in designing (blind citation_f)). Design cognition research generates knowledge about the cognitive processes involved in design activities, and how they interact. fMRI can in turn tell us what brain regions and networks are associated with cognitive processing during design. For example, the majority of the studies in Table 1 contribute knowledge about the brain regions associated with ideation and decision making processes in design. Design cognition is a subset of human cognition more generally, and it is therefore quite likely that design activities neurally overlap with activities in other contexts. fMRI can also shed light on the extent of this overlap. For instance, several authors in Table 1 highlight similarities by connecting their results with findings from cognitive neuroscience. Goucher-Lambert et al. (2017) found that sustainable product decision making was associated with regions that are also activated in moral reasoning and judgment in other areas. Goucher-Lambert et al. (2019), Fu et al. (2019), and (blind citation_a) all observed overlap between regional activation in design ideation tasks and more generic creative ideation tasks in the general population. There have not yet been extensive empirical comparisons using fMRI, although Alexiou et al. (2009) did observe differences in frontal activation during open-ended ‘design’ problem solving and more constrained problem solving found in other contexts. fMRI can also potentially provide insight into neural overlap between designers from different domains, and between designers and non-designers, although no such studies are currently reported.

There are a range of different fMRI paradigms in cognitive neuroscience. However, all of the fMRI design studies to date appear to be based on the subtraction paradigm. In subtraction studies, an experimental task is compared with a control task. The tasks are closely matched, but the control task does not include the key cognitive process of interest in the experimental task. Brain activation associated with the control task is then effectively ‘subtracted’ from activation in the experimental task, leaving only neural regions that are uniquely associated with the cognitive process under study (Friston et al., 1996; Smith, 2004; Soares et al., 2016). The tasks and key findings from subtraction in existing design fMRI studies are summarised in Table 1.

Table 1: fMRI studies reported in design journals

Authors	Tasks studied	N^1	Ppt background	Key fMRI results
Alexiou et al., 2009	Room layout task under two conditions: (i) constrained (problem solving); and (ii) open-ended (design).	17	Range from some familiarity with design to formal architectural training.	• Design and problem solving tasks associated with increased activation in prefrontal cortex. • Design task associated with increased activation in right dorsolateral prefrontal cortex.
Sylcott et al., 2013	Select preferred option from products with varying: (i) form only; (ii) function only; and (iii) form and function.	14	Consumers (no further details).	• Decisions based on form or function associated with increased activation in supplementary motor area, insula, and anterior cingulate. • Decisions based on both form and function additionally associated with increased activation in amygdala.
Goucher-Lambert et al., 2017	Select preferred option from products with varying attributes under two conditions: (i) with info on environmental impacts; and (ii) with info on a material property (control).	11	Consumers – mix of engineering/innovation students and others.	Decisions involving environmental impacts associated with increased activation in the superior/medial frontal gyrus and the inferior/middle temporal gyrus.
Fu et al., 2019	Open-ended product design ideation task under two conditions: (i) with visual example (fixation); and (ii) no example (control).	18	Undergraduate students in various years of study, all industrial design minors (17 mech. eng. majors, one bio-med. eng.).	Ideation tasks using an example were associated with increased activation in right inferior temporal gyrus, left middle occipital gyrus, and right superior parietal lobule and decreased activation in left lingual and superior frontal gyri.
Goucher-Lambert et al., 2019	Open-ended product design ideation task under three conditions: (i) near stimuli; (ii) far stimuli; and (iii) control (words from design task).	21	Graduate students in engineering, design, or product development.	Conditions involving near and far stimuli associated with increased activation in various regions of the left and right temporal and parietal cortex.
Blind citation_a	• Product design ideation task under two conditions: (i) constrained; and (ii) open-ended. • Imagery manipulation task (control).	29	Practicing product design engineers with at least 2 years' professional experience.	• No differences in activation between open and constrained tasks. • Ideation associated with increased activation in left cingulate gyrus, and preliminarily right superior temporal gyrus.

[1] N = sample size. Several studies excluded participants who completed the experimental procedure from the analysis due to data quality issues. This column reports the number of participants included in the analysis.

2 Considerations for developing and executing fMRI design studies

In (blind citation_a), we report an fMRI study investigating the neural correlates of ideation in product design engineers. The study focused on practicing designers, and required us to adopt a multidisciplinary approach. Whilst the results are applicable specifically to ideation in product design, we have been able to distil some fundamental methodological considerations for fMRI design studies from our experiences.

In Figure 1, we outline the key phases and activities involved in developing and executing an fMRI subtraction study. We have tried to do so in a manner that is accessible for design researchers new to fMRI, and pragmatically reflects the iteration involved in practice. The quality of fMRI results depends not just on data collection and analysis procedures, but also on the way that constructs are conceptualised in relation to the research question. Accordingly, the process in Figure 1 begins with conceptualisation, followed by experimental design, data collection, and analysis. We have focused on subtraction because it is the paradigm adopted in all fMRI design studies to date (including our own); we acknowledge that the discussion will likely evolve as further paradigms are explored in future.

In the following sub-sections, we elaborate on the activities and highlight considerations of particular relevance in design studies. We do not delve into the technical details of MRI scanners and analysis packages; the aim is to provide an overview of the key decision points and associated research quality issues. Where possible, we illustrate how the activities have been carried out across the fMRI design studies reported in Table 1. As conveyed in the introduction, the discussion here should be viewed as an introductory overview rather than a definitive methodology. It is not a substitute for training in fMRI or the expertise that comes from collaboration with cognitive neuroscientists, which we discuss further in Section 3.1.

2.1 Defining constructs

As discussed in Section 1, fMRI subtraction involves the comparison of cognitively similar tasks that differ in terms of a key process of interest. Brain activation associated with shared cognitive processes is ‘subtracted’ out during analysis, leaving only regions of activation uniquely associated with the process under study. To identify regions of brain activation associated with design activities using this approach, it is necessary to clearly define the cognitive processes relevant to the research question at the outset. This knowledge provides the basis for defining experimental tasks (Section 2.2.1) and logical analytical contrasts (Section 2.4.1). Two key activities involved in this phase are: (1) identifying relevant processes from the literature; and (2) bridging between the ontologies of design cognition research and cognitive psychology/neuroscience.

Defining processes for study is not a trivial task, and may require considerable time, effort, and iteration. In our study, the extensive literature on design cognition provided a starting point for identifying processes relevant to design ideation – we established categories of cognition involved in conceptual design through a systematic review of design protocol studies. We then drew from the well-established cognitive ontology in psychology/neuroscience to more clearly define specific processes. For example, if design cognition research tells us that ‘memory’ is involved in ideation, psychology research can help us break this down into more specific constructs such as ‘episodic memory’ and ‘semantic memory’ (blind citation_b). Through this ontological bridging, we conceptualised design ideation as involving: (i) lower-order memory retrieval and visual imagery processes; and (ii) higher-order evaluation, modification, and creative generation processes. Table 2 provides an overview of the research questions and related constructs investigated in fMRI design studies. As shown, constructs are defined at different levels of granularity – e.g. designing (Alexiou et al., 2009), which involves ideation, which involves a range of lower-level processes such as memory retrieval and imagery (blind citation_a) as well as higher-level constructs such as analogical reasoning (Goucher-Lambert et al., 2019) and fixation (Fu et al., 2019).

