The Fifth International Conference on Design Creativity (ICDC2018)
Bath, UK, January 31st – February 2nd 2018

POSSIBLE NEUROBIOLOGICAL MECHANISMS BEHIND CREATIVE DESIGN

R. D. Orpwood

Department for Health, University of Bath, Bath, UK

Abstract: Understanding of the way objects and behaviours are represented in the brain provides some insight into how creative ideation may take place. This paper uses an example of the design of a simple mechanical device to explore the potential brain mechanisms that may lead to a creative idea. The hypothesis presented uses the links between sensory and motor representations in the cerebral cortex to compile novel structures that could lead to the behaviour desired. Although the analysis presented is for a simple and specialised aspect of creative design, it is felt the underlying principles could have more general application.

Keywords: *Creative design, Neuroscience, Sensory representations, Motor representations, Iterative manipulations, Mechanical device*

1. Introduction

There has been a growing literature focussing on the neural underpinnings of creativity, with much empirical work using fMRI or EEG techniques. The general picture that emerges from the fMRI studies is that areas that are associated with ideation often coincide with the brain's so-called default-mode network, the regions that are active during non-focussed thinking (eg Beaty et al, 2014). Imaging studies such as the use of fMRI also suggest that the pre-frontal cortex is associated with evaluation and goal direction (eg Mok, 2014). EEG studies have indicated that synchronisation of brain activity in the alpha frequency band, often linked to aspects of default- mode network activities, is also associated with idea generation (eg Schwab et al, 2014). These conclusions give some broad outline about where activity is located during creative acts but doesn't give much indication about how things work. Some authors have commented that progress in the field has been rather limited (Dietrich & Kanso, 2010; Arden et al, 2010), and a recent critical review has felt there should be less work exploring where activity occurs during creativity and more emphasis on mechanisms (Dietrich & Haider, 2017).

In order to explore core potential mechanisms it is preferable to use a quite simple example that is typical of the creative design process. The example used in this paper is the simple creative design of a basic mechanical device to meet a particular need, and it focusses on the process of creative ideation, the activity of creatively forming ideas in the mind. For a simple mechanical device the design engineer is provided with a desired behaviour that it is wished to achieve. As far as ideation is concerned, the designer's job is to conceptually come up with a mechanical artefact that can achieve this desired behaviour to an acceptable level, based on the knowledge and experiences of the designer.

Can this activity be mapped onto our understanding of the neurobiology of our brains? Goel suggests that such activity is a by-product of real-world problem solving involving the transformation of representations (Goel, 2014). This paper focusses on representations, and explores key brain mechanisms involved in their formation, and tries to show how their manipulation can lead to creative ideas.

2. Representation in the brain

2.1. Basic organisation of the brain

An influential model of the basic organisational principles of the brain was originally provided by Fuster (2003). Known as the perception-action cycle, it is summarised in Figure 1. This model focusses on the two key functions of the brain; making sense of incoming sensory information from the environment, and the outputting and control of muscle contractions in order to interact with the environment.

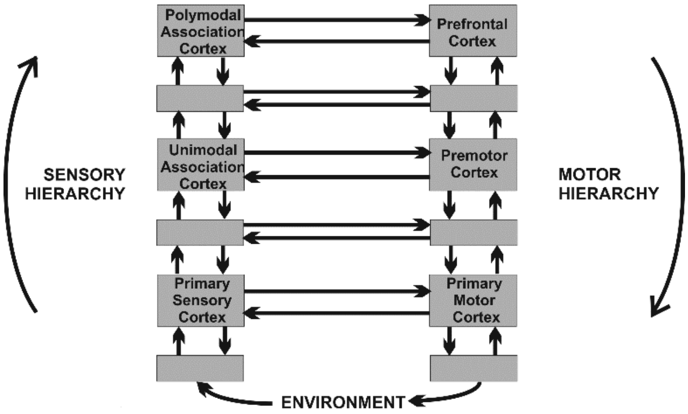


Figure 1. Simplified model of core brain activities (adapted from Fuster, 2003)

