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How can neuroscience help understand design and craft activity? The promise of cognitive neuroscience in design studies

Abstract
Designing and making crafts is a complex, multifaceted process that requires sophisticated, professional thinking and competence, described as reflection in action and as an embodied process in which the hand, eye and mind collaborate. This article discusses these cognitive and embodied aspects central to designing and making crafts in light of cognitive neuroscience. Understanding the specific cognitive processes and forms of knowledge used in creative practices is essential. In this article, we propose that cognitive neuroscience provides valuable tools for analysing thinking and acting processes relevant to designing and making. We discuss the challenges and opportunities that the use of brain imaging methods, in particular, provides for understanding design activities, skills and cognition. Additionally, we present two neuroscientific experimental settings from our empirical studies in which the methods of cognitive neuroscience are applied to study and detect the interrelations between drawing, forming, skill learning and the functional activities of the brain and its subareas. We argue that cognitive neuroscience provides valuable instruments and methods which complement traditional design research.

Keywords: craft, design, making, cognitive neuroscience, brain imaging methods

Introduction

Designing is a goal-directed, iterative, creative activity that requires the sustained cultivation of sophisticated cognitive competencies (Simon, 1977; Ralph & Wand, 2009). Cognitive neuroscience, in turn, represents a multidisciplinary effort to analyse the neurobiological substrates underlying various cognitive processes using experimental methodologies from physiology, psychophysics, electrophysiology and functional neuroimaging. To what extent can cognitive neuroscience provide answers to scientific questions regarding the cognitive competencies related to designing and making? Designing and making are complex, multifaceted activities, but cognitive neuroscience studies typically investigate very simple and repeatable cognitive processes. Therefore, can reliable experimental settings that enable the detection of particular interrelations between design competencies and the functional activities of the brain and its subareas be created? How can design research benefit from the results of neuroscientific research? Until recently, design researchers lacked tools that enabled them to tackle the neural basis of designing (Goel & Grafman, 2000; Alexiou, Zamenopoulos, Johnson, & Gilber, 2009).

Although the body and mind traditionally have been studied separately, the recently emerged research field of embodied cognition integrates philosophy, psychology and neuroscience (Varela, Thompson, & Rosch, 1991; Lakoff & Johnson, 1999). Embodied cognition theory emphasises how cognition involves and builds on sensorimotor experiences through interactions with the environment (Koziol, Budding, & Chidekel, 2012). Research on embodied cognition has been conceptually elegant but included few empirical studies on design practice, in which embodiment plays a crucial role. However, it has been generally accepted that the mind is highly affected by the actions and experiences of the body, and vice versa (Hari & Kujala, 2009). Cognitive, sensory motor, emotional and social factors are all involved when creating a new item with the hands. Current research on brain systems is deepening understanding of the neural foundations of embodiment, skill learning and social interaction relevant to design and craft (for a review, see Hari & Kujala, 2009).

Designing and making crafts are understood to involve complex problem-solving processes in the mind–body which are fundamentally creative in nature and apply conceptual ideas to the design of material artefacts (Keller & Keller, 1999; Nilsson, 2013). As Nilsson (2013) has pointed out, the physical actions of making are essential in all creative practices in art, craft and design, both in relation to actual designing and to the uses of domain-specific knowledge. Emphasising the important role of materiality, some researchers have even proposed that making should be considered an academic discipline that encompasses a great variety of artefacts and human-made environments (Nilsson, 2013). Therefore, for us, art, craft and design stand as similar processes, and their enactments are both cognitive processes (ideation, problem solving) and embodied processes (experimenting, constructing and making).

Designing and craft making are fundamentally material centric, and engagement with and manipulation of physical materials are integral to these processes. Sketching, for instance, is generally considered the designer's most important thinking tool (Goel, 1995; Seitamaa-Hakkarainen & Hakkarainen, 2000). The selection of materials and tools for the specific design context often alters sketches produced during the process (Mäkelä & Nimkulrat, 2011; Kosonen & Mäkelä, 2012; Nilsson, 2013). Despite extensive study of visualisation, the role of material exploration and experimentations has not received as much attention (Ramduny-Ellis, Dix, & Evans, 2010).