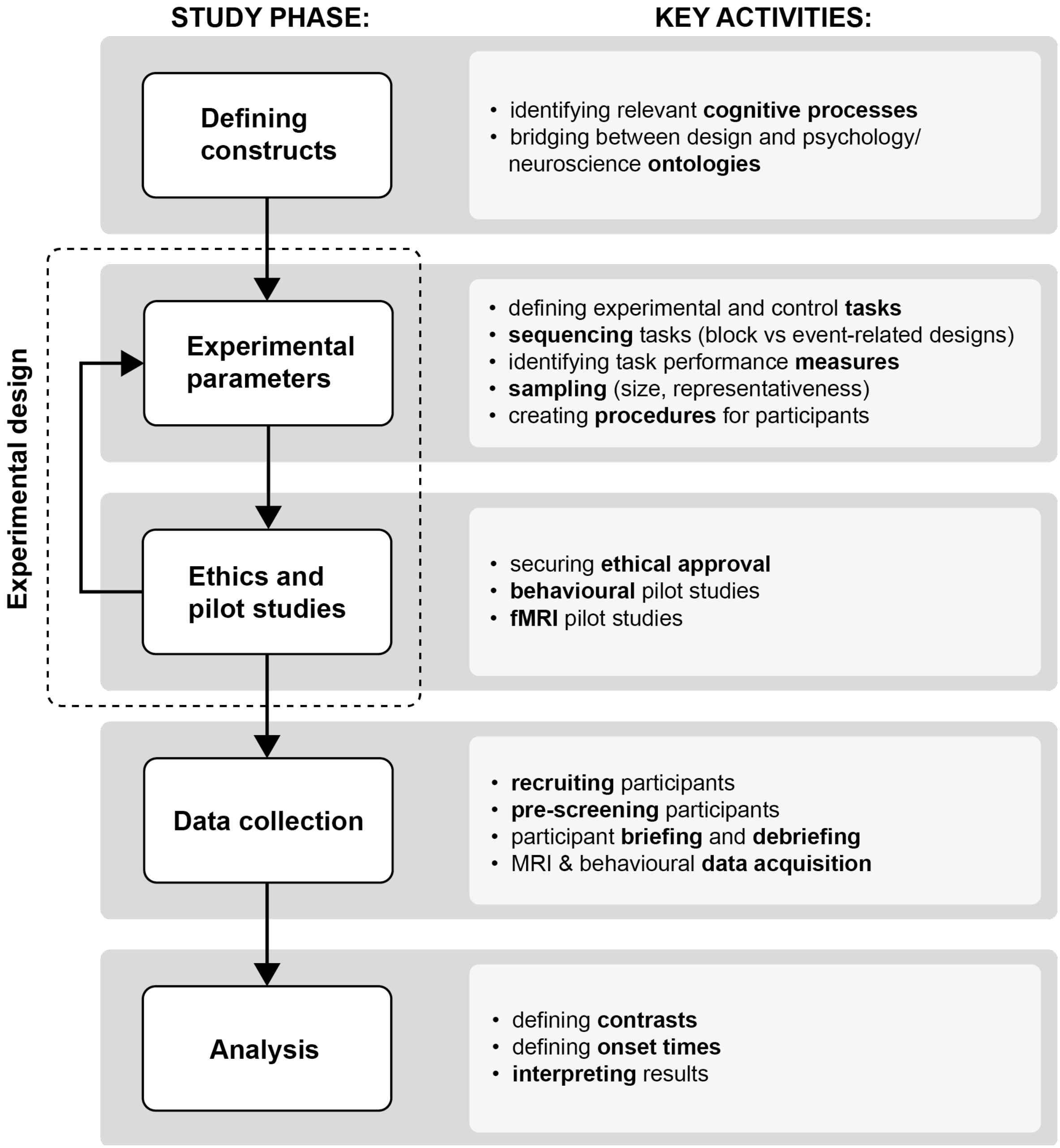


Figure 1: Phases and activities involved in developing and executing fMRI design studies within the subtraction paradigm

Table 2: Relationship between research questions, constructs, and tasks in fMRI design studies

Authors	**Research question(s)**[1]	**Key constructs**[1]	**Tasks studied (summary)**[2]	**Key cognitive difference between tasks**[1]
Alexiou et al., 2009	Can design activity be distinguished from problem solving at the neural level?	• *Problem solving:* reasoning about problems with given stopping criteria, predefined legal moves, and a unique solution (well-defined problems). • *Designing:* reasoning about problems with no stopping criteria, requiring the definition of moves and problem specification (open-ended problems).	Design and problem solving	Level of problem definition
Sylcott et al., 2013	What brain regions are associated with product decision making using aesthetic (form) and performance (function) information?	*Preference judgement:* judging preference for a particular product option based on combinations of product attributes.	Preference judgments involving form and function	Type of attribute interpreted
Goucher-Lambert et al., 2017	What brain regions are associated with multi attribute product decision making involving sustainability?	*Preference judgement:* judging preference for a particular product option based on combinations of product attributes.	Preference judgments with and without sustainability	Type of attribute interpreted
Fu et al., 2019	What brain regions are associated with design fixation?	*Design fixation:* unconscious attachment to ideas/concepts that constraints the production of outputs in conceptual design.	Ideation with and without fixation	Involvement of fixation processes
Goucher-Lambert et al., 2019	Does analogical distance between the problem and inspirational stimuli affect brain activation in design ideation?	• *Ideation:* generation of ideas to address a design problem. • *Analogical reasoning:* process of applying information from a source to a target.	Ideation with stimuli of different analogical distance from design problem	Involvement of analogical reasoning, with stimuli differing in distance from the design problem
Blind citation_a	What brain regions are associated with design ideation, and are there any differences in activation between open-ended and constrained ideation tasks?	*Design ideation:* the generation of novel ideas to address a design problem, involving memory retrieval, generative processing, higher-order evaluation and modification, and visual imagery processing.	Ideation and visual imagery manipulation	Involvement of generative processing, i.e. the creation of a novel idea

[1] Based on interpretation of what is written by the authors.

[2] See Table 1 for full details on experimental and control tasks summarised here.

2.2 Experimental design

Experimental design refers to the development and piloting of tasks, measures, and procedures that will enable the research questions to be answered in a reliable and replicable way. fMRI experiments on cognitive activities (including designing) may be viewed as a subset of neuroscience experiments more broadly, where the dependent variable is brain activity (measured by cerebral blood oxygenation) and independent variable is a cognitive task. They adopt a time-series design, where brain activity is measured across time as the task is manipulated. In order to control for the relatively high variability in brain activity between individuals, fMRI experiments also typically adopt a within-subjects design, where every participant experiences all levels of the independent variable (Harrington, 2020). This highlights six key activities involved in the experimental design phase: (1) defining tasks; (2) identifying task performance measures; (3) sequencing tasks over time; (4) drawing a sample of participants; and (5) defining experimental procedures that are consistent across participants. A sixth important activity that runs in parallel with the above is securing ethical approval and piloting the design.

2.2.1 Defining tasks

Subtraction requires two kinds of task: experimental tasks, which elicit the cognitive processes involved in the design activity being investigated (Section 2.1); and a control task, which allows brain activation associated with the key process of interest to be isolated.

The existing body of literature on design tasks is a sensible starting point for defining experimental tasks. For example, we defined ideation tasks for our study based on: (i) literature on the characteristics of concept generation tasks in design (e.g. Sosa, 2018); and (ii) examples of tasks from design competitions, student projects, and cognitive studies on design ideation. Behavioural pilot studies (Section **Error! Reference source not found.**) can then be conducted to assess whether the expected cognitive processes are elicited, and refinements made where necessary.

Defining control tasks can be more complicated, because design activities are often complex, higher-order cognitive phenomena that involve multiple interacting processes (blind citation_b). As such, it can be challenging to determine which processes should be subtracted out. We approached this by considering that ideation is essentially the production and manipulation of mental representations. The key process that distinguishes it from similar activities is ‘creative generation’, i.e. the creation of *new* ideas. A control task that involves all of the processes in our conceptualisation of ideation except creative generation is visual imagery manipulation. That is, retrieving a known product from memory, forming a visual mental image of it, and performing a routine manipulation on the image (e.g. rotation or resizing).

Table 2 relates the experimental and control tasks investigated in fMRI design studies back to the underlying constructs defined by authors. In our own interpretation of the articles, we found that it is not always clear what the difference in cognitive processing is between the tasks. For example, Sylcott et al. (2013) compare product preference judgments involving form and function attributes. They suggest that these may differ in terms of “analytical versus emotional processing," but the specific processing differences are not clearly defined. Comparing the tasks can still reveal differences in neural activation between the tasks, but it may be more challenging to connect the fMRI results to cognition later on (discussed in Section 2.4.3).

2.2.2 Sequencing tasks and controlling extraneous variables

The sequence in which experimental and control tasks are presented to participants depends partly on whether a block or event-related design is used. As noted in Section 1, fMRI measures changes in oxygenated blood flow associated with neuronal activation. This is called the hemodynamic response (HDR). In a block design, tasks of the same type are grouped together and presented in a continuous block. The HDR in this case is sustained (Figure 2a), and does not return to baseline until the end of each block. This type of design typically has relatively high statistical power, but cannot distinguish between the different events that occur within a block (e.g. the presentation of a stimulus versus the subsequent behavioural response). In an event-related design, tasks can be presented in a random order and moment-by-moment changes in the HDR can be distinguished (Figure 2b). That is, the different elements of a task are treated as individual 'events.' This type of design may have lower statistical power, but it has greater flexibility and allows for more fine-grained analysis of fluctuating brain activity (Lindquist, 2008; Soares et al., 2016).

Each design has advantages and disadvantages, and is suitable for different investigations. In some studies, presenting tasks in blocks may not be appropriate or possible due to learning effects or fatigue. For example, it is difficult to sustain rapid, continuous generation of ideas, so presenting our ideation tasks in blocks could have caused participants to tire during the experiment. Event-related designs can be appropriate in studies where the timing of task responses varies and is difficult to control. For instance, the time taken to generate ideas naturally varies across different designers and tasks. In an event-related design the 'events' can be defined by the behaviour of the participant (e.g. by pressing a response button once they have completed the task instruction). As shown in Table 3, the majority of fMRI design studies appear to have adopted event-related designs (although the design type is not always explicitly mentioned by authors). Goucher-Lambert et al. (2019) adopted a mixed block and event-related design, which enabled them to analyse their dataset from two perspectives (Section 2.5).