The brain receives sensory information into the cerebral cortex that is deciphered by means of the sensory cortex. This deciphering is a hierarchical process, with simple aspects of the outside world derived by the lower levels of the sensory cortex, and increasingly more complex aspects derived the further up the sensory hierarchy you go. For example, at lower levels in the visual part of the sensory cortex, simple shapes and colours are recognised, but toward the top this recognition extends to whole objects. In parallel with this sensory hierarchy is a motor hierarchy. At the lower levels of this hierarchy are simple patterns of muscle contraction to effect a desired movement. At the higher levels are complex behaviours such as cooking a meal. The basic flow of activity is one of sensory information being received into the sensory hierarchy, progressing through the increasingly complex levels of that hierarchy, and then flowing back down the motor hierarchy to activate individual muscles. In this way the brain is making sense of its environment, and reacting to that understanding by carrying out movements. Importantly though, particularly for creative problem solving, there are also links at all levels between the sensory hierarchy and the motor one. Of course the above description is a great oversimplification of what the brain gets up to. There are all kinds of other activities such as attention and motivation, emotional interactions, engagement with memories, language, navigation and many others, not to mention the ability to be aware. But the perception-action cycle suggests that at the core of the brain’s functioning is the process of sensory deciphering leading to motor activities.

2.2. Representation and the process of perception

The two key hierarchies of organisation in the brain are also representational. At any level in the sensory hierarchy the activity taking place represents an aspect of the physical environment. At the top the activity represents whole objects and situations. Similarly activity in the motor hierarchy represents aspects of bodily movements, and at the top represents complex behaviours.

The brain is able to explore these sensory and motor representations in a very dynamic way, and a useful example of these dynamics is the act of perception. Perception is the process of making sense of incoming sensory information, and at its core it requires the exploration of sensory representations. Consider the situation where the brain is receiving visual information from, say, an apple in its environment. Basic patterns relating to shape and colour are interpreted at lower levels, and these interpretations fed forward to higher levels. At a level where whole objects are represented, an initial hypothesis is made about the identity of the information being fed forward through the sensory hierarchy, and this hypothesis is fedback to the levels lower down. The lower levels are then able to compare their activity with the top-down estimate. If there is a mismatch, the higher levels are encouraged to modify their initial hypothesis. The theory of predictive processing sees this modification process involving the feeding forward of an error signal to the higher levels (Clark, 2013). Some theories see it as a local comparison that adjusts the feedforward activity according to the mismatch that has occurred (Grossberg, 2001). Using the new fed forward activity the higher levels can generate a modified hypothesis about the identity. Eventually there would be agreement between the top-down guess about the identity and the lower level activity. So perception is an iterative predictive process requiring higher levels in the sensory hierarchy to make an active judgement about identity according to the brain's prior experience (Figure 2).

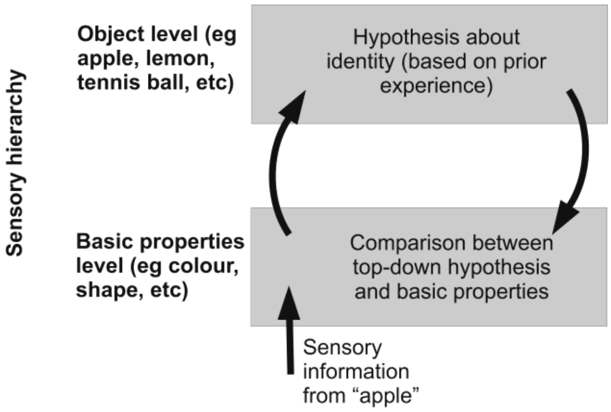


Figure 2. Perception is an iterative process that manipulates representations in the sensory hierarchy

The areas of the brain in action during perception are also in action during the process of imagination. What would happen if the brain were asked to imagine an apple rather than directly looking at it? There are links that have been learnt between activity in the language areas and object representations in the sensory cortex. So when the word "apple" is focussed on there will be activity initiated in the sensory cortex that underpins the imagined object. The same higher area of the sensory cortex activated during the perception of an apple would be activated when it is simply imagined. There are numerous studies using brain imaging that show this correspondence between perception and imagining (eg Kosslyn et al, 1995; de Borst and de Gelder, 2017).

