Exploring the neurological basis of design cognition using brain imaging: some preliminary results

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The paper presents a pilot interdisciplinary research study carried out as a step towards understanding the neurological basis of design thinking. The study involved functional magnetic resonance imaging (fMRI) of volunteers while performing design and problem-solving tasks. The findings suggest that design and problem solving involve distinct cognitive functions associated with distinct brain networks. The paper introduces the methodology, presents the findings, and discusses the potential role of brain imaging in design research.

Keywords: design cognition, problem solving, design problems, research methods, cognitive neuroscience

Design is a natural human activity present in many professions (from engineering and architecture, to policy making) and a significant force for innovation and change in our societies. Despite the fact that the activity of design and the activity of science are tightly linked, design can be contrasted to science in that design is considered to be about imagining and synthesising new realities, rather than analysing and describing existing ones. Design can also be contrasted to art, as it is essentially guided by human purposes and is directed towards the fulfilment of intended functions. Design research as a domain of investigation therefore is by and large based on the assumption that design is a distinct discipline coupled with a distinct mode of thinking and knowing (Lawson, 1997; Cross, 2006).

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Although design is customarily taken to be a high level cognitive ability, and many empirical and computational studies are focussed on design cognition, there is to date very little research that touches on the biological or neurological basis of design (e.g. Cross, 1984, 1990; Goel and Grafman, 2000; Vartanian and Goel, 2005). On the other hand, there are many neurological studies that focus on creativity and aesthetics in art (e.g. Ramachandran

www.elsevier.com/locate/destud
0142-694X $ - see front matter *Design Studies* **30** (2009) 623–647
doi:10.1016/j.destud.2009.05.002

and Hirstein, 1999; Zeki, 1999; Martindale et al., 2007), but not on recognising or characterising design as a distinct cognitive phenomenon. The gap is to an extent due to the fact that researchers have until recently lacked the tools for approaching this subject. However, with new techniques for imaging brain activity becoming more widely available, this now presents a significant opportunity for exploration. Interdisciplinary research combining insights from design studies and cognitive neuroscience can be instrumental for testing a variety of hypotheses crucial for design research: for example, whether design thinking is distinct from artistic or scientific thinking, and whether design is essentially a social ability. There may be many objections from the design community to the idea that neurological research can offer important insights into design. Investigating these objections (and trying to refute or justify them) is a significant feat in itself and an important question from which to start an exploration into this area.

The paper presents a pilot interdisciplinary research study carried out as a step towards understanding the neurological activity that is associated with the capacity to recognise and carry out design tasks. Such study has a potentially dual contribution. It can help generate and test hypotheses about the nature of design activity, hence contributing to design theory, but it can also help generate and test hypotheses about the role and function of different brain areas, thus contributing to cognitive neuroscience. The paper draws on, and targets, both domains of knowledge but the focus is by and large in the first area.

1 *Cognitive neuroscience and design*

Cognitive neuroscience uses various methods, including behavioural tests and brain imaging techniques to investigate the neural basis of cognition, and particularly to understand how cognitive functions are supported by different brain areas. Contemporary cognitive science generally considers that (at a smaller or greater extent) the brain has a modular organization, meaning that it is 'structurally and functionally organized into discrete units of ''modules'' and that these components interact to produce mental activities' (Gazzaniga, 1989, p. 947). Much of our knowledge about functional specialisation is derived from studies of people with damage to specific brain regions. Matching structural abnormalities with specific behavioural abnormalities or performance impairments is particularly instructive for understanding the anatomical and functional organization of the brain. Such studies can demonstrate remarkably specific deficits following brain damage (Shallice, 1988), for example impairment in recognising faces but not other types of visual stimuli (McNeil and Warrington, 1993), or impairment of short-term but not long-term memory (Shallice and Warrington, 1970). Results such as these can influence both psychological theories of the mental processes that contribute to various abilities, and neuroscience accounts of how these processes relate to the function of specific brain areas.

Cognitive neuroscience studies of course do not only focus on people with brain lesions, or developmental brain disorders. Another area of research is focussed on capturing brain activity during the performance of certain cognitive tasks. At the core of such research is developing experimental paradigms that allow making correlations between brain activity and cognitive activity. Most brain imaging research involves comparing brain activity associated with two or more tasks performed by the same participants (e.g. paying attention to shapes versus colours, or performing a verbal versus a visual task). A common approach is 'cognitive subtraction', where a pair of tasks is administered. The two tasks are similar in all respects except that only one task involves mental process X (e.g. looking at black and white versus colour photographs, to investigate colour perception). Differences between the two tasks, say in brain region A, would suggest that this region supports process X. An alternative approach is to compare two or more groups of participants performing the same tasks (e.g. Calvo-Merino et al., 2005), for example to investigate the effects of expertise on the brain. Such research greatly informs the development of hypotheses about the involvement of different brain regions in certain cognitive abilities.

Functional Magnetic Resonance Imaging or fMRI, which is the brain imaging technique used in this study, was developed at the beginning of the 1990s (Ogawa et al., 1990). In contrast to typical brain MRI which uses magnetic and radio waves in order to visualize the 'structure' (or form) of the brain, fMRI captures changes in blood oxygenation which are associated with neural activation, thus aiming to capture the 'function' of the brain. The fMRI technique is non-invasive and has particularly good spatial resolution (picking up activity at the level of voxels of around 2–4 mm). The use of fMRI in cognitive science is one of the more rapidly growing areas of research focussing on the identification of brain areas that are specifically associated with different cognitive functions (Cabeza and Nyberg, 2000).

Certainly, localization of cognitive functions is not straightforward; it is often the case that a number of spatially distributed areas in the brain work together during a cognitive task, and so determining the interaction between different regions becomes of critical importance. Additionally, it is possible that the same cognitive process may be performed by recruiting different networks of neurons; and so it may not be possible to discover a unique association between certain functions and structures in the brain. Nonetheless, fMRI research is particularly well-suited to the investigation of the spatial organization of brain processes supporting cognitive functions and has already contributed greatly to the understanding of the neurological basis of cognitive abilities. Knowledge of the specialised function of certain areas can help us unpick certain characteristics of design cognition and inform design theory. Such research allows us to empirically examine existing theories about design cognition, and generate hypotheses about the role and importance of different cognitive abilities or functions, such as verbal, visual and spatial reasoning, abstract thinking, creativity, memory and emotion. Take for example visual cognition: design research has studied visual cognition through psychological or behavioural studies, and has formulated theories about the primacy of visual reasoning in design thinking and creativity (e.g. Schön and Wiggins, 1992; Oxman, 2002). Previous neuroscience and brain imaging studies have generated important evidence associating specific brain regions with visual cognition. By monitoring and comparing the activation of these regions during design and non-design we can then further explore the role and importance of visual thinking in design and its relation to other types of cognitive functions, thus providing additional evidence to support or refute theoretical hypotheses. Understanding the relationship and role played by different brain regions during design is also important for design education and the development of teaching and learning curricula. For instance, different brain regions are known to be developed at different timescales and at different stages in a child's development. Unravelling the association of design thinking with the activation of different brain regions may help us make more informed decisions about teaching design and creative problem-solving abilities in schools.