The present study is part of the Handling Mind: Embodiment, Creativity and Design research project which integrates expertise in neuroscience, educational psychology and design research to develop and test neuroscientific methods for studying creative embodied processes and skill learning in the fields of art, craft and design. The goal of the present project is to generate and test hypotheses concerning design activity and the role and function of different brain areas in the design and craft processes. Design research, at present, shows two broad areas of deficiencies: 1) the investigation of the neuroscientific basis of design practice; and 2) empirical research on the embodied aspects of design. Advances in neuroscience indicate that naturalistic settings for studying design cognition are feasible. Therefore, we propose that cognitive neuroscience can be applied to study 1) design activity and associated cognitive processes; 2) the differences between design conditions and design fields; and 3) between-group differences related to the intensity and types of design training. We see cognitive neuroscience as an alternative tool for design studies that could complement more traditional design research.

To examine the challenges of conducting neuroscientific studies on design and crafts, we first review studies of design cognition focusing on the specific competencies of designing and cognition. We cover studies on design expertise related to analogical thinking (i.e. visual analogies) and visualisation, including spatial and mental rotation, and we address the relevance of distributed and embodied cognition to design. The second section provides a concise description of the cognitive neuroscience methods relevant to design research and highlights challenges to studying designing and skill learning. Finally, we describe two neuroscientific experimental settings from our empirical studies exploring these cognitive and embodied processes in designing and making. However, the detailed results of these studies are reported elsewhere.

Previous research on design cognition and embodiment

Studies on design expertise indicate that design thinking is a distinct mode of knowing (Cross, 2004, 2006; Lawson & Dorst, 2009). Design tasks entail complicated processes of searching for workable, aesthetic, functional solutions, and such tasks are commonly viewed as prototypical cases of complex, ill-defined problems (Goel & Pirolli, 1992; Goel, 1995) without unique or predetermined solutions (Simon, 1969, 1977; Akin, 1986). Design problems are also regarded as wicked in nature (Rittel & Weber, 1984). To manage the infinite possibilities, the designer must limit the design space by using external and internal constraints (Goel & Pirolli, 1992; Goel, 1995; Lawson, 2006). The design process involves successively reframing the design space and advances iteratively through cycles of ideation, testing and modification (Goel & Pirolli, 1922; Goel, 1995; Seitamaa-Hakkarainen & Hakkarainen, 2001). Only recently have researchers started to tackle problem-solving processes using neuroscientific research methods and to analyse differences in the pursuit of (ill-defined) design and well-defined problem-solving tasks (Goel & Grafman, 2000; Alexiou et al., 2009; Gilbert, Zamenopoulosb, Alexiou, & Johnson, 2010). Although research on design expertise emphasises designers' knowing, the intuitive aspects of the design process have not yet received much attention. According to Cross (2004), considerable work remains to adequately understand design expertise.

Research on expert/novice differences in problem-solving performance, starting in architectural design (Akin, 1986; Suwa & Tversky, 1997) and expanding to product design (Goel & Pirolli, 1992; Eisentraunt & Günther, 1997), played an important role in establishing the field of design research. Design studies have examined the knowledge, strategies and methods designers use to solve design problems (Akin, 1986; Goel & Pirolli, 1992). Most design studies have relied on empirical investigations tracing design processes by thinking-aloud protocols and have described design activity as movement through problem space (Akin, 1986; Goel, 1995; Seitamaa-Hakkarainen & Hakkarainen, 2001). Dorst and Cross (2001) proposed that the space of proposed solutions and the space of structuring problem co-evolve by moving design problems and solutions between these two spaces and by creating matching problem–solution pairs. Similarly, Seitamaa-Hakkarainen and Hakkarainen (2001) suggested that designers iteratively move between the composition (i.e. visual design) and construction design (technical) spaces.

Furthermore, analogical thinking and reasoning are important cognitive processes for creativity (Boden, 1992; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2012) and designing (Ball & Christensen, 2009; Ozkan & Dogan, 2013). Analogical thinking is defined as a process of mapping and transferring information from one domain (source or analogy) to another domain based on similarities between the stimulus and target (Goldschmidt, 2001). Analogical reasoning moves from a known example to an abstraction and from an abstraction to a new idea to solve a problem (Casakin & Goldschmidt, 1999; Casakin, 2004; Ozkan & Dogan, 2013). Visual analogies are considered central strategies in solving design problems for both novices and expert designers (Casakin & Goldschmidt, 1999; Casakin, 2004). Visual displays act as stimuli and either expand the space of creative solutions (Goldschmidt & Smolkov, 2006; Goldschmidt & Sever, 2010) or constrain and recycle old ideas (Purcell & Gero, 1996). When abstract or unusual representations are used as possible source analogues, designers invoke more analogies and are better at analogizing (Perttula & Sipilä, 2007). To boost the use of analogies and to avoid cognitive fixation, many design studies have manipulated the given examples or the instructions for analogical thinking (for a review, see Ozkan & Dogan, 2013). Visual analogies improve design quality, and it is especially important that students learn to use analogies to improve their problem-solving processes (Casakin & Goldschmidt, 1999).