2.3. Complex representations

If a complex behaviour is imagined then the representations activated are likely to involve a number of areas in both the sensory and motor cortices. Consider, for example, the behaviour of eating an apple. Representations in higher sensory areas relating to apples and jaws will be activated together with representations of eating in the higher motor areas. There has been much debate about how these individual representations could be "bound" together as a single image. However some authors feel a distributed set of representations is all that is necessary. Binding may just result from attention focussing on a particular set of representations at a given moment in time (Alexander and Dunmall, 1999).

The behaviour of eating an apple is a prior experience. Language will activate many such experiences, all of which can be recalled by attention. You could imagine biting into an apple, or rotating it in your hand, a whole host of prior experiences could drop out. But the settled image at any moment in time will be a combination of sensory and motor representations reflecting a particular recalled experience. This set of activated representations is constantly shifting and settling on alternative recalled experiences, a behaviour equivalent to the supposed role of the default-mode network in unstructured associative thinking (eg Andrews-Hanna et al, 2014; Mayseless et al, 2015)). The overall image at any moment in time is the set of representations currently activated (Figure 3). This settling into a given response is very much like network activity settling into a series of attractor states, a behaviour that has been argued to possibly underpin the emergence of awareness (Orpwood, 2017). This theory would imply that it is at these settled moments that the brain would become aware of a complex representation.

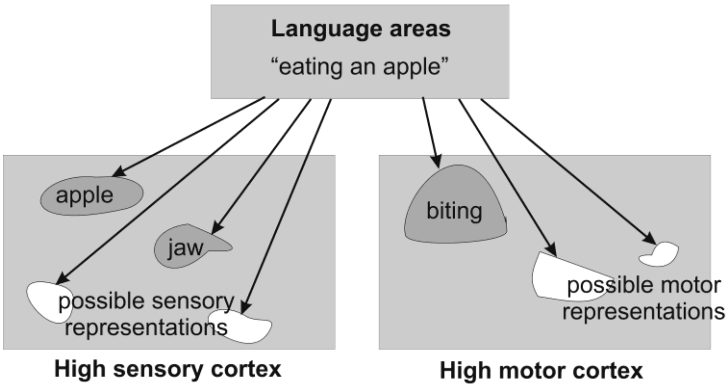


Figure 3. Representation of "eating an apple" in sensory and motor cortex. The darker areas are activated representations

3. Creative design engineering

3.1. Interaction between representations in sensory and motor cortex

This paper wishes to build on the understanding of the basic behaviour of the sensory and motor cortices, and to consider the links between the sensory and the motor hierarchies to show how they could underlie the process of creative ideation.

As well as the feedforward and feedback links that are in action within the sensory and motor hierarchies, there are also links between the two hierarchies (Figure 4). Taking the example of eating an apple, the behaviour of biting is likely to be represented at quite a high level in the motor hierarchy. There would be a number of links to this behaviour representation from the higher levels of the sensory hierarchy, such as representations of a person's jaw, and of an apple, etc. But these sensory representations will also have links to many other behaviours represented in the motor cortex, not just biting but behaviours such as holding an apple, or peeling one, etc. Any given sensory representation will have links to a wide variety of motor representations. The actual links activated at any given moment would be dependent on the focussing activity of attention.

As well as these links from the sensory cortex to the motor cortex there are also links going the other way. From the representation of the behaviour of eating an apple there would be links back to the apple and face representations in the sensory cortex. But again there would be links to many other sensory representations as well, such as other food stuffs, cutlery, etc. If attention focussed on the behaviour of