Let us consider some previous research in cognitive neuroscience which is relevant to our study and discuss how it can help study design cognition.

1.1 Related work

Of relevance to our exploration of the neurological basis of design is research concerned with the understanding and localization of functions such as planning, problem solving and creative thinking. Existing research commonly recognises that the prefrontal cortex represents the neural basis of high order cognitive functions, and is involved in complex planning and problem-solving – abilities often tested with tasks like the Tower of London or Tower of Hanoi puzzles (e.g. Goel and Grafman, 1995; Baker et al., 1996; Fincham et al., 2002; Gilbert and Burgess, 2008). More generally, the prefrontal cortex is thought to be important in situations where the mapping between stimuli and action is uncertain, novel or undefined, and seems to play the role of formulating new schemata (goals and means) for creating such stimulus–response relations (Shallice and Burgess, 1996; Miller and Cohen, 2001). Creative thinking is also largely attributed to the activation of brain circuits in the prefrontal cortex, although other areas such as the temporal lobe are also found to be involved (see Dietrich, 2004). Studies of creative cognition often focus on an isolated mental process or ability, such as insight, imagery, generation of novel words or stories, divergent thinking, hypothesis generation and set-shifting (e.g. Bowden et al., 2005; Howard-Jones et al., 2005; Vartanian and Goel, 2005).

These studies are very relevant but do no specifically seek to discover the neural correlates of design cognition. How can we put under 'neurological' scrutiny the assumption that design is associated with a characteristic/distinguishable way of thinking and knowing? How can we set apart design from other high level cognitive abilities? For instance, although creativity is a desirable characteristic of design, and exceptional designers are creative thinkers, it is not a necessary condition for design. This point is advanced by reference to a distinction between routine, non-routine and creative design problems and tasks − see Gero (2000). Additionally, creativity is not a condition *unique* to design as it is also involved in scientific as well as artistic creation.

1.2 Distinguishing design activity

From the point of view of cognitive neuroscience, we need to devise an experimental setting that will allow us to compare design with another closely related cognitive function, measure the accompanying brain activity, and correlate differences in brain activity with differences in cognitive activity. To decide how to do this it is necessary to resort to design theory. In the design literature, design is most commonly defined in relation to problem solving. Although there is some ambiguity as to whether design is a special case of problem solving or a completely distinct mode of thinking, the distinguishing characteristics of design are more or less generally agreed. One way to distinguish design is with regards to the notions of problem and solution space. Generally, the problem space represents a set of requirements and the solution space represents a set of constructions that satisfy these requirements. In problem-solving theory, the problem space is a representation of a set of possible states, a set of 'legal' operations, as well as an evaluation function or stopping criteria for the problem-solving task (e.g. Ernst and Newell, 1969; Newell and Simon, 1972). The solution space incorporates all those solutions that achieve the requirements expressed by the problem space. According to this view, design problems are ill-defined problems, in the sense that the means (i.e. the representation of the problem space and the possible operations over the problem space), as well as the ends (i.e. the evaluation function or the stopping criteria) are not given in the task environment but are part of the design process (Simon, 1973; Goel and Pirolli, 1992). Other researchers prefer to talk about the mutual influence between problem and solution in design tasks: while problem solving supposes the existence of a defined problem that circumscribes the solution, designing involves defining the problem together with the solution (Dorst and Dijkhuis, 1995; Dorst and Cross, 2001). For this reason, design problems are often characterised as 'wicked' problems (Rittel and Webber, 1984), a notion that incorporates the idea that such problems are open-ended; they do not have a single, optimal solution; and require subjective interpretation and evaluation. In the following, we take the distinction between design and (well-defined) problem solving as the basis for our investigation.

2 Main concepts and methodological approach

So, to test the hypothesis that design activity can be distinguished from problem solving on a neurological basis, we propose an experimental setting where subjects are asked to perform two types of tasks while in the fMRI scanner: one that corresponds to problem solving and one that corresponds to design.

In the problem-solving tasks a criterion for deciding the termination of the task is given, as well as a definition of legal moves. Although a problem-solving task may require creative thinking and hypothesis formation or inductive reasoning, the problem itself is well-defined, the legal moves are known and the solution is unique (i.e. there is a unique set of equivalent solutions). A sample problem solving task is shown in Figure 1.

In the design tasks there is no predetermined final state or criterion for deciding the termination of the task (the task is open-ended). The task requires defining the problem as well as the solution space: it requires the creation and interpretation of a set of moves, as well as the creation of a function (criteria) for evaluating the solution. A sample design task is shown in Figure 2.

It is important to note here that as mentioned above, design researchers take different views about the relation, or difference, between design and problem solving. Some see design as part of problem solving, while others see the two as separate paradigms. Additionally, the picture can become more complex if we assume that during a task one may employ both types of thinking. The unique difference between the two types of tasks as defined above is that the design task requires not only generation of solutions but also interpretation of the problem requirements and definition of the criteria for evaluating the solution. This view resonates strongly with many design researchers' views about design and its potential difference with (well-defined) problem solving (see also Dorst, 2006). The distinction between well-defined problem-solving tasks and design tasks has a methodological role in this study: it allows us to identify whether the two tasks are accompanied with different patterns of