Table 3: Overview of key experimental design parameters in fMRI design studies

Authors	**Design type**[1]	**Tasks under study (summary)**[2]	**Baseline task**	**Sequencing of task trials**[3]	**Task performance measure(s)**	**Key experimental procedures**
Alexiou et al., 2009	ER*	Design and problem solving	Rest period of 15 s	Order of trials counter-balanced across ppts.	None	• Task instructions presented on screen. • Design and problem solving solutions recorded using mouse to drag items on screen. • Streaming software captured all on-screen activity, and snapshots of solutions automatically saved.
Sylcott et al., 2013	ER*	Preference judgments involving form and function	Indicate whether two options are the same or different.	• Trials organised in runs, in pseudorandom order. • Runs counterbalanced across ppts.	• Preference ratings • Reaction time	• Task instructions presented on screen using Macstim software. • Product preferences indicated via response glove.
Goucher-Lambert et al., 2017	ER	Preference judgments with and without sustainability	Discriminate between high and low frequency tones.	• Trials in random order.	• Preference ratings • Reaction time	• Task instructions presented on screen using E-Prime software. • Product preferences indicated via response pad strapped to hand.
Fu et al., 2019	ER*	Ideation with and without fixation	Rest period of 15 s.	• Trials organised in sets. • Trials ordered to minimise effects of fatigue, order, and design problem. • Ppts randomly assigned to sets.	• Concept quality • Concept novelty • Feature transfer from examples	• Task instructions presented on screen. • Generated ideas verbally described and audio recorded via microphone.
Goucher-Lambert et al., 2019	M	Ideation with stimuli of different analogical distance from design problem	1-back memory task	• Trials organised in sets. • Pairings of design problem to task type counterbalanced across sets. • Ppts assigned to sets.	• Concept novelty • Concept usefulness • Stimuli usefulness • Stimuli relevance	• Task instructions presented on screen using E-Prime software. • Response glove used to indicate generation of ideas. • Response glove used to rate: (i) stimuli relevance, and (ii) idea novelty and uniqueness.
Blind citation_a	E	Ideation and visual imagery manipulation	Indicate when a fixation cross changes colour.	• Trials organised in sets, in pseudorandom order based on task type.	Concept novelty	• Task instructions presented on screen using Matlab software.

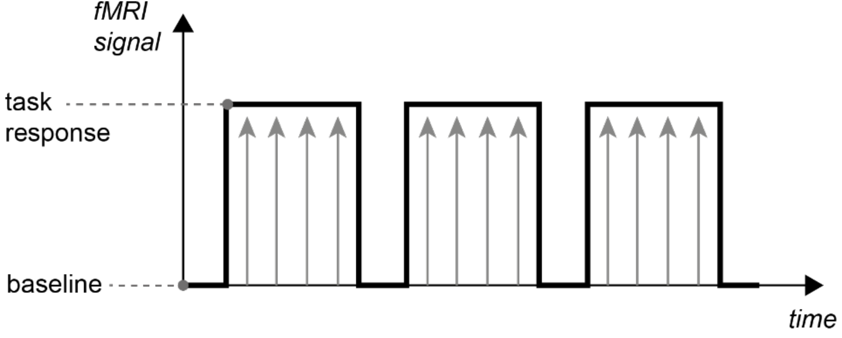
				- Sets counterbalanced across ppts based on design problem/imagery focus.		- Hand-held button used to indicate generation of idea or mental image. - Generated ideas verbally described and audio recorded via microphone. - Ideas sketched by ppts after scan based on audio recordings.

[1] ER = event-related; M = mixed block and event-related. Inclusion of * indicates that type of design was not clearly stated by the authors and has been inferred based on other reported details.

[2] See Table 1 for full details on experimental and control tasks summarised here.

[3] A trial is a repetition of a task. For example, in our study: the ideate task required participants to generate ideas to address a given design problem. Each participant completed 20 trials of this task, where each trial focused on a different design problem.

(a) Block design



(b) Event-related design

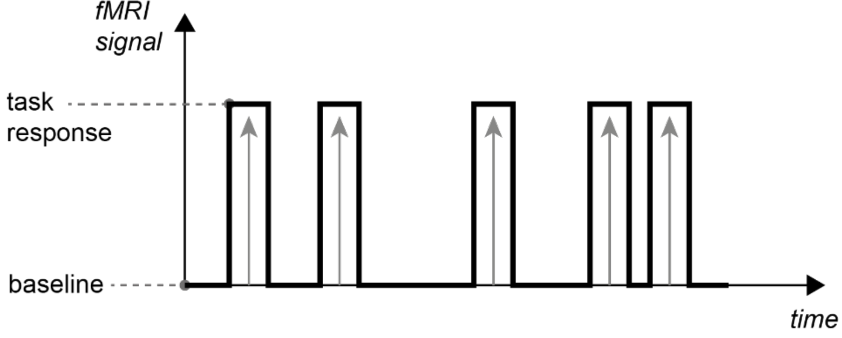


Figure 2: Block versus event-related fMRI designs (adapted from Soares et al., 2016)

As discussed in Section 1, the brain activation associated with experimental and control tasks is contrasted during analysis to identify differences between the conditions. However, this does not allow the regions of activation associated with each task individually to be identified. To do this, the tasks must be compared in turn with a ‘baseline’ condition. As such, some studies additionally include a baseline task to enable this kind of analysis. However, a suitable baseline task is hard to define. Brain activity at rest is not necessarily appropriate, because this state involves complex processing (although rest periods are used in some studies in Table 3, e.g. Alexiou et al., 2009; Fu et al., 2019). Even in the absence of a task, the participant’s brain may still be very active due to unconstrained self-initiated thinking (Hurlburt et al., 2015; van den Heuvel & Hulshoff Pol, 2010). An alternative baseline is cognitive processing that is involved in the experimental tasks, but does not contribute to the phenomena under study. For example, all ideation and manipulation tasks in our study involved visual perception of instructions and a fixation cross during generation periods. However, this was not considered to actively contribute to the generation of ideas/images. As such, the baseline condition was defined as visual perception with no ideation or mental imagery processing. During baseline tasks, participants were asked identify colour changes in a fixation cross presented on screen. A similar approach was taken by Sylcott et al. (2013), who asked participants to view sets of “shape and function specification groups” in between preference judgment tasks and decide whether they were the same or different. This then allowed them to subtract out “perceptual aspects of the decision and isolate activity specific to preference judgment.” Taking a different approach, Goucher-Lambert et al. (2017) used a tone discrimination task as the baseline in their study on decision making because it activated brain regions that did not overlap with the regions of interest identified for their analysis. Baseline tasks used in other studies are listed in Table 3.

In addition to the types of tasks used, decisions must be made about the number of trials of each task to be included in the experiment (i.e. repetitions of each task). Generally speaking, more trials increases statistical power. However, this increases the length of the fMRI scan, which may increase discomfort for participants and reduce task performance. As such, it may be necessary to optimise the number of trials included through pilot studies (Section **Error! Reference source not found.**). We conducted pilot studies to determine the maximum task durations that would minimise overall scan length whilst remaining within the average capability of participants with respect to:

- instruction reading time (18 s);
- number of concepts/images generated per task (up to three); and
- time allowed to generate the concepts/images (85 s for ideation and 30 s for manipulate).

This enabled us to include 20 ideation trials (10 open-ended and 10 constrained), 10 manipulate trials, and 20 perceptual baseline trials. To ensure that (a) participants were able to sustain the generation of new ideas and visual images throughout the experiment, and (b) the results were generalisable beyond the experiment, we defined a range of different task instructions focusing on different design problems (ideation) and artefact categories (manipulate). Problems and artefacts were then varied across the trials. A similar approach is adopted in other studies on ideation, e.g. Fu et al. (2019) use 10 design problems across their ideation trials, and Goucher-Lambert et al. (2019) use 12.

In order to robustly conclude that any observed differences in brain activation are due to the tasks under study (i.e. the independent variable), it is important to control for extraneous variables across tasks and trials (Harrington, 2020). For example, Alexiou et al. (2009) highlight that it is important to ensure tasks are matched in aspects such as difficulty and timing. They defined the design and problem solving tasks in their study so that “the stimuli are identical, the number of instructions and the cognitive effort needed to understand them are as close as possible, and the time required for their resolution is similar.” In our study, we controlled for cognitive effort by matching design problems in terms of their perceived difficulty as rated by designers, as well as the number of words and lines to be read in the instructions. Task timings were controlled as above. It may also be important to control for order effects, if the order of tasks could affect performance (Harrington, 2020). This can be achieved by randomising and/or counterbalancing the sequence in which trials are completed participants. As shown in Table 3, authors have adopted various strategies to control for order effects, e.g.: randomising trial order across participants; organising trials into pseudo/randomised sets, and then counterbalancing sets across participants; and organising trials into sets ordered based on factors such as fatigue and design problem features, and then randomly assigning participants to sets.