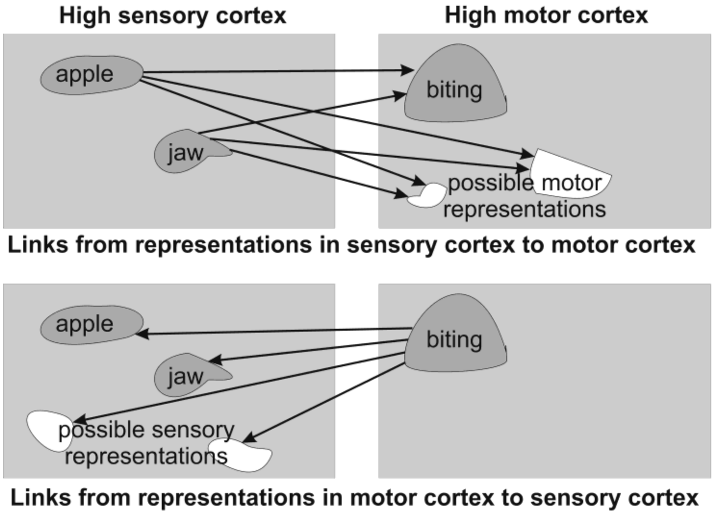


Figure 4. Links between representations in sensory cortex and motor cortex

biting in the motor area then the links to the sensory area could activate a large number of individual sensory representations.

All these sensory/motor links will have resulted from the learning and experience that the brain has acquired during its existence to that point in time. Different brains will have different repertoires of sensory/motor links, all depending on their experiences. This representational structure provides the backdrop needed for the brain to explore the links between structure and function. To form an idea for a mechanical device, it needs to be able to find a set of structural representations that leads to a desired behavioural representation.

3.2. Understanding a design problem

As was described above, the behaviour of eating an apple is a prior experience that can be recalled. However what happens if a novel behaviour is described that hasn't been experienced, and the brain is asked to find a structure that has that behaviour? Consider the situation where the brain is asked to find a way of eating an apple without using hands. This might be a need for someone with a disability for example. The artefact needed is not part of prior experience.

First of all the problem needs to be understood. The desired behaviour would be communicated to the brain through the medium of written or spoken language, and there are links between these language representations, and both sensory and motor representations. Jeannerod's work shows very clearly how action words activate the same areas of the motor cortex as the actual behaviours themselves (Jeannerod, 2006). If a design engineer is asked to design a device for no-handed apple eating, then the language links would activate areas of both the sensory and motor hierarchies that relate to the problem. Sensory areas representing apples, and jaws and hands, and motor areas representing the behaviour of eating are all likely to be activated. These activations of representations involve the process of imagination of course. They are not activated through a process of perception. What cannot be done at this stage is the re-activation of an image of a device for enabling no-handed apple eating. It hasn't previously been perceived so cannot exist in the imagination at that particular moment in time.

3.3. Manipulating sensory/motor representations

So how could the brain use these representational activations to come up with an idea for a device to hold the apple steady so it can be eaten? The device does not exist, just the representations of aspects of it. A possible starting point could be the activation of a representation of a behaviour of securely holding something. The behaviour of holding in the motor cortex is likely to link to many representations in the sensory cortex that can lead to the behaviour of holding, such as clamps or straps or string, etc. Links that have been more commonly experienced are likely to be more strongly activated, and become dominant. Perhaps in this case the dominant representation is a mechanical clamp. The overall image that the brain compiles could be of an apple held down with a kind of clamp. This is a compiled image, bringing together representations of components of prior experiences.

The compiled sensory representations would activate a new imagined behaviour representation in the motor cortex. A comparison can be made between this behaviour and that desired. Empirical work suggests executive control networks involving the pre-frontal cortex are involved in such evaluative activity (Ellamil et al, 2012; Mok et al, 2014). The new imagined behaviour would link back to representations in the sensory cortex. Aspects of the behaviour that were close to the one required would strengthen sensory activity. Aspects that were not so close would inhibit it. This iterative process would continue until the new imagined behavioural outcome is judged to be sufficiently close to the desired behaviour. The creatively designed solution to the problem is therefore the resulting collective of sensory representations (Figure 5). Imaging studies reflect this process and suggest an interaction between control and default-mode networks during creative acts. The default-mode network seems to be involved with the generation of creative ideas, with frontal control networks monitoring, evaluating and controlling the process (eg Beaty et al, 2014).