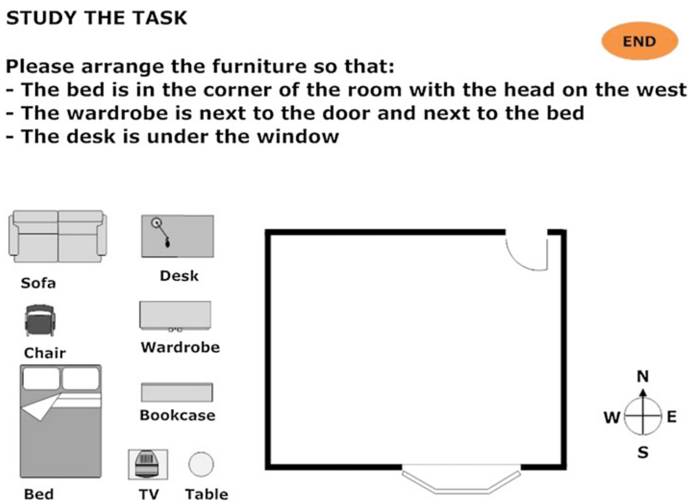

Figure 1 An example of a problem-solving task used in the experimentation

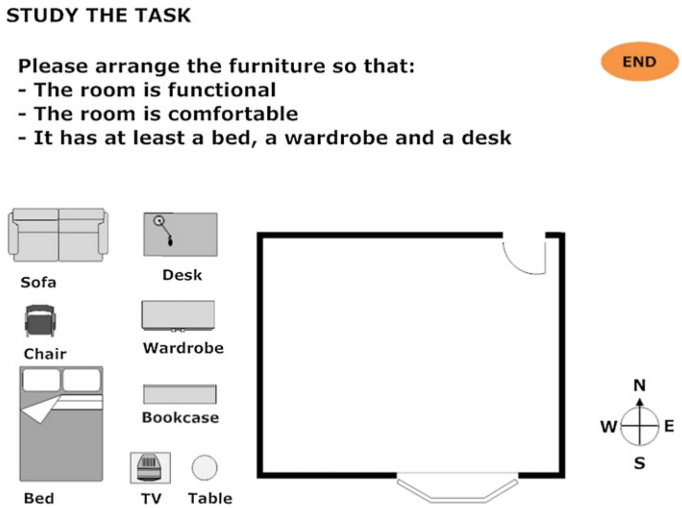

Figure 2 An example of a design task used in the experimentation. The problem-solving task in Figure 1 and the design stimuli shown here are devised so that they match each other as closely as possible

brain activation and therefore associate these differences with differences in cognitive functions. However, it is not necessary to assume a strict separation between design and problem-solving tasks to interpret the present results. Even if the two types of task are considered to vary along a continuum, with the design tasks being relatively ill-defined in comparison with the problem-solving tasks, a cognitive subtraction between the two will reveal brain areas more strongly engaged in solving ill-defined design problems.

The distinction between problem solving and design may be clear enough in these terms, but the precise definition and creation of appropriate problem-solving and design tasks is far from straightforward. As mentioned, previous research using brain imaging has tended to focus on very specific, isolated contrasts, for example convergent versus divergent thinking. The aim of this project was to take a richer, more holistic view of what constitutes a design problem or task. Hence, tasks had to be complex enough to qualify as 'prototypical' design tasks, yet simple enough to be solvable within the time constrains imposed by the brain imaging methodology (i.e. within a matter of seconds).

The greatest challenge was matching problem-solving and design tasks as closely as possible in terms of difficulty, number of constraints, and time, so that we can ensure that any observed differences in the participants' responses are due to the nature of the tasks rather than other extraneous differences. For instance, in the sample pair of tasks above, care is taken so that the stimuli are identical, the number of instructions and the cognitive effort needed to understand them are as close as possible, and that the time required for their resolution is similar.

In this way we can assume that any differences in brain activation during problem-solving and design tasks can be attributed to differences in cognitive activity. Based on the studies briefly mentioned previously, we expect to find heightened activation in the prefrontal cortex, but when we contrast design with problem solving, we expect to discover activation in areas associated specifically with the additional need for generation, evaluation and interpretation of goals and appropriate problem formulations.

Note that the particular tasks shown in the figures are essentially spatial in nature and very close to the type of task that has been employed to empirically study design cognition since the 60s (e.g. Eastman, 1968, 1969). However, the set of tasks used in the experiment were designed so as to equally include other more visual or abstract reasoning tasks (e.g. graphic design, reasoning with abstract shapes etc). To evaluate the appropriateness of the tasks chosen, and ensure that the level of difficulty and time given was apposite, we conducted semi-structured interviews after the end of the scanning sessions to elicit participants' views. The tasks, the experimental setting and the results from the participants' evaluation are discussed in more detail in the next sections.

2.1 The experimental set up

The pilot fMRI study was performed with the participation of eighteen subjects. There were eleven female and seven male participants aged 27–60 (the mean age was 37.3). All participants had some experience and familiarity with design, and ten of them had formal training in a design discipline (architecture, multi-media or graphic design, interior design, product design, art etc). The study was carried out in accordance with an ethics approval granted by the Ethics Committee of the Open University and in accordance with guidelines of the British Psychological Society and the Data Protection Act 1998.

Imaging was performed with a Siemens TIM Avanto 1.5 T MRI scanner. A head coil was placed on the top of the head of each participant. A mirror was attached to the head coil which allowed participants to view the stimuli projected clearly onto a screen hanging outside the magnet and within their visual field. Headphones were used to reduce the noise made by the scanner while in operation. The participants used a trackball mouse to click-and-drag objects displayed in order to fulfil a set of instructions presented to them (see figures above).

There were eight problem-solving and eight design tasks presented at an alternate order. To avoid any effects due to the order in which problem-solving and design tasks were presented we used a latin square design for ordering the tasks. This was a matrix with eight columns (representing eight participants) and sixteen rows (representing the number of tasks) defined so that no entry appears more than once in the same column or row. The same sequence was used for the next eight participants and so on. The stimuli (i.e. the set of items below the instructions) were exactly matched in the design and problem-solving conditions, so that each stimulus was encountered once in each condition. The order of tasks was counterbalanced between participants, so that there was no systematic bias in the order in which particular items were encountered in the two conditions. Each task involved two stages: a *study* phase, in which participants were given 30 s to read and understand the instructions but also start formulating their solutions, and a *performance* phase in which 50 s were given in order to carry out the task by using the trackball mouse. This two step study-perform process was introduced in order to balance the trade-off between time needed to complete a design task, and time required to obtain meaningful and good quality brain activation data from the scanner. By dividing the task in two stages we were able to more precisely isolate activation during design thinking, but also to increase the overall time needed to carry out each task. In design research and practice it is commonly held that designers think about the design solution during, or via, the process of formulating an external representation (e.g. a drawing, or a sketch) and so this division was considered to be somewhat artificial and was adopted in the experimental setting quite reluctantly. The retrospective interviews, however, showed that despite the unusualness of the setting, in the majority of the tasks the participants succeeded in formulating a (at least one) solution within the 30 s given, which also meant that the second stage was primarily (although not exclusively) used in order to perform the task by manipulating the objects on the screen. In-between tasks a rest period of 15 s was introduced as a baseline against which activation during task conditions can be measured.

Participants were also asked to note when they have finished their task by pressing a fake end button on the screen. Streaming video software was used to record the entire activity on the screen, and snapshots of the participants' solutions at the end of each 50 s interval were also automatically saved to inform the analysis process.

2.2 Evaluation of the experimental design

All the participants were briefly interviewed after they had completed the experiment. A list of questions had been drawn beforehand to guide the semi-structured interviews. The list contained questions about the overall experience, the process and the content of the experiment (Table 1).