2.2.3 Identifying performance measures

To provide evidence that participants engaged in the expected cognitive processes (as opposed to off-task activity) during fMRI scanning, behavioural measures of cognitive performance can be implemented. These can also be used in covariate analysis, where relationships between cognitive performance and brain activation are explored (Section 2.4.1). Given our focus on creative generation (i.e. the generation of new ideas), we applied concept novelty as a performance measure. A variety of performance measures have been applied in other fMRI studies of design, dependent on the tasks used as shown in Table 3.

If it is necessary to gather behavioural data during fMRI scanning to assess performance, consideration must be given to how this will be done within the constraints of the scanning environment. This is not always straightforward for common design behaviours such as sketching and gesturing. There have been fMRI studies on the neural basis of sketching in cognitive neuroscience, using MRI-safe tablets (Miall et al., 2014) and pencil/paper (Schaer et al., 2012) to capture sketches from participants while they lie down in the scanner. A similar approach may be suitable for investigating brain activity during design sketching. If sketching is simply being used to record outputs during the study of other design activities (e.g. ideation), and is not itself under study, then control tasks that enable the associated neural activation to be subtracted out in the analysis must be developed. For example, in our study, we could have asked participants to sketch the artefacts they visualised during manipulate tasks (our control). However, there are potential disadvantages to this approach. For instance, sketching can increase complexity for participants in what is already a demanding environment, as well as fatigue over the course of the experiment. Physical movements also introduce noise and artefacts into the data (Havsteen et al., 2017), although Schaer et al. (2012) demonstrate that it may be possible to keep motion below an acceptable threshold level during basic sketching tasks.

If sketching is not directly under study, alternative approaches for recording design outputs are possible. For instance, in our study, we recorded a brief verbal summary of the concepts generated at the end of each ideation task, and then asked participants to sketch their ideas in a more comfortable environment after the fMRI scan using this as a memory prompt (illustrated in Figure 3). We then used these sketches as a basis to evaluate concept novelty. As shown in Table 3 (column 7), none of the other studies on ideation involved sketching during fMRI scanning. Fu et al. (2019) recorded verbal descriptions of ideas, then transcribed these as the basis for evaluating ideation performance. Goucher-Lambert et al. (2019) did not record generated ideas at all, instead asking participants to rate the novelty and uniqueness of their own ideas in the scanner using response buttons. Whilst these approaches avoid the issues of complexity, fatigue, and noise outlined above, they also have disadvantages – e.g. sketches produced *post hoc* may not accurately represent the ideas generated in the scanner (blind citation_a), and ideation tasks that do not permit sketching are arguably low in ecological validity (Fu et al., 2019). As discussed further in Section 3.4, these kinds of trade-offs are a major challenge for fMRI research on design.

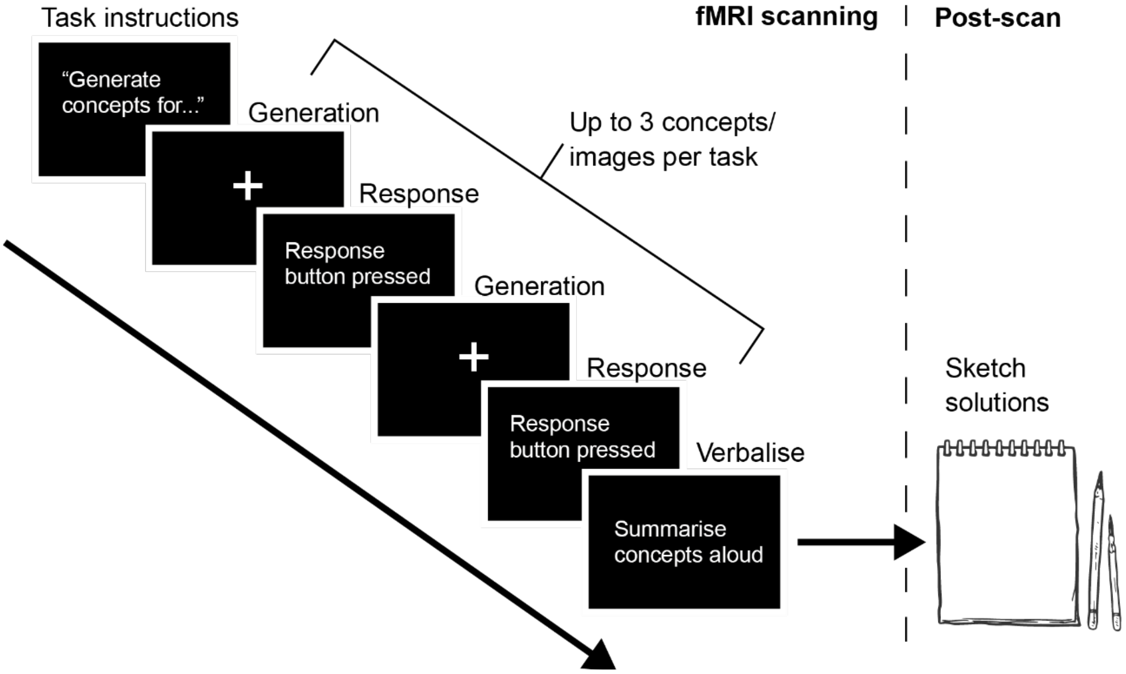


Figure 3: Verbalisation and sketching of concept in ideation tasks used in (blind citation_a)

2.2.4 Sampling

As with cognitive studies, sampling decisions in fMRI revolve around two key attributes: (1) sample size; and (2) representativeness. Regarding (1), sample size is affected by the expected magnitude of the experimental effect under study (effect size). If effect size is known or can be reliably estimated, the sample size required to achieve sufficient statistical power can be calculated. However, this cannot be calculated directly when both the effect under investigation and the study design are novel (Desmond & Glover, 2002; Mumford & Nichols, 2008). This is often the case in fMRI design studies, given the limited knowledge about brain activation and the lack of established experimental protocols. An alternative is to follow the sample sizes used in studies on similar phenomena. In our study, we based sample size (N=30) on fMRI studies of visual creativity ($13 \leq N \leq 48$ (blind citation_d)) and the only existing fMRI study in the design literature at the time (N=18 (Alexiou et al., 2009)). The samples in all other studies (Table 1) fall into this size range. It is not clear what the basis for sample size is, with the exception of (Goucher-Lambert et al., 2017) who conducted a power analysis using pilot data. Regarding (2), results can only be generalised to populations that the sample is representative of. In this respect, much of the debate on the effects of design experience and expertise in cognitive design studies (Cross, 2004) is also applicable to fMRI.

2.2.5 Defining experimental procedures

From a practical perspective, it is necessary to plan how the designed experiment will actually be run in a consistent manner across all participants. The acquisition of the fMRI data is normally carried out by qualified radiographers or technicians, who will advise on MRI scanner parameters and run the scanning session. However, the research team are typically responsible for other important aspects of the experimental procedure, including how task instructions will be communicated to participants and how behavioural data will be acquired.

A script may need to be programmed to present instructions to participants on a screen at the correct point during the experiment. This script may also need to control the recording of behavioural data (including task responses) at the appropriate points. The technical requirements and package used to develop the script will depend on the team, study, and equipment used – we used Matlab (others have used E-Prime and Macstim to present task instructions, as per Table 3). In addition to presenting task instructions, our script controlled the recording of two kinds of behavioural data: (i) responses from hand-held triggers, indicating when the participant had generated an idea; and (ii) verbal descriptions of concepts from a microphone inside the scanner. Column 7 in Table 3 provides an overview of the key software, equipment, and procedures used to present task instructions and gather behavioural data in other studies.

2.2.6 Ethics and pilot studies

A critical activity that should be considered from the outset of study development is securing ethical approval. Depending on the MRI scanning facility used, this may involve approval from external ethics boards as well as university committees. Securing ethical approval can be an iterative and protracted process – e.g. nine months in our own study, with several rounds of changes to the experimental protocol before approval was granted. No fMRI scanning should take place until ethical approval has been granted for this activity. However, ethics applications typically require details on the experimental design, so it may be necessary to conduct behavioural pilot work in parallel with preparing ethics documentation (ensuring that this pilot work itself abides by ethical principles and institutional policies). In reality, pilot studies are required to iteratively test and refine procedures throughout the experimental design phase (**Error! Reference source not found.**); the activities in Sections 2.2.1 – 2.2.5 are not linear.