As discussed, a key aspect of design expertise and design cognition is the role of visualisation and visual representations (i.e. sketching and model making). According to Jacucci and Wagner (2007), the physical artefacts are representations of the work and emerge during the design process, while materiality is a vital aspect of design representations, indicating the conceptual and material aspects of design ideas. Research on sketching and drawing has attracted much interest among design researchers (Goel, 1995; McGown, Green, & Rodgers, 1998; Lawson, 2006; Perry & Sanderson, 1998; Seitamaa-Hakkarainen & Hakkarainen, 2000). Goel (1995) investigated the kinds of visual representations designers generate, especially the sketches they create to transform design tasks into the desired artefacts. Designers use various visual and concrete materials, three-dimensional (3D) models and abstract concepts (Al-Doy & Evans, 2011; Goldschmidt & Sever, 2010; Gonçalves, Cardoso, & Badke-Schaub, 2013) and reason and make decisions through the construction and manipulation of models of various sorts (Goel, 1995; Perry & Sanderson, 1998). Goel (1995) argued that designers produce and manipulate representations of artefacts rather than artefacts themselves and that designers are aware of the ways that various systems of representation affect their thought processes. Goel (1995; Perry & Sanderson, 1998) maintained that freehand sketches play an important role in the creative, explorative, open-ended phase of problem solving. Furthermore, designing requires the ability to handle spatial relations, orientation and mental rotation, that is, to learn to mentally manipulate the elements of complex spatial shapes. A designer needs these visual spatial abilities, for example, to perceive how a sketched drawing would look from behind or the side (Kavakli & Gero, 2001; Silvestri, Motro, Maurin, & Dresp-Langley, 2010). In addition, designers need to be able to imagine how materials might affect the design, for example, what kind of surface could be created with certain threads and weave structures.

As stated in the introduction, empirical research on embodied cognition has only recently emerged and has focused on the human body and associated bodily experiences. ‘Embodiment’ refers to the fact that a great deal of human thinking takes place at unconscious, implicit, non-linguistic levels (Lakoff & Johnson, 1999; Pfeifer & Bongard, 2006; Gibbs, 2005); therefore, we should not study the mind in isolation from the situated body. The mind and body are bound to a material world and to bodily experience (Varela et al., 1991; Lakoff & Johnson, 1999). However, empirical studies that combine the study of mind and body in relation to design and craft practice are extremely rare. Embodied cognition studies are aimed at understanding how the body and mind interact in the process of thinking, that is, how artisans relate their bodies, tools, materials and space in their work settings (Patel, 2008). Investigation of embodied processes is important as design activities are both physically and socially distributed (Hutchins, 1995). Physically distributed cognition refers to cognitive processes distributed through the material environment, concrete tools and physical artefacts that help solve more complicated tasks. Socially distributed cognition refers to cognitive processes distributed across the members of a social group, for example, among members of a design team. Both aspects of distributed cognition are crucial as designing frequently involves teamwork and relies on various material inspiration sources, representations and models. The emerging research field of social neuroscience emphasises the interactions among tools, the physical environment and the embodied activities in cognitive processes (Hari & Kujala, 2009). The skills of design and craft making are based on the extensive use of various embodied senses and tactual and sensor-motoric operations. As a multi-modal process, design activities involve tactile attention and processing, and studies indicate that designers’ senses never operate independently but are interrelated and embodied in one another (Spence & Gallace, 2007; Gallace, 2012). In learning a craft skill, the embodiment of tools and methods and the experiential knowledge of materials gained over time are crucial and lie at the heart of both design and craft practices. Practitioners of a skilled activity are attuned to working with a material, action or movement they have performed, encountered and handled countless times; without conscious effort, practitioners can imagine and predict the perceptual consequences of these actions. The human brain is a super-plastic entity that constantly reorganises itself according to the emerging and changing needs of activities (Hari & Kujala, 2009). When a particular activity is practiced intensively, the brain changes to facilitate performance of this activity, as in skill learning. Over two decades, the neural mechanisms involved in the perception or observation of motor activities have been intensely studied using a variety of neurophysiological and neuroimaging methods (for a review, see Rizzolatti & Craighero, 2004). Investigations have shown that the sensor motor areas of the brain are activated in response to using hand-related action verbs (Candidi, Leone-Fernandez, Barber, Carreiras, & Agliot, 2010)) and seeing other people working (Borghi & Cimatti, 2010) or hand-held tools (Witt, Kemmerer, Linkenauger, & Culham, 2010). Following another person's work activates the motor reflection of the mirror neuron system (Borghi & Cimatti, 2010). Therefore, analysing changes in neural activity associated with learning new craft skills appears to be important for expanding knowledge of design cognition.