Table 1 A list of initial questions used in the retrospective interviews

How was the experience? Did you feel claustrophobic?
How did you find the experiment?
Could you identify the existence of different kinds of tasks? What do you think the difference was?
Did you find that the design and problem-solving tasks had the same level of difficulty?
Do you think that the time given for each task was sufficient?
How would you rate your performance in each task, using a scale from 1 to 10?
Discuss how you approached the tasks (was there some evolution in the process, did you use some specific strategy)? Can you give some examples?
Do you have any suggestions for improving the experiment (both in terms of content and process)?

The first couple of questions attempted to solicit the participants' views about their overall experience and their level of comfort and enjoyment. Everyone who took part completed the experiment without interruptions due to discomfort or feeling of claustrophobia. They all found the experience worthwhile and interesting, although they felt that it is rather demanding physically. A couple of participants had to substitute their glasses with plastic ones for use inside the magnetic field, which after a while made them feel uncomfortable and distracted. None of them was distressed about being in the scanner. None of the participants found the noise to be excessively loud or unpleasant. Some participants found the experience particularly fun and stimulating (and a couple even found it comforting).

The participants were then asked to reflect on the tasks and their own cognitive process. They were also asked to indicate whether they thought they did think 'designerly' and whether they generally acted as they usually do when faced with a design task.

It is important to note that the participants were informed about the general aim of investigating design and problem-solving cognition, but were not informed in advance about the hypothesised difference between design and problem solving. So in the interview participants were asked whether they identified the existence of different types of tasks, and were invited to express their own perception of any difference.

All but three participants identified that there were two groups of tasks. According to the participants' own words, one group contained tasks which were 'more logical', 'more prescribed', or 'more objective'. In these tasks 'you had to follow the instructions', 'do what you were told', 'understand the rules and obey them'. The tasks 'were right or wrong' contained 'clear instructions' and had 'a finite answer'. The other group contained tasks which were more 'open-ended', 'free-style' or 'subjective'. In these tasks 'you had to use your own interpretation', 'think about more options, or more implications' 'take control of what you are doing' and 'decide how you interpret, how you want to create'. The tasks 'were more subjective, you couldn't say there was a right or wrong answer', they were 'open to interpretation' and required 'qualitative judgements'. As discussed, the aim of our experimental design was to have two distinct groups of tasks: the first was meant to include tasks for which the criteria for deciding when a solution is found would be given, as well as a definition of legal moves leading to the solution. The second was meant to consist of tasks which would be open-ended, and would require interpretation and evaluation of the criteria for deciding what constitutes a solution. The participants' observations confirm that our experimental design was successful in that respect.

Most of the participants also behaved in a different way to match the different tasks: in the problem-solving tasks they were more attentive to following the instructions and checking they comply to them, whereas in the design tasks they felt that were more ‘free’ to act, and allowed themselves to be more introspective and make their own evaluations. Despite the fact that the difference was identified by the participants, a few of them did not approach the two kinds of task in a different way. For example, one participant exceptionally approached both tasks as a challenge for doing something creative and always tried to question, or ‘break’ the instructions and what is permissible with the constraints given. Another saw them both as ‘tests’ which had to be completed within the time given, without attempting to do something out of the ordinary.

On questioning the appropriateness of the design tasks in particular, fifteen out of eighteen participants found that these were ‘typical’ design tasks, and indicated that they did approach them in the same way they normally do in their own practice. Three participants considered that the design tasks were not typical, either because the tasks were not elaborate enough (focussed perhaps on a particular area of design each time), or because they did not personally engage with them in a ‘designerly’ way, which would allow them to enter into an iterative design cycle. The participants were also asked to evaluate the task complexity or difficulty relevant to time and nearly all of them considered that the time given was appropriate for most of the tasks to be completed. Some said they wanted more time for one or two tasks.

The balance between complexity and time is an important point for discussion in this experiment. What seems to emerge from the participants’ responses is that the tasks were indeed characteristic at a basic level: they were complex enough to require thinking in typical design terms and the timing was sufficient for the participants to formulate one solution albeit perhaps not the most complete or satisfactory one. The consensus seems to be that most real-life design tasks would be more complex and would require a longer time to solve, but the experimental tasks presented to the participants were typical in a minimalist way, and thus appropriate for the purposes of this investigation.

The observation of some participants that the design tasks should be more complex, or more elaborate, together with the fact that the problem-solving tasks were perhaps considered to be easier, raises the question whether design tasks are in essence more complex. This is a very interesting question for further investigation, although we are inclined to consider that this distinction is tenuous; there are many problem-solving tasks which are themselves quite difficult and require considerable time to solve. We could argue then that complexity is perhaps a characteristic of design, but the characterisation itself should be categorical and not quantitative.

Another interesting observation that some participants made was that they would prefer to have more options available to them when formulating their solutions, for example, to have the option of manipulating colours or to have a larger choice of objects. This is understandable considering how designers work in practice and we had here to make concessions to be able to adhere to the technical and practical requirements of the experiment. Future investigations will have to further consider this issue, especially as the introduction or generation of more parameters/dimensions in a design problem (the enlargement of the problem space) is thought to be crucial for creative design. On the other hand of course, design tasks are inherently constrained in terms of resources (including materials and choice of objects) and it would be a mistake to equate design with having more choice. Thus particular emphasis was placed on having equal variety in the problem-solving and the design tasks in terms of choices and constraints.

The same argument in essence applies to the request for more time. Because of the nature of the fMRI studies, time was the biggest restriction in this experiment, but time is itself one of the usual constraints in the design process. One possible resolution would be to change the experimental protocol, for instance to incorporate a three-stage cyclic study-perform-evaluate process where participants are given additional time to reflect on their first solution and reformulate it. This would perhaps allow participants to think more critically about their responses and even enable them to seek more innovative solutions. On the other hand, this setting could also be considered as more prescriptive and imposing a particular practice or view of the design process.

Finally, it is worth noting that the participants were also asked to evaluate their solutions according to how happy or satisfied they were with each of them. The actual solutions that the participants proposed, and the results of the self-marking process, have not yet been systematically processed or used to inform our data analysis. The idea is to perhaps use them in the future to identify creative solutions and isolate creative individuals for further study of their data.

3 Results

The data obtained from the experiment were studied using SPM8, a statistical package developed by the Wellcome Trust Centre for Neuroimaging in UCL for the analysis of brain imaging data sequences. The software works within Matlab (Mathworks, Inc.). SPM involves procedures so that the images obtained from the MRI scanner are realigned in order to compensate head movements, and spatially normalised into a standard space, a template brain (the Montreal Neurological Institute MNI template), in order to be able to compare activation between participants. The data are also spatially smoothed in order to improve registration between participants and increase statistical reliability. For more details about SPM see Friston et al. (2007).