The majority of the studies in Table 3 discuss pilot work as an important factor in their decisions about experimental parameters (although do not necessarily describe their methods in detail). In behavioural pilot studies, methods from both design cognition research and psychology may be applied. In our study, we completed four behavioural pilots with a total of 35 product design engineers (11 students and 24 professionals). We tested various iterations of our tasks and Matlab script with participants on a laptop in an office environment. A variety of methods were used to assess how effectively the tasks elicited the cognitive processes of interest, including qualitative interviews about self-reported processing and quantitative psychometric tests. Development and piloting can be a lengthy process, taking over 12 months in our study due to the lack of precedents in the literature (see Section 3.1). Plans for fMRI design studies (particularly on design activities that have not previously been investigated) should ensure that sufficient time is allocated to the front-end of the project to allow for exploration and iteration.

Once ethical approval has been secured, it is important to pilot the procedure in the MRI scanning environment before starting full scale data collection. This can highlight both problems with the script (e.g. issues with behavioural data capture from equipment) and difficulties for participants completing the procedure under full experimental conditions. Goucher-Lambert et al. (2019) also used pilot fMRI data to inform decisions about their analysis strategy (Section 2.4.2).

2.3 Data collection

As mentioned in Section 2.2.5, the acquisition of fMRI data is carried out by radiographers/technicians. This typically includes setting up participants in the scanner, running the MRI scans, and transferring data post-scan. There are three key data collection activities to be handled by the research team, all relating to participants: (1) recruitment; (2) pre-screening; and (3) briefing and debriefing:

Recruitment for fMRI studies involves many of the same tasks as cognitive design studies (e.g. advertising, obtaining consent, and reimbursement). One specific issue to consider with fMRI is that participation can entail a considerable time commitment. Participants may be required to travel to a specialised scanning facility, and the experiment plus setup and debriefing time can run to several hours. This can make it more difficult to secure participants, and increase reimbursement costs. This can be particularly problematic in studies of professional designers. For instance, the professional participants in our study had to commit a whole working day. As such, reimbursement had to be reasonably competitive with a designer’s hourly rate.

Potential fMRI participants must pass a pre-screening process to ensure they do not have any contraindications to MRI scanning (e.g. ferrous metal implants, mental or neurological conditions, pregnancy, and claustrophobia). Handedness should also be considered; left-handed people are generally excluded from studies due to potential differences in neural organisation. It is also advisable to screen participants based on their performance in the experimental tasks, to minimise the risk of later exclusions and/or negative effects on the results. For instance, we asked potential participants to complete an example set of ideation and manipulate tasks following the experimental timings and procedure at a laptop. This provided training for the participants, and allowed us to assess their ability to perform at the required pace and without sketching concurrently.

Finally, to ensure that participants are able to engage with the procedure and any equipment correctly and consistently, they should be briefed on the experiment in advance of the scan. It can also be helpful to debrief participants post-scan to check that the procedure was completed correctly and identify any issues that could potentially affect the results. For instance, we interviewed all participants post-scan about their cognitive processing during the ideation and manipulate tasks. We also asked them to fill out a questionnaire on their experiences during the scan and how they perceived the creativity of their concepts. This allowed us to identify any participants who may differ from the rest of the sample in approach and/or performance for reference during fMRI analysis. A similar approach appears to have been taken in Fu et al. (2019), who surveyed participants about their experiences after completion of the experiment.

2.4 Analysis

Once data has been collected from the full sample, it must be analysed to answer the research questions. The most widely applied fMRI analysis approach is based on the General Linear Model (GLM) (Soares et al., 2016). This appears to be used in all design fMRI studies to date, and is therefore the focus here. The GLM approach involves modelling regressors that are predicted to affect the measured fMRI signal. This includes manipulated variables (e.g. tasks), as well as variables that were not manipulated but may still have an effect (e.g. body motion).

Analysis essentially involves performing multiple t-tests across the brain to determine which voxels show significant activation (or deactivation) in response to the model variables, and contrasting the activation associated with different variables to answer the research questions. The analysis outputs for individual participants are combined to obtain results for the whole sample (Monti, 2011; Smith, 2004; Soares et al., 2016).

Analysing fMRI data requires specialised expertise and software packages (e.g. SPM (Wellcome Centre for Human Neuroimaging, 2021), or AFNI (National Institute of Mental Health, 2021)), and the aim here is not to provide a how-to guide on the technical details (which are covered in depth elsewhere, e.g. Ashburner et al. (2020)). There are many variations in the analysis strategies adopted in different fMRI design studies, depending on the questions to be answered and tasks studied. As such, we will not attempt to provide a summary of the details here. However, we will discuss three fundamental activities that are involved across all existing studies and may be unfamiliar to design researchers new to fMRI: defining appropriate (1) contrasts and (2) onset times, and (3) linking brain activation and cognition during the interpretation of results.

2.4.1 Defining contrasts

In basic terms, a contrast refers to a set of model variables that are being compared in the analysis (Smith, 2004). The main contrasts of interest typically include the experimental conditions, and are therefore ultimately derived from the research questions guiding the study. In order for such a contrast to be meaningful, the conditions must follow subtractive logic – that is, they can be assumed to differ only in terms of the key cognitive process under study (as discussed in Section 2.2.1). For example, in our study, we assumed that the manipulate condition included the same processes as the ideate condition, except for creative generation. When we subtracted the manipulate condition from the ideate condition in the GLM, we identified the voxels that are more significantly activated in the ideate condition. It could then be concluded that this activation was likely associated with the 'additional' creative generation process in the ideate condition. As conveyed in Sections 2.1 and 2.2.1, determining how subtraction will be implemented is not always straightforward in the study of design activities given their cognitive complexity. It is advisable to consider this during the early stages of study conceptualisation and design, otherwise it may be difficult to define meaningful contrasts during analysis.

Covariates can also be included in contrasts. In this context, a covariate is a variable that may be expected to covary with activation in the brain regions under study (Hyatt et al., 2020). For example, we included years of design experience as a covariate in our ideation study – we may expect more experienced designers to be more proficient in generating novel concepts, and therefore to exhibit greater activation (or deactivation) in regions associated with ideation. Including covariates in fMRI contrasts allows these kinds of relationships to be explored, to provide further evidence that the observed activation is associated with the process under study as opposed to extraneous factors.

2.4.2 Defining onset times

The fMRI data gathered from each participant consists of a time series representing blood oxygenation occurring in each voxel of the brain over the course of the experiment. Given that the whole brain volume may encompass hundreds of thousands of voxels, this means that the dataset consists of hundreds of thousands of time series, where each voxel represents an area of approximately 2-4 mm^3 and the time series represents an observation approximately every 1-3 seconds. In order to model the conditions as regressors in the analysis, it is therefore necessary to determine when the task responses occur in each condition. These are termed onset times (Monti, 2011). In a block design, onset times are typically determined by the start of each block and are therefore constant. However, in event-related designs, onset times may vary because responses can be defined by participants (Section 2.2.2, Figure 2). For example, our participants were free to generate a concept at any point within an 85 s period after reading the task instructions.

It is not always straightforward to define onset times for open-ended tasks in event-related designs. For example, consider ideation. The period over which an idea is created is not clear – does it start during the task instructions, or afterwards? Is it instantaneous, and corresponds with the response button press? How much does it vary from task to task and participant to participant? Can participants consistently self-report the event using the button? Do participants have different interpretations of the instruction to 'press the button once you have created an idea'? The same questions apply to other design tasks – for example, when is a decision made during decision making? When has a judgment been made during evaluation? At what point is a problem representation formed during problem definition? In our study, we defined the onset times for ideation as follows: for the first concept, immediately after the task instructions disappeared; for the second and third concepts, immediately after the response button was pressed to indicate generation of the previous concept. However, there are several different ways we could have defined onset times as conveyed above, and there is no guarantee that our definitions are reflective of each participant's cognition. Goucher-Lambert et al. (2019) also studied ideation, and adopted a different definition – looking at brain activity 5-7 seconds prior to the button press (a decision based partly on pilot data). This highlights another way in which study conceptualisation can impact fMRI results, discussed further in Section 3.1.

2.4.3 Interpreting fMRI results

It is generally accepted that there is not a one-to-one mapping between cognitive processes and brain regions, and the same region may contribute to many different cognitive functions in complex ways (Poldrack, 2006, 2011). Thus, cognitive processes cannot be reliably inferred from regions of activation identified in an fMRI study. Rather, fMRI can most effectively tell us about the brain regions associated with cognitive processes defined *a priori* (Section 2.1) and elicited through carefully designed experimental tasks (Section 2.2.1). Care should therefore be taken when interpreting the results of fMRI studies from a cognitive perspective.