To conclude, design cognition has been investigated extensively, but work on the neural basis of designing and making is lacking. Cognitive neuroscience does not tell us what or how designers think but can be used to analyse their activities in specific situations and to trace brain activity associated with their problem solving. Next, we briefly describe neuroscience methodologies and highlight challenges in studying designing and skill learning.

Brain research methodologies and their relation to design research

Despite rapid advances in neuroscientific research, the challenge is to develop experimental settings that allow examination of the interrelations between brain activity and design cognition, especially in more naturalistic settings. All neuroscience methods, however, have limitations that affect the feasibility of the types of investigation and research questions posed. In the following section, we introduce some neuroscientific research methodologies and explain how they can be applied to study design cognition. Then, we illustrate how we created neuroscientific research settings to investigate skill learning and to study drawing and forming.

First, functional magnetic resonance imaging (fMRI) is a neuroscientific instrument that can provide a complete picture of the brain activity involved in solving complex design tasks. In fMRI, the blood-oxygenation-level-dependent (BOLD) signal is used to detect any changes in brain areas caused by fluctuations in oxygen use during the task. This method can produce a full image of brain areas and their oxygen use. Traditional fMRI experiments shed light on the following types of questions: 1) Which brain areas are activated in task A compared to task B? 2) Do individuals in group X and group Y have different brain areas activated by task A and task B? Such questions are of great importance in comparing design professionals and novices and in assessing different design tasks and their neural correlates.

Many design researchers argue that it is important to distinguish between ordinary problem-solving tasks and design tasks (Goel & Pirolli, 1992; Cross, 2004). The prefrontal cortex serves as the neural basis of higher-order cognitive functions and is involved in complex planning, creative thinking and problem solving (Goel & Grafman, 2000; Speed, 2010). To examine the neural basis of planning, problem solving and creative thinking in design, Alexiou et al. (2009) used fMRI to analyse differences between ill-defined design and well-defined problem-solving tasks. Alexiou et al. (2009) revealed different patterns of brain activation in the study phase (learning a task) and the performance phase (moving objects). In particular, the right dorsolateral prefrontal cortex showed greater activity during design than problem-solving tasks (Gilbert et al., 2010). Overall, design tasks required a more extensive network of brain areas than well-defined tasks. Different parts of the premotor cortex were activated when shifting from the learning phase to moving objects (Alexiou et al. 2009; Gilbert et al., 2010). As well, the motor and premotor areas of the brain were activated not only when performing but also when observing particular movements (Alexiou et al. 2009). According to Alexiou et al., (2009), it appears important to better understand the role of doing in designing and its relation to visual, spatial and verbal reasoning.

However, in fMRI experiments, participants usually cannot move and are restricted to a recumbent position in the cylindrical tube of an fMRI scanner. A head coil is placed on the top of a participant's head, and a mirror is attached to the head coil. In an experiment, the stimulus is projected onto a screen outside the scanner but within participant's field of vision (Alexiou et al., 2009; see also Gilbert et al., 2010). Participants use a mouse to click and drag objects displayed on the screen. A challenge in fMRI studies is to design valid experiments that can be performed without extensive movements. Such studies must be sufficiently complex to qualify as prototypical design tasks but simple enough to be solved within the time constraints imposed by the brain imaging methodology.