For data quality reasons, the data series from seventeen out of eighteen participants were used in the analysis. The analysis was carried out on the basis of comparison between different types of activity (or phases) defined in the experiment: studying (S), performing (P), studying design tasks (DS), studying problem-solving tasks (PS), performing design tasks (DP) and performing problem-solving tasks (PP). The software allows looking at the brain activation of participants at an aggregate level, and making comparisons so as to identify whether specific areas are more activated during particular phases. *T* tests were performed in order to evaluate the statistical significance of the results, using an uncorrected threshold of $p < 0.001$.

3.1 Studying versus performing

First, we compared activation during the study and the performance phases irrespective of whether participants were engaged in design or problem solving. In other words we examined which areas are more activated during the study phase compared to the performance stage (S > P) and vice versa (P > S). The results show a clear pattern of activation differentiating the two phases (Figure 3). The performance phase shows heightened activation in areas in the premotor cortex (associated with the planning of movement), primary somatosensory cortex (associated with touch) and cerebellum (associated with the integration of sensory perception, coordination and control of movement). The study phase, in contrast to the performance phase, shows heightened activation in areas in the anterior and dorsal prefrontal cortex (which as we discussed is involved in high level cognitive processes), the secondary visual

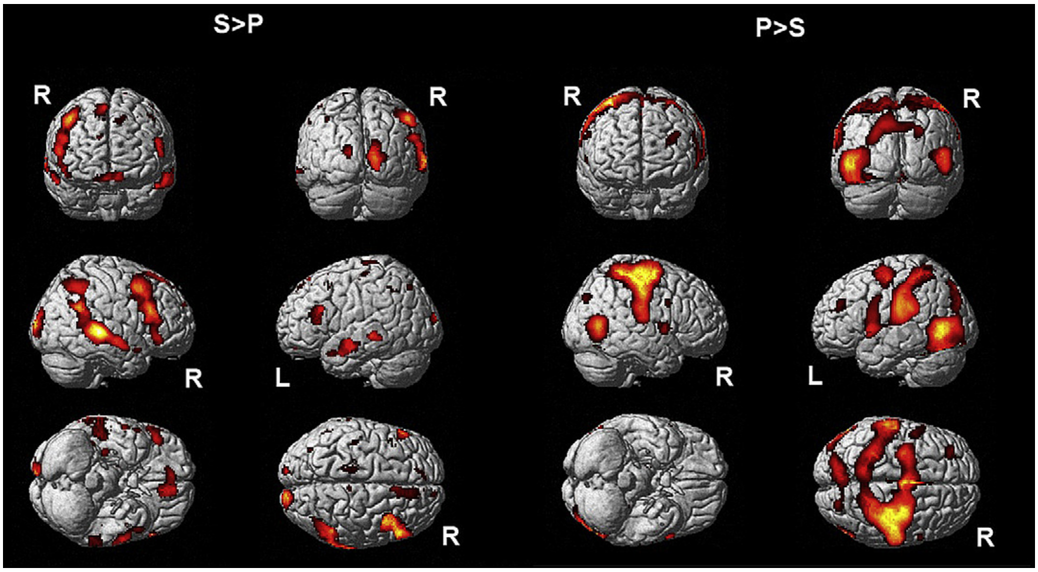

Figure 3 3D brain images produced from statistical parametric maps showing activation when comparing studying versus performing (left), and performing versus studying (right) (p < 0.001). The top row shows anterior and posterior views, the middle row shows lateral views and the bottom row shows inferior and superior views cortex, and areas associated with language. The results reflect the experimental separation of the tasks in two distinct phases, and confirm the hypothesis that during the study phase the participants were primarily involved in thinking about problems and solutions, while in the performance phase they were primarily engaged in carrying out their solutions by using the mouse.

The analysis shows that the two phases are accompanied with elevated activation in different parts of the premotor cortex (Brodmann Area 6 or BA6). The literature suggests that motor and premotor areas of the brain are activated not only when we perform particular movements, but also when we observe or imagine them (Grafton et al., 1997; Hari et al., 1998; Lotze et al., 1999). But what does the involvement of the premotor cortex in S > P mean? Is the premotor cortex involved just in preparation for action or does it indicate some form of 'embodied' cognition, implying that body movement and body perception are an essential part of our cognitive activity? For a discussion on embodied cognition and different views of how body interaction with the world may take part in cognition see Wilson (2002). The experiments reported here are to our knowledge unique in that they reconstruct (to some minimal extent) typical design and problem-solving situations where the subjects are able to develop their solutions through an interaction with an external representation (a 'drawing'). We may therefore hypothesise that it is this task environment that exposes the involvement of premotor cortex functions. Another observation is while the highly activated premotor areas in the performance phase are medial, the highly activated premotor area during the study phase is lateral, so there is a possibility that we have some form of specialisation within the premotor area for different functions. Our experiment and analysis do not allow making vigorous assertions about the importance and role of the premotor cortex in design and problem solving, but further exploration of the above ideas may help better understand the role of 'enacting' or 'doing' in design 'thinking' and its relation to visual, spatial and verbal reasoning.

3.2 Studying design versus studying problem solving

The next step concerns the comparison between the phases of studying design (DS) and studying problem-solving (PS) tasks. In particular, the analysis is focussed on identifying areas that are significantly more activated during DS as compared to PS (DS > PS) and vice versa (PS > DS).

Starting from the most general observation, both contrasts show heightened activation in the prefrontal cortex: DS > PS is associated with heightened activation in the dorsolateral and medial prefrontal cortex, and PS > DS is associated with heightened activation in the anterior insula (Figure 4). This generally seems to validate our initial hypothesis that the prefrontal cortex (PFC) plays a significant role in supporting design and problem-solving thinking. But, is there any functional differentiation in the prefrontal cortex that reflects the experimental distinction between design and problem-solving tasks? What do we