If the processes under study have been robustly defined and elicited during the study, then conclusions can be drawn about the brain regions associated with these processes from the results of the fMRI analysis. The results may be compared with similar studies in the literature to provide further support for these conclusions, postulate explanations about the roles that particular regions may play in a task, and highlight potential neural similarities/differences between related tasks and activities (as discussed in Section 1).

If processes have not been clearly defined *a priori*, it can be more difficult to link observed brain activation to cognitive processing. For instance, Goucher-Lambert et al. (2019) observed significant activation in the temporal gyrus during design ideation tasks. They highlight that a meta-review of semantic processing (Binder & Desai, 2011) shows the middle temporal gyrus to be consistently activated across semantic processing and memory tasks. Thus, because they observed activation in this region during design ideation, they suggest that semantic processing and memory may be involved. However, their experimental tasks were not designed to elicit these specific processes, and the middle temporal gyrus has been shown to be associated with other processes too (van Kemenade et al., 2019). Thus, although their conclusions seem reasonable, it is not necessarily clear from the fMRI results alone what role this region plays in design ideation. The authors fully acknowledge the limitations of this kind of reverse inference, but highlight that it may be necessary in the absence of robust prior knowledge about brain activity in design. In our own study, we made similar inferences based on cognitive neuroscience studies of creative ideation – suggesting that the anterior cingulate cortex (ACC) may facilitate the generation of unique solutions in design ideation by suppressing highly obvious/unoriginal concepts. However, the ACC has been implicated in a broad range of cognitive processes (Apps et al., 2016), and it is therefore possible that our interpretation is incorrect (or incomplete).

To try to address some of the weaknesses of reverse inference, Goucher-Lambert et al. (2017) applied a meta-analytic approach to support analysis and interpretation of fMRI data in their study on sustainable product decision making. They firstly conducted a meta-analysis of a large number of fMRI studies to identify neural regions associated with processes of interest in existing work. They then analysed these as regions of interest in their of fMRI data, observing significant activation. This kind of approach may provide stronger evidence than reverse inference from individual studies. As discussed in Section 3.3, there is a need for more foundational fMRI research, as well as meta-analysis across studies, to extend the empirical evidence base for the neural regions involved in designing.

3 Challenges and recommendations for fMRI research on design

To conclude this Research Note, and provide a springboard for further discussion, we consider four key challenges for fMRI research on design that emerge from the empirical work and activities covered in Sections 1 and 2. In our view, addressing these challenges is critical if fMRI is to become a meaningful method for advancing knowledge about the minds and brains of designers. We also make some recommendations for how the community might begin to tackle the challenges.

3.1 Establishing fMRI protocols for design research

Part of the motivation for this Research Note is the lack of established experimental protocols for fMRI design studies. There has been a relatively small number of studies to date (six, Table 1), so the existing methodological knowledge base from which researchers can draw is limited. Additionally, many of the phenomena under study are novel and require novel approaches. Due to the lack of precedents, considerable trial, error, and iteration is currently involved in study development.

Navigating study design and execution also requires expertise in fMRI and cognitive neuroscience that design researchers typically do not have. In addition to the technical details of fMRI scanning parameters and analysis (which are not covered in this paper), there is a need to understand the impact that conceptual decisions can have on the results. For example, as conveyed in Section 2.2.1, the way that the cognitive processes involved in a design activity are conceptualised directly affects the tasks that must be defined to enable subtraction during analysis. If these implications are not considered at the beginning of study conceptualisation, it may be difficult to carry out meaningful analysis later on. Similarly, onset times (Section 2.4.2) define the cognitive/neural events being analysed – thus, defining these in different ways will produce different results. These factors are also important for comparability and replicability. Studies investigating the same design activity but adopting different underlying conceptualisations may not be directly comparable in syntheses and meta-analyses, and it may not be possible to replicate the findings of a study that does not transparently report its conceptual decisions. We propose three recommendations towards addressing some of these challenges:

1. Expanding the methodological literature on fMRI in design research through the publication of methodology articles as well as more conventional results articles. Importantly, these must report failures and lessons learned alongside successes. This may require effort from authors, editors, and reviewers to shift away from the traditional focus on 'positive results'. Initiatives such as this Research Notes collection could provide a suitable model. Consideration should also be given to what may be learned from established fMRI protocols adopted in cognitive neuroscience studies overlapping design (e.g. visual creativity (blind citation_d) and sketching/drawing (Miall et al., 2014)).

2. Openly sharing experimental protocols, tasks, measures, etc. for reuse or adaptation by other design researchers, through institutional data repositories (see (blind citation_c) for an example from our study) or broader repositories for design research (e.g. Design Research Society, 2021; The Design Society, 2021b) and fMRI (e.g. OpenNeuro, 2021). This could reduce the amount of time required for study development in the front-end of projects by providing at least a starting point for methodological decisions.

3. Ensuring that conceptual and methodological decisions are transparently reported in fMRI papers on design, to provide both a point of reference for study development and to ensure appropriate interpretations and comparisons. This could be facilitated through the development of standard reporting structures for fMRI design studies (Poldrack et al., 2008), and/or open sharing practices as proposed above.

Collaboration between design researchers and cognitive neuroscientists can help with the above challenges, increasing both the robustness and creativity of studies. As more advanced fMRI approaches are imported to design research, the need for such collaboration will only increase. However, cross-disciplinary working is itself challenging due to the lack of a common language between the fields. For example, in our multidisciplinary team, considerable time was spent sharing conceptual and methodological knowledge and building a shared understanding of the phenomena under study. At the end of the study, neither side is an expert in the other field; however, we have developed ways of communicating and learning that enable us to tackle future research questions more effectively. From this perspective, we propose a fourth recommendation:

4. More concerted efforts to build an interdisciplinary network that fosters collaboration, cross-disciplinary learning, and the development of a common language for fMRI research on design. Currently, collaboration between design, psychology, and cognitive neuroscience tends to occur in an *ad hoc* way. Recent initiatives such as the Design Society's special interest group on Cognitive Design Science (The Design Society, 2021a) could help to facilitate more sustained connections. Networks such as this may also be able to establish training programmes in fMRI for design researchers, covering the basics of study design, data collection, analysis, and cross-disciplinary working.

3.2 Establishing a common cognitive design ontology

In order for fMRI to meaningfully advance our understanding of designing as a mental activity mediated by the brain, we must be able to link brain imaging results from fMRI studies to cognition and activities in the design process. As discussed in Section 2.4.3, there are limits on what brain activation can inherently tell us about cognition through reverse inference. Instead, we need robust knowledge about cognition during design activities as the starting point for formulating questions about brain activation (and study designs to answer them).

As discussed in (blind citation_b), there is considerable variation in the concepts and terminology used to describe cognition by design researchers. It is not clear what processes exist in this domain, and how they should be defined for study. A related issue is that the concepts and terminology used by design researchers frequently do not align with the ontology of cognitive psychology and neuroscience. The work reported in (blind citation_b) suggests that whilst there may be some cognitive processes unique to design, the fields do share numerous constructs. Thus, research on related activities such as creative thinking, problem solving, and decision making in cognitive psychology/neuroscience could support design researchers in conceptualising fMRI studies and interpreting findings. However, the lack of ontological alignment currently presents a barrier.

To address the above challenges, our main recommendation is the development of a common ontology of cognitive processes in design that aligns with the ontology of cognitive psychology/neuroscience. This would provide a shared and consistent basis for developing studies and interpreting/positioning the results, and increase comparability as discussed in Section 3.1. It would also enable design researchers to integrate their findings with broader theories of human cognition and brain function. Likewise, it would enable cognitive psychologists and neuroscientists to draw from design research in their work on creativity, and perhaps begin to address some of their own challenges – e.g. the lack of knowledge on creative professionals such as designers. In (blind citation_b), we conducted an initial mapping between constructs in design cognition research and psychology to produce a generic classification of processes involved in conceptual design activities. However, further ontological development is needed to identify and refine constructs across the design process. Work by Poldrack et al. (2011) in cognitive neuroscience could potentially provide a model for this.

3.3 Establishing foundational knowledge on regions of neural activation in design

As discussed in Section 1, fMRI design studies to date have focused on a narrow range of activities and domains. Limited existing knowledge about the neural regions underpinning designing can make it difficult to formulate specific hypotheses and identify regions of interest for analysis. It is likely that design activities neurally overlap with activities in other contexts, and existing studies have highlighted potential similarities and differences compared with decision making, problem solving, and ideation tasks in other contexts. However, the extent of overlap/distinction is unclear, and there is a lack of empirical evidence. There is also a lack of knowledge on functional overlap between different groups of designers. While different activities and design domains have been compared by Vieira et al. (2019) and Vieira et al. (2020) using EEG, it is difficult to draw conclusions about neural localisation (and hence overlap) using this method.