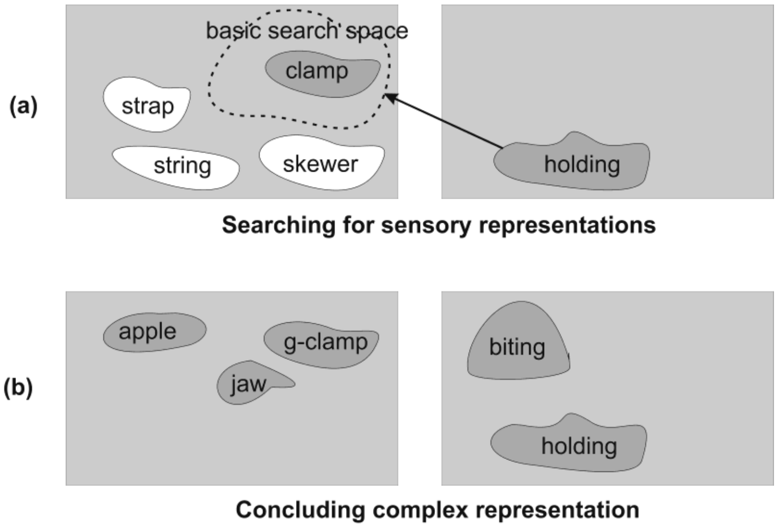


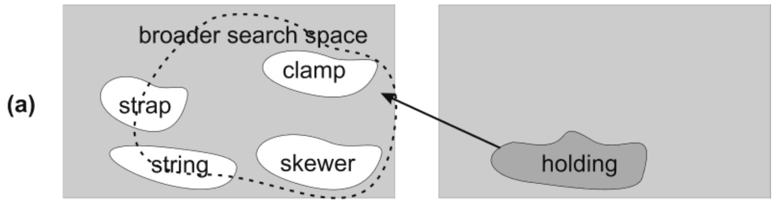
Figure 5. a) Links from desired behaviour to representations in sensory cortex, and b) concluding experience after a few iterations

3.4 Finding more original solutions

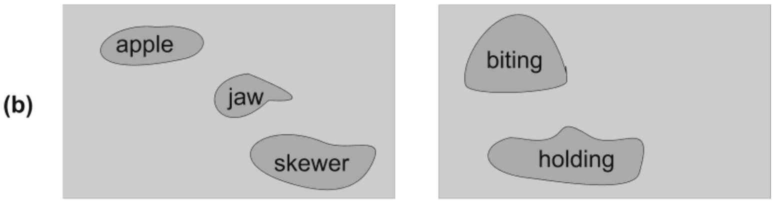
The process up to this point is creative in that the sensory representation that has been compiled doesn’t actually exist in reality, but it is not very original. There are two ways the brain could come up with alternative, more creative, solutions. One is to expand its range of possibilities for a solution, ie broaden the solution space. The other is to explore the underlying principles behind the behaviour sought.

3.4.1 Broadening the solution space

To broaden the solution space the brain needs to relax the range of sensory representations activated by the behaviour required, as described above. A highly focussed feedback might lead straight to representations such as clamps. However if the feedback from the behaviour area is broadened then it will be likely to encompass some alternative ideas. Rather than simply coming up with a clamp it might encompass representations in the sensory cortex of skewers or sticky tape, etc. Attending to one of these other sensory representations, possibly involving the pre-frontal cortex as suggested by empirical work, would provide an alternative starting point for further iterative refinements, as with the clamp (Figure 6).



Broader search for sensory representations



More original concluding representation

Figure 6. a) Broadening the search space in sensory cortex, and b) a more original solution

3.4.2 Exploring the underlying principles behind the desired behaviour

Exploring the underlying principles behind the desired behaviour could lead to a much more creative solution. In order to do this the brain could use the hierarchies that have been described for the sensory and motor cortices. As was discussed above, at high levels in the motor hierarchy, representations of specific high level behaviours are found, such as holding. Lower down representations of underlying component behaviours are found that can feed up to such higher level representations. For example at this lower level you might find representation of frictional force.