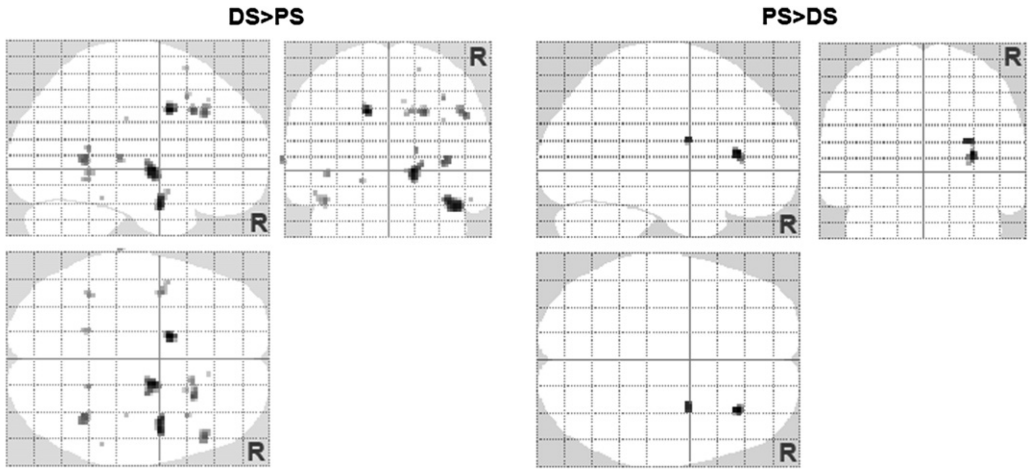

Figure 4 Statistical parametric maps showing activation when comparing the phases of studying design versus studying problem-solving tasks (left) and studying problem-solving versus studying design tasks (right) ($p < 0.001$*)*

know about the functional differentiation within PFC and its relation to other areas of the brain and what can be deduced from this knowledge about the peculiarity of design thinking when compared to problem solving?

Let us focus first on the dorsolateral prefrontal cortex (DLPFC) which is the most researched in the relevant literature. The dorsolateral prefrontal cortex is involved in executive function, working memory and directed attention (Miller and Cohen, 2001). Research shows that damage in this area may result in impaired executive function. This may manifest itself in 'difficulty generating hypotheses, and flexibly maintaining or shifting sets' (Loring and Meador, 2006, p. 164), difficulty which is normally assessed through various tests examining generative fluency as well as the ability to plan and develop organizational strategies. The dorsolateral prefrontal cortex corresponds approximately with Brodmann Areas 9 and 46 (see Figure 5 below). Our findings show that Brodmann Area 9 (BA 9) on the right hemisphere is more activated in the DS phase than the PS phase. A nearby region appears to show greater activation in the PS phase than the DS phase, but this

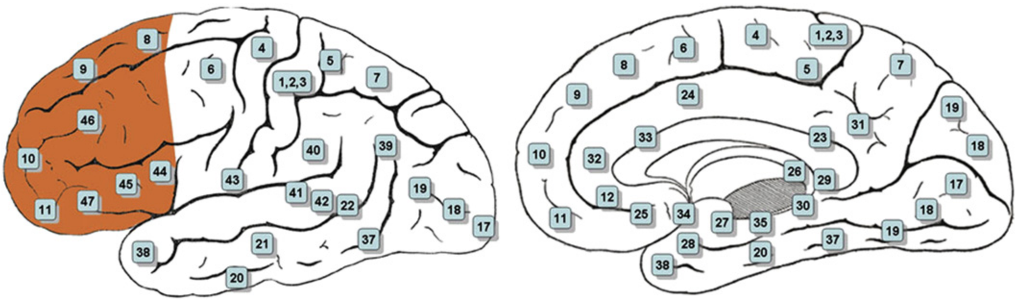

Figure 5 A map of the human brain with labels showing the different Brodmann Areas. The darker area on the lateral view roughly corresponds to the prefrontal cortex. Areas BA 9 and BA 46 are in the dorsolateral prefrontal cortex

region corresponds to the anterior insula, believed to play a greater role in emotional processing (Calder et al., 2001), not the DLPFC.

Goel et al. have extensively investigated the role of the dorsolateral prefrontal cortex in 'ill-structured problem solving' tasks through patient and fMRI studies. Let us briefly review some results and suggestions from this work.

Goel and Grafman (2000) examined a patient (an experienced architect) with a lesion on the *right dorsolateral prefrontal cortex* region. Through a protocol analysis study comparing the activity and performance of the patient with a control subject, the authors concluded that the patient had difficulty dealing with lateral transformations (movements from one idea to another). They hypothesised that the ability to perform lateral transformations is related with a mechanism that supports ill-structured mental representations and computations and so the right dorsolateral prefrontal cortex is necessary for the formation of such representations and inferences.

Vartanian and Goel (2005) also carried out fMRI studies to examine participants' responses while performing Match Problems (problems which involve subtracting matches organised on a plane so as to achieve configurations that satisfy some specific goals). The tasks were designed to drive participants to perform lateral transformations, or mental 'set-shifts', by asking them to determine the number of ways in which the goal state could be achieved in each case. Comparison of activation during Match Problem versus baseline tasks, showed activation in *right ventral lateral PFC* (BA 47) and *left dorsal lateral PFC* (BA 46), revealing that both areas are implicated in the ability to generate hypotheses. A further comparison of successful versus unsuccessful responses in Match Problems showed activation in right ventral lateral PFC (BA 47), left middle frontal gyrus (BA 9) and left frontal pole (BA 10), which led to the hypothesis that ventral lateral PFC (BA 47) is critical component of the neural mechanisms of set-shift transformation. The final analysis conducted in this experiment, examined those brain regions whose activation increased when generating more hypotheses. The analysis showed that activation in *right dorsal lateral PFC* (BA 46) covaried as a function of the number of solutions generated in Match Problems. The hypothesis of the authors in this case was that the involvement of right BA 46 may be due to increased demand for working memory, conflict resolution, or progress monitoring.

The Match Problems described by Vartanian and Goel are close to our problem-solving tasks as the goal state, evaluation function and transformation operations (that map the initial state onto the goal state) are specified. The interesting aspect of these Match tasks is that although the transformation function is specified, its application is not immediately obvious and finding the solution requires set-shifts, or reconsidering the constraints of the problem encoded in the stimuli. The experiment we report here did not consider set-shifting as a necessary requirement for problem-solving or design tasks; although the ability to generate lateral transformations is important for creative reasoning it is not necessary for design reasoning. Nonetheless, our results generally do agree with the above findings as they show that right PFC in general and the dorsal areas in particular, play an important role in cognitive processing of ill-structured problems.

We can acquire a more complete picture about the relationship/difference between design and problem solving and the role of DLPFC if we look in more detail at all the areas activated in DS versus PS (Table 2). We see that there is statistically significant accompanying activation in the anterior cingulate cortex (left BA 24 and right BA 32), middle temporal gyrus (BA 21), and middle frontal gyrus (BA 8). These areas are not activated in the PS > DS contrast.