Foundational knowledge about the neural regions involved in design activities will clearly expand as the field continues to grow. Nonetheless, we propose three recommendations to foster and promote this critical activity:

1. More exploratory studies are required to provide an initial view on brain activation in different design activities, across different designers (including experts versus novices), and in different design domains (e.g. product design, engineering design, architectural design). Systematic comparisons between designing and related activities, and between designers and non-designers, are also needed to generate empirical evidence on the extent of neural overlap. Building up integrated knowledge across these aspects is a critical step towards general models and theories of design neurocognition. Furthermore, without this foundational knowledge, it is difficult to investigate more complex topics (e.g. decoding the information content of brain activity patterns).

2. As foundational knowledge is generated, there must be a concerted effort by authors to connect their work with other design fMRI studies as well as studies in relevant areas of cognitive neuroscience. This includes relationship-building via the interpretation of findings, but also extending existing knowledge by testing new hypotheses.

3. Sharing fMRI data on design through open access repositories (such as those mentioned in Section 3.1) should be strongly encouraged. This could potentially speed up the theory building cycle by facilitating further analysis of data, detailed meta-analyses across studies, and replication studies. All of these activities require reporting transparency, as discussed in Section 3.1.

A key goal of design research generally is to create impact for design practice. In this respect, a fourth recommendation for fMRI research on design is to begin to explore and define its practical applications and impact. For example, it is possible that fMRI results could inform the development of new design tools based on neurotechnologies – e.g. by highlighting brain regions to be targeted in brain-computer interfaces (blind citation_e) and neurofeedback systems (Shealy et al., 2020). This is an important open question for design neurocognition research generally.

3.4 Balancing fMRI constraints and ecological validity

As conveyed in Section 2, study development can involve a number of trade-offs between fMRI constraints and ecological validity (i.e. the extent to which the study reflects the natural thinking and behaviour of a designer). Most fundamentally, an MRI scanner is a noisy, enclosed, uncomfortable setting. This can reduce even the most proficient designer's performance below their natural capabilities. Screening can be used to filter out designers who cannot perform under these conditions, and training can be provided. However, the conditions themselves cannot be changed without advancements in scanning technology.

Some key trade-offs arise around the activity of sketching, as discussed in Section 2.2.3. Other trade-offs relate to the temporal characteristics of designing. Design activities can unfold in a non-linear way over minutes, hours, days, weeks, months, and even years. In contrast, fMRI is typically used to study processes lasting seconds to minutes, with short tasks that are systematically repeated many times to enable differences in the fMRI signal between conditions to be detected. Additionally, it is not feasible to ask a designer to carry out design tasks in an MRI scanner for more than around an hour due to discomfort and fatigue. It is quite possible that cognitive processing under these conditions differs from processing in more naturalistic settings. This raises questions about how generalisable current fMRI findings are to designing outside of the lab.

Overall, balancing empirical constraints and ecological validity is perhaps one of the most significant challenges for fMRI research on design. Overcoming the issues in many cases requires longer term advances in scanning technology. However, as indicated in Section 2 and above, solutions can in some cases be found through innovative experimental approaches and the use of increasingly available MRI-safe technology (e.g. sketching tablets). More advanced fMRI techniques may also open up avenues for more ecologically valid design studies. For instance, hyperscanning (simultaneous MRI scanning of more than one person) may enable the study of team-based design activities (Czeszumski et al., 2020), reflecting the frequently collaborative nature of designing "in the wild" (Ball & Christensen, 2018: p1). As such, our key recommendation for increasing ecological validity in the immediate future is more exploratory work to develop and pilot novel approaches for fMRI research on design. This will require collaboration between design researchers and cognitive neuroscientists as discussed in Section 3.1, and openly sharing the findings to promote learning and uptake in the wider community.

4 Conclusion

Functional magnetic resonance imaging (fMRI) enables identification of the brain regions and networks underpinning cognitive tasks. This method has the potential to significantly advance our understanding of design as a cognitive activity mediated by the brain, but is challenging to apply due to the involvement of constraints that clash with some of the characteristics of designing. Furthermore, there is a lack of clear guidance on how it can be applied as a design research method. There is no singular 'fMRI methodology' for design studies, as fMRI involves a variety of paradigms and techniques. However, there is a need for a general framework to provide direction on the key activities involved and how they can impact the quality of results.

In this Research Note, we reflect on our own experiences and the work of others to outline the phases and activities involved in developing and executing fMRI design studies. The resulting process is centred around particular approaches to fMRI data collection and analysis, drawing from the focus of existing work. However, it provides the initial underpinnings for a more comprehensive framework, and an introductory overview for design researchers new to fMRI.

We hope that other researchers will continue the dialogue sparked in this paper, adding their own perspectives and experiences towards the development of a shared and continually-evolving framework for fMRI design studies. To provide a springboard for this discussion, we also outline four key challenges for fMRI research on design and recommendations for how we might start to address them as a community. Four critical areas are identified: establishing experimental protocols; establishing a cognitive design ontology; generating foundational knowledge about brain activation; and balancing fMRI constraints against ecological validity.

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Details removed for peer review.

Data statement

Details removed for peer review.

References

Blind citation_a (details removed for peer review).
Blind citation_b (details removed for peer review).
Blind citation_c (details removed for peer review).
Blind citation_d (details removed for peer review).
Blind citation_e (details removed for peer review).
Blind citation_f (details removed for peer review).
Alexiou, K., Zamenopoulos, T., Johnson, J. H., & Gilbert, S. J. (2009). Exploring the neurological basis of design cognition using brain imaging: some preliminary results. *Design Studies*, *30*(6), 623–647. https://doi.org/10.1016/j.destud.2009.05.002
Apps, M. A. J., Rushworth, M. F. S., & Chang, S. W. C. (2016). The Anterior Cingulate Gyrus and Social Cognition: Tracking the Motivation of Others. *Neuron*, *90*(4), 692–707. https://doi.org/10.1016/j.neuron.2016.04.018
Ashburner, J., Barnes, G., Chen, C.-C., Daunizeau, J., Flandin, G., Friston, K., Jafarian, A., Kiebel, S., Kilner, J., Litvak, V., Moran, R., Adeel, W. P., Klaas, R., Sungho, S., Zeidman, T. P., Gitelman, D., Henson, R., Hutton, C., Glauche, V., … Phillips, C. (2020). *SPM12 Manual*. https://www.fil.ion.ucl.ac.uk/spm/
Ball, L. J., & Christensen, B. T. (2018). Designing in the wild. *Design Studies*, *57*, 1–8. https://doi.org/10.1016/J.DESTUD.2018.05.001
Bandettini, P. A. (2012). Twenty years of functional MRI: The science and the stories. *NeuroImage*, *62*(2), 575–588. https://doi.org/10.1016/j.neuroimage.2012.04.026
Binder, J. R., & Desai, R. H. (2011). The neurobiology of semantic memory. *Trends in Cognitive Sciences*, *15*(11), 527–536. https://doi.org/10.1016/j.tics.2011.10.001
Cross, N. (2004). Expertise in design: an overview. *Design Studies*, *25*(5), 427–441. https://doi.org/10.1016/J.DESTUD.2004.06.002
Czeszumski, A., Eustergerling, S., Lang, A., Menrath, D., Gerstenberger, M., Schuberth, S., Schreiber, F., Rendon, Z. Z., & König, P. (2020). Hyperscanning: A Valid Method to Study

Neural Inter-brain Underpinnings of Social Interaction. *Frontiers in Human Neuroscience*, *14*. https://doi.org/10.3389/fnhum.2020.00039

Design Research Society. (2021). *Design Research Society Digital Library*. https://dl.designresearchsociety.org/

Desmond, J. E., & Glover, G. H. (2002). Estimating sample size in functional MRI (fMRI) neuroimaging studies: Statistical power analyses. *Journal of Neuroscience Methods*, *118*(2), 115–128. https://doi.org/10.1016/S0165-0270(02)00121-8

Friston, K. J., Price, C. J., Fletcher, P., Moore, C., Frackowiak, R. S. J., & Dolan, R. J. (1996). The Trouble with Cognitive Subtraction. *Neuroimage*, 97–104.