How can these links within the motor hierarchy be used to compile a new solution? The representation of the holding down of the apple would be at a high level in the motor hierarchy. Feedback from this representation to lower levels in the motor hierarchy could activate representations of the underlying principles behind the clamping, such as frictional behaviours. An iterative search could then take place at this lower level between the motor and sensory cortices. The search would consist of looking at sensory representations at this level that could lead to frictional behaviours. This search could lead to a sensory representation such as a very rough surface. So at this lower level there could be a conclusion of rough structures in the sensory cortex that could generate the frictional force behaviour in the motor cortex. The rough structure representations could then be fed back up to the higher layer of the sensory cortex to activate objects with those sensory properties, such as sandpaper. A new iterative search could then take place at the higher level to see what sort of apple-holding behaviours might result. The sandpaper–like solution could be a starting point, but further iterations at this level might end up with something like a spikey structure that might be judged to be okay for holding the apple for eating. It doesn’t sound like a practical solution at this point, but it is an original solution. It is a long way from any prior experience (Figure 7).

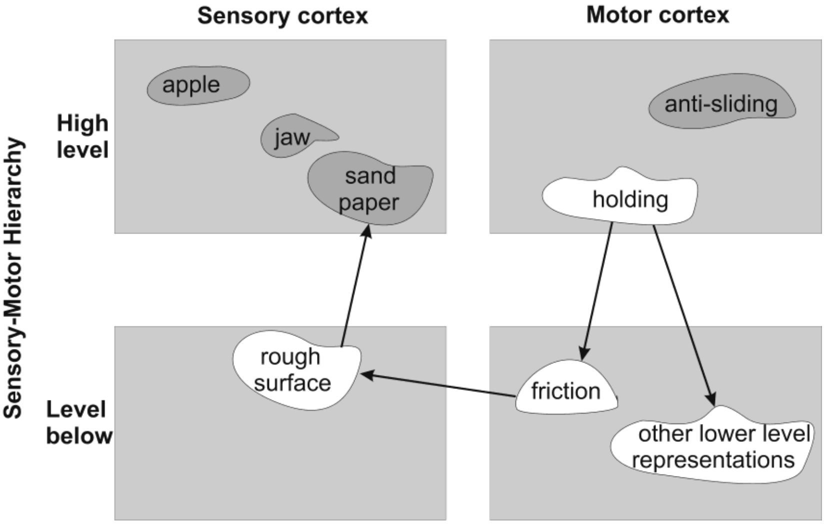


Figure 7. Manipulating lower-level representations to find a more original solution, showing the links involved, and a concluding set of representations

3.4.3 'Alternative uses' task

The use of these within-hierarchy iterations could enable creative solutions to the "alternative uses" task. The test asks people for as many uses as possible for, say, a house brick. The links at the higher cortical layers could bring out basic prior experiences such as building a wall. However if the underlying sensory properties of the house brick were explored then more creative solutions could be found. Within the sensory hierarchy the levels below the house brick object would contain representations of such features as linear shape, weight, etc. Iterations between the sensory and motor representations at this lower level might lead to behaviours such as linear behaviours or squashing. Such low level behaviours could then feed forward to behaviours at the higher level that were more original, such as drawing a line, or flattening pastry (Figure 8).

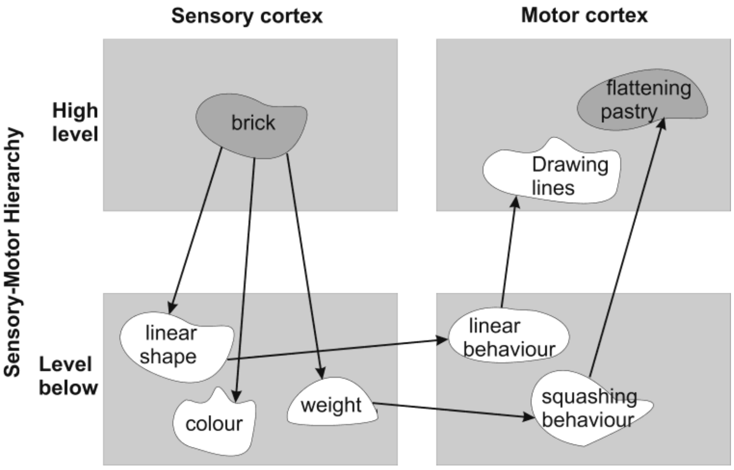


Figure 8. Using lower-level representations to find 'alternative uses' solutions

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