The anterior cingulate cortex (ACC) is also part of the PFC and like the dorsolateral prefrontal cortex is generally thought to take part in executive function, particularly in supporting the coordination and modulation of information processing in other brain areas. It is also generally acknowledged that the ACC is associated with cognitive as well as emotional (affective) functions which are linked structurally to the dorsal and rostral parts of the cingulate cortex, respectively. What is particularly relevant to our study is that dorsal ACC and areas of the lateral prefrontal cortex work together during tasks that involve high levels of cognitive effort. The exact role played by each area, however, is an open question. One prominent theory about ACC is that it plays a role in conflict/competition monitoring. However, there is disagreement as to whether ACC activation precedes or follows activation in lateral PFC areas, and whether it thus plays a role in conflict detection (by influencing sensory selection) or conflict resolution (by influencing response selection), or both. Perhaps the most general conjecture is that ACC mediates attention and selection of appropriate responses or behaviours, while the lateral PFC is engaged in the generation and maintenance of schemata (goals and means) for responding to novel tasks. It has also been suggested that ACC plays an evaluative role, being part of a network of cells that partake in evaluation of motivation, anticipation of tasks and events, error detection and encoding of reward values. For more details on this discussion see Bush et al.

Table 2 Regions showing significant difference in activation when comparing the phase of studying design versus studying problem-solving ($p < 0.001$). Regions are designated using MNI (x, y, z) coordinates. Results are shown for $Z > 3.5$

Region	*BA*	*Hemisphere*	*x*	*y*	*z*	*Z score*
Anterior cingulate gyrus	24	L	−14	6	38	4.15
	32	R	14	22	38	3.33
Middle temporal gyrus	21	R	44	0	−22	3.96
Middle frontal gyrus	8	R	24	22	38	3.57
Dorsolateral prefrontal cortex	9	R	50	30	36	3.53

(2000, 2002); Milham et al. (2001); Paus (2001); Botvinick et al. (2004); Carter and Van Veen (2007); Sohn et al. (2007).

It seems then that the activation of the ACC may be a significant clue to explaining the difference between design and problem solving at a neurocognitive level. We can speculate that the activation of the ACC in the design study phase corresponds to the fact that the design problems were open-ended; the goal state (or target response) was not given, and could not be uniquely circumscribed by the information provided in the stimuli. In other words, finding a solution to the design tasks involved evaluation and selection among multiple (perhaps conflicting) hypotheses about the goal state. Taking everything together, we therefore hypothesise that in design tasks, the ACC worked together with the DLPFC (BA 9) in order to facilitate generation and evaluation of possible responses and support selective attention (Figure 6). Further studies will be required to evaluate the precise role of these two brain regions in design cognition.

Returning to Table 2, we also observe the activation of an area in the right middle temporal gyrus (BA 21). The temporal lobe is associated with language and semantic processing, multi-sensory integration, as well as memory encoding and retrieval. BA 21 in particular, is found to take part in semantic retrieval tasks for verbal as well as non-verbal materials (objects) and hence seem to reflect semantic operations (Cabeza and Nyberg, 2000). The fact that activation is located on the right may relate to the general idea that the right hemisphere is engaged primarily in visuo-spatial tasks, whereas the left hemisphere is more specialised in language and word tasks. For example, Martin et al. (1997) found greater right than left middle temporal lobe activation in

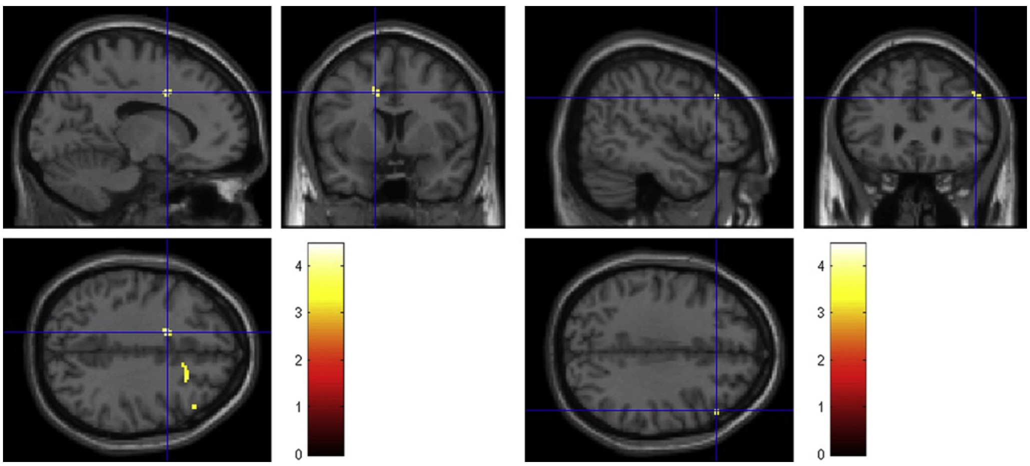

Figure 6 Brain images produced by statistical parametric maps for the DS > PS comparison ($p < 0.001$*). The position of the blue hairline cross shows the location of left ACC activation (left) and right DLPFC (right)*

tasks that involve the encoding of object forms, but greater left activation during semantic encoding of object pictures, as well as words. Another interpretation can be drawn on the basis of a study by Chou et al. (2006), which examined the neural correlates of semantic judgments to visually presented words in young children. The study suggests the right BA 21 may be associated with coarser semantic coding, that allows distantly related concepts to be analysed and encoded. In the same study, BA 21 is also associated with ACC activation. In our experimental setting then, activation of the right BA 21 may mean that this area was engaged in design tasks due to an increased need for creating semantic associations to help determine the context and objectives of each task.

Finally, heightened activation in DS > PS was also found in the medial frontal gyrus (area BA 8). BA 8 includes the frontal eye fields, a region associated with voluntary eye saccades and gaze control. Although it is difficult to ascertain whether the area found in the study is indeed located in the frontal eye fields, the heightened activation in studying design versus studying problem-solving tasks may be due to increased demand for examining, comparing and attending to various features of the stimuli. However, there is no evidence from the interviews for such a behavioural difference between design and problem solving and so we must treat this interpretation with caution. What seems more pertinent to our study is the idea that BA 8 is associated with decision making under increased uncertainty. Volz et al. (2005) found that BA 8 activation increases with increased uncertainty in tasks where participants have to predict events (abstract visual stimuli) under parametrically varying degrees of (un-)certainty. They also report that BA 8 is often accompanied with activation in the anterior cingulate cortex (BA 24 and BA 32) and discuss some interpretations and explanations about the relationship or dissociation between the two regions. For example, by reviewing various studies, they suggest that BA 8 is recruited to resolve decision conflict (when conflict exists at the knowledge level) whereas areas BA24/32 are recruited to resolve response conflicts (when conflict exists at the perceptual level). The validity of this hypothesis remains to be tested, but overall there seems to be a clear indication that BA 8 and ACC often work in concert in order to support the monitoring, evaluation and resolution of uncertainties and conflicts in complex decision making situations. Interestingly, the above study also reports increased accompanying activation in the DLPFC (BA 9/46) in relation to internally attributed uncertainty (uncertainty expressed as function of previous experience and knowledge).