Fu, K. K., Sylcott, B., & Das, K. (2019). Using fMRI to deepen our understanding of design fixation. *Design Science*, *5*. https://doi.org/10.1017/dsj.2019.21

Glover, G. H. (2011). Overview of functional magnetic resonance imaging. *Neurosurgery Clinics of North America*, *22*(2), 133–139. https://doi.org/10.1016/j.nec.2010.11.001

Goucher-Lambert, K, Moss, J., & Cagan, J. (2017). Inside the mind: using neuroimaging to understand moral product preference judgments involving sustainability. *ASME Journal of Mechanical Design*, *139*(4), 041103–041103–041111. https://doi.org/https://dx.doi/org/10.1115/1.4035859

Goucher-Lambert, Kosa, & McComb, C. (2019). Using Hidden Markov Models to Uncover Underlying States in Neuroimaging Data for a Design Ideation Task. *Proceedings of the Design Society: International Conference on Engineering Design*, *1*(1), 1873–1882. https://doi.org/10.1017/dsi.2019.193

Goucher-Lambert, Kosa, Moss, J., & Cagan, J. (2019). A neuroimaging investigation of design ideation with and without inspirational stimuli—understanding the meaning of near and far stimuli. *Design Studies*, *60*, 1–38. https://doi.org/10.1016/J.DESTUD.2018.07.001

Harrington, M. (2020). *The Design of Experiments in Neuroscience* (3rd ed.). Cambridge University Press.

Havsteen, I., Ohlhues, A., Madsen, K. H., Nybing, J. D., Christensen, H., & Christensen, A. (2017). Are movement artifacts in magnetic resonance imaging a real problem? A narrative review. *Frontiers in Neurology*, *8*(232). https://doi.org/10.3389/fneur.2017.00232

Hu, M., Shealy, T., & Milovanovic, J. (2021). Cognitive differences among first-year and senior engineering students when generating design solutions with and without additional dimensions of sustainability. *Design Science*, *7*, 1–30. https://doi.org/10.1017/dsj.2021.3

Hurlburt, R. T., Alderson-Day, B., Fernyhough, C., & Kühn, S. (2015). What goes on in the resting-state? A qualitative glimpse into resting-state experience in the scanner. *Frontiers in Psychology*, *6*(OCT), 1535. https://doi.org/10.3389/fpsyg.2015.01535

Hyatt, C. S., Owens, M. M., Crowe, M. L., Carter, N. T., Lynam, D. R., & Miller, J. D. (2020). The quandary of covarying: A brief review and empirical examination of covariate use in structural neuroimaging studies on psychological variables. *NeuroImage*, *205*. https://doi.org/10.1016/j.neuroimage.2019.116225

Jia, W., & Zeng, Y. (2021). EEG signals respond differently to idea generation, idea evolution and evaluation in a loosely controlled creativity experiment. *Scientific Reports*, *11*(1), 1–20. https://doi.org/10.1038/s41598-021-81655-0

Lindquist, M. A. (2008). The Statistical Analysis of fMRI Data. *Statistical Science*, *23*(4), 439–464. https://doi.org/10.1214/09-STS282

Miall, R. C., Nam, S. H., & Tchalenko, J. (2014). The influence of stimulus format on drawing-a functional imaging study of decision making in portrait drawing. *NeuroImage*, *102*, 608–619. https://doi.org/10.1016/j.neuroimage.2014.08.015

Monti, M. (2011). Statistical Analysis of fMRI Time-Series: A Critical Review of the GLM

Approach. *Frontiers in Human Neuroscience*, *5*(MARCH), 28. https://doi.org/10.3389/fnhum.2011.00028

Mumford, J. A., & Nichols, T. E. (2008). Power calculation for group fMRI studies accounting for arbitrary design and temporal autocorrelation. *NeuroImage*, *39*(1), 261–268. https://doi.org/10.1016/j.neuroimage.2007.07.061

National Institute of Mental Health. (2021). *AFNI (Analysis of Functional NeuroImages)*. https://afni.nimh.nih.gov/

Nguyen, P., Nguyen, T. A., & Zeng, Y. (2018). Empirical approaches to quantifying effort, fatigue and concentration in the conceptual design process. *Research in Engineering Design*, *29*(3), 393–409. https://doi.org/10.1007/s00163-017-0273-4

OpenNeuro. (2021). *OpenNeuro: A free and open platform for sharing MRI, MEG, EEG, iEEG, ECoG, and ASL data*. https://openneuro.org/

Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences*, *10*(2), 59–63. https://doi.org/10.1016/j.tics.2005.12.004

Poldrack, R. A. (2011). Inferring mental states from neuroimaging data: from reverse inference to large-scale decoding. *Neuron*, *72*(5), 692–697. https://doi.org/10.1016/j.neuron.2011.11.001

Poldrack, R. A., Fletcher, P. C., Henson, R. N., Worsley, K. J., Brett, M., & Nichols, T. E. (2008). Guidelines for reporting an fMRI study. *NeuroImage*, *40*(2), 409–414. https://doi.org/10.1016/j.neuroimage.2007.11.048

Poldrack, R. A., Kittur, A., Kalar, D., Miller, E., Seppa, C., Gil, Y., Parker, D. S., Sabb, F. W., & Bilder, R. M. (2011). The cognitive atlas: toward a knowledge foundation for cognitive neuroscience. *Frontiers in Neuroinformatics*, *5*, 1–11. https://doi.org/10.3389/fninf.2011.00017

Schaer, K., Jahn, G., & Lotze, M. (2012). FMRI-activation during drawing a naturalistic or sketchy portrait. *Behavioural Brain Research*, *233*(1), 209–216. https://doi.org/10.1016/j.bbr.2012.05.009

Shealy, T., Gero, J., Hu, M., & Milovanovic, J. (2020). Concept generation techniques change patterns of brain activation during engineering design. *Design Science*, *6*, 1–27. https://doi.org/10.1017/dsj.2020.30

Shealy, T., Gero, J., Milovanovic, J., & Hu, M. (2020). Sustaining Creativity With Neuro-Cognitive Feedback: a Preliminary Study. *6th International Conference on Design Creativity (ICDC)*, 84–91. https://doi.org/10.35199/icdc.2020.11

Smith, S. M. (2004). Overview of fMRI analysis. *The British Journal of Radiology*, *77*, 167–175. https://doi.org/10.1259/bjr/33553595

Soares, J. M., Magalhães, R., Moreira, P. S., Sousa, A., Ganz, E., Sampaio, A., Alves, V., Marques, P., & Sousa, N. (2016). A Hitchhiker's guide to functional magnetic resonance imaging. *Frontiers in Neuroscience*, *10*, 515. https://doi.org/10.3389/fnins.2016.00515

Sosa, R. (2018). Metrics to select design tasks in experimental creativity research. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *0*(0), 1–11. https://doi.org/10.1177/0954406218778305

Sylcott, B., Cagan, J., & Tabibnia, G. (2013). Understanding Consumer Tradeoffs Between Form and Function Through Metaconjoint and Cognitive Neuroscience Analyses. *Journal of Mechanical Design*, *135*(10), 101002-1-101002–101013. https://doi.org/10.1115/1.4024975

The Design Society. (2021a). *Cognitive Design Science Special Interest Group*. https://cognitive.designsociety.org/

The Design Society. (2021b). *Thesis repository*.

https://www.designsociety.org/group/33/Thesis+repository

van den Heuvel, M. P., & Hulshoff Pol, H. E. (2010). Exploring the brain network: A review on resting-state fMRI functional connectivity. *European Neuropsychopharmacology*, *20*(8), 519–534. https://doi.org/10.1016/j.euroneuro.2010.03.008

van Kemenade, B. M., Arikan, B. E., Podranski, K., Steinsträter, O., Kircher, T., & Straube, B. (2019). Distinct Roles for the Cerebellum, Angular Gyrus, and Middle Temporal Gyrus in Action–Feedback Monitoring. *Cerebral Cortex*, *29*(4), 1520–1531. https://doi.org/10.1093/cercor/bhy048

Vieira, S., Gero, J. S., Delmoral, J., Gattol, V., Fernandes, C., Parente, M., & Fernandes, A. A. (2020). The neurophysiological activations of mechanical engineers and industrial designers while designing and problem-solving. *Design Science*, *6*, 1–35. https://doi.org/10.1017/dsj.2020.26

Vieira, S. L. da S., Gero, J. S., Delmoral, J., Gattol, V., Fernandes, C., & Fernandes, A. A. (2019). Comparing the Design Neurocognition of Mechanical Engineers and Architects: A Study of the Effect of Designer's Domain. *Proceedings of the Design Society: International Conference on Engineering Design*, *1*(1), 1853–1862. https://doi.org/10.1017/dsi.2019.191

Wellcome Centre for Human Neuroimaging. (2021). *SPM - Statistical Parametric Mapping*. https://www.fil.ion.ucl.ac.uk/spm/

Zhao, M., Jia, W., Yang, D., Nguyen, P., Nguyen, T. A., & Zeng, Y. (2020). A tEEG framework for studying designer's cognitive and affective states. *Design Science*, *6*, 1–47. https://doi.org/10.1017/dsj.2020.28