On the whole, the findings of our analysis suggest that there is a more extensive neural network involved in the activity of understanding and resolving design tasks than the network involved in problem-solving tasks. This specialised network crucially incorporates the dorsolateral prefrontal cortex, dorsal areas in the anterior cingulate cortex, as well as areas in the medial temporal lobe and medial frontal gyrus. These seem to be valuable results both from the perspective of design research and from the perspective of cognitive science in general. In design research, the study can help clarify and offer arguments in support of fundamental assumptions about the relationship and difference between design and problem solving. More generally, this study contributes a methodology for generating and validating theoretical hypotheses about the nature of design and the conditions that enable design abilities. From a cognitive neuroscience perspective, the study offers new data to support the development of theories about the role and functional relationship between these brain areas. In this sense, the identification of design problems may help re-consider, or re-frame the study of certain cognitive functions.

4 Discussion and future work

Although this is only a preliminary and quite limited study, the results show that research in cognitive neuroscience and particularly neuro-imaging studies may offer interesting insights into the nature of design tasks and design thinking.

The findings suggest that design and problem solving involve distinct cognitive functions associated with distinct brain networks. The discovered activation in the right dorsolateral prefrontal cortex for design versus problem solving is consistent with previous studies focussing on features of design and problem solving such as insight and the ability to perform lateral transformations and set-shifts. Additionally, the results are consistent with the view that design cognition essentially also involves evaluation and modulation of alternative goal states, or conditions of satisfaction, which may be supported by the anterior cingulate cortex. Compared to problem-solving, studying design tasks recruits a more extensive network of brain areas. We suggest that these brain areas work together in order to undertake semantic operations, evaluate means and ends of appropriate responses and representations, support the resolution of conflicts, and modulate decision making under uncertainty.

At the risk of wild speculation, we can try to connect our results with design theory at a more detailed level. One interesting hypothesis is that ACC may be associated with operations that modulate the problem space, while the DLPFC is associated with operations that modulate the solution space. Both design and problem solving activities arise in a situation where known plans or schemata are not sufficient for responding to novel tasks and therefore new ones need to be generated. The generation and modulation of such representations and plans for action are supported by processing in the DLPFC. However, while in problem-solving situations the task environment contains the conditions for assessing what constitutes a correct response or solution, in design these conditions (which we can call conditions of satisfaction) are not given and require the evaluative involvement of the subject itself. What then distinguishes design is the need to define the conditions of satisfaction (or problem space) together with a language of possible solutions (solution space). The additional ACC activation during design thinking may be loosely interpreted as an indication that ACC plays a role in representing the conditions of satisfaction. (It is interesting to note that because ACC supports cognitive and affective functions, the activity of generating and representing the conditions of satisfaction may have cognitive as well as emotional quality; the latter may be particularly important as designing is often thought to induce emotional engagement.) We can further speculate that there is a functional differentiation in the DLPFC reflecting the different roles played by DLPFC in problem solving and design. Both tasks require the generation of new schemata and alternative solutions but there is a difference in cognitive function as problem solving only requires the evaluation of alternatives against the conditions of satisfaction. In design, by contrast, the generation of alternatives takes effective part in defining the conditions of satisfaction (together with the ACC). Undoubtedly further experimentation and analysis are needed in order to be able to explore this speculation and understand how DLPFC and ACC may work together in design (i.e. understanding the functional and temporal interaction between the two).

There is, however, a number of different avenues for further analysis of the current experimental data. The focus of the analysis here was on identifying areas of the brain that partake in the cognitive processing of design and problem solving. Further analysis should consider not only the activation in particular brain areas, but also the interaction and functional links between regions, particularly the interaction between ACC and DLPFC: crosstalk between the two areas may shed light into the idea that problem and solution spaces co-influence or co-evolve with each other. Another possibility would be to explore effects of expertise in design and problem-solving abilities by dividing our small sample into experts and novices. Previous research on design cognition using electroencephalography has reported differences in the brain activation patterns of experts and novices (Göker, 1997). Our sample included five subjects who have been trained and worked as professional designers for over 4 years; five subjects who have been trained as designers but have not worked professionally for more than 2 years and are not currently practising; and eight subjects who have no formal design training. This small sample gives us the opportunity to explore differences depending on training and/or level of expertise.

Further, more focussed, investigations in the future may help understand the interaction between problem-solving and design abilities and whether one subsumes or necessitates the existence of the other; for instance, whether problem solving can be associated with a distinct phase of design, which perhaps follows exploration and goal finding. Exploring differences between experts and novices may be useful for investigating this question, but also for understanding the development of design abilities. Neuro-imaging studies focussed on children of different ages would also be valuable for exploring developmental aspects of design ability with important educational implications.

Another interesting avenue for future research is to develop experimental paradigms for exploring collaborative design using fMRI. The idea that design is essentially a social ability is a relatively undeveloped notion in design research and has never been approached from the perspective of cognitive neuroscience. This research could contribute to a better understanding of social cognition in design and the conditions that facilitate it.

We are currently working on a similar experiment investigating the cognitive processes involved in the resolution of design and problem-solving tasks by monitoring brain activity through electroencephalography (EEG). EEG is another non-invasive technique used in cognitive neuroscience studies and has the advantage of high temporal resolution. This will give the opportunity to deepen and complement the knowledge obtained through fMRI by concentrating on dynamical properties of brain activation. It has been previously hypothesised that design can be understood and modelled as a kind of dynamical coordination process (Alexiou, 2007), or a particular type of phase transition from an un-organised to a well-organised universe (Zamenopoulos and Alexiou, 2007; Zamenopoulos, 2008). It is hoped that this kind of empirical research may help better explore and corroborate, or refute, these hypotheses.

Such research will essentially involve the application and development of new methods for analysing dynamical properties, modelling structural and functional relationships, and integrating EEG and fMRI data. Complexity science can offer methodological tools for analysing and modelling dynamical systems and complex network structures and existing research on creativity and complexity seems to be particularly promising in that respect (e.g. Bhattacharya and Petsche, 2002, 2005a, 2005b). We believe that extending this interdisciplinary collaboration between design research, cognitive neuroscience and complexity can offer important insights into the nature of design cognition and support the development of theories and methods for enabling and supporting design activity.

Acknowledgements

Many thanks to the staff at the Birkbeck-UCL Centre for NeuroImaging (BUCNI), and particularly Marty Sereno and Joe Devlin, for their kind help and support. The study was supported by the AHRC/EPSRC Embracing Complexity in Design research project grant SJG is supported by a Royal Society University Research Fellowship.

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