Some neuroscientific analogy studies using fMRI have confirmed that the activation of various areas in the prefrontal cortex can be seen as a key component in a larger network for making analogies (Bunge, Wendelken, Badre, & Wagner, 2005; Luo et al., 2003; Speed, 2010). Although it is not clear exactly how this network achieves analogical reasoning (Speed, 2010), fMRI can be employed to study the neural basis of visual analogical thinking, for example, by comparing experts and novices or participants from different design field. Earlier design research (Casakin, 2004; Ozkan & Dogan, 2013) provided excellent examples and a baseline for planning an experimental setting to study visual analogies: the type of design tasks, visual analogy categories and visual displays (i.e. visual stimuli). When applying this setting to an fMRI study, the visual display could be projected onto the computer screen, and experts and novices could identify and rate images by clicking a mouse or move objects by dragging them. Such an investigation is suitable for assessing the impact of the expertise level or the design field on the preferred distance of source analogues (see Casakin, 2004; Ozkan & Dogan 2013). First-year students without previous design experience can be useful to determine a baseline. Following the set-up used by Casakin (2004) and Ozkan and Dogan (2013), the fMRI experiment could consist of several carefully planned sub-tasks. The visual stimulus could be within-domain images from the domain studied and between-domain images from remote domains. Task participants could evaluate the usefulness of each provided visual stimuli as a source domain for designing a field-specific object (e.g. a lamp) or choosing the analogy category (e.g. architecture, artefacts, nature, lamps) that best serves as an analogical source domain for designing particular objects. The fMRI could be used to compare experts' and novices' different preferences of within- and between-domain visual stimulus. However, a main limitation of using fMRI in visual reasoning is that studying actual design process (cf. Casakin, 2004) is impossible as conducting brain imaging during the act of drawing is impeded by the necessary restriction of movement.

The fMRI setting can also be used to examine skills of two-dimensional (2D) and 3D spatial reasoning and mental rotation. Most designers are trained as visualizers and have acquired specific visual skills and competencies (Goodwin, 1994). As stated, these skills require the ability to handle spatial relations, orientation and mental rotation, that is, to learn to mentally manipulate the elements of complex spatial shapes. For example, in garment design, a flat-pattern design is central to form giving, and the 3D form is developed in two dimensions (Salo-Mattila, 2014). Shepard and Metzler (1971) introduced the concept of mental rotation. In their experiment, participants were presented with a pair of perspective line drawings of chiral shapes (i.e. asymmetrical 3D cubes). Each pair was rotated from its original position by a certain amount, and participants were shown the mirror image of the 3D cubes. Participants were asked to indicate as quickly as possible by pressing a button whether the two objects depicted were identical or mirror images. Recently, mental rotation has been investigated using several neuroscientific techniques, including fMRI (e.g. Cohen et al., 1996; Jordan, Heinze, Lutz, Kanowski, & Jäncke, 2001; Vingerhoets, de Lange, Vandemaele, Deblaere, & Achten, 2002).

Cohen et al. (1996) repeated Shepard and Metzler's (1971) classic study using fMRI to observe local changes in blood flow in the brain during mental rotation. In the study, the comparison condition was identical to that in Shepard and Metzler's (1971) study, except that both members of each pair appeared at the same orientation, and mental rotation was not needed. The study revealed that mental rotation engages cortical areas involved in tracking moving objects and encoding spatial relations (Cohen et al., 1996). Given the extensive research on the mental rotation of 3D objects, Cohen's et al. study might provide a model for an experimental setting to study expert/novice and design-field-related differences in 2D and 3D spatial-reasoning skills and mental rotation. In design contexts, mental rotation can be studied by comparing the previously described classic settings with various visual objects (e.g. different sorts of stimuli pairs, pictures of hands and tools) and by comparing experts, novices and laypeople. Novice and expert designers are likely to respond differently to diverse stimuli modalities, while differences between design professions (e.g. architecture, industrial design, graphic design) might be related to working with 2D- or 3D representations.

Another method called optical imaging can provide further possibilities for studying visual reasoning outside the laboratory. Optical imaging, or near infrared spectroscopy (NIRS), utilizes changes in the absorption and scattering properties of light as it travels in brain tissue. When brain tissue is active, more oxygenated blood travels to the area, and in event-related optical signals (EROS), brain activity affects chemicals and liquids in the brain, prompting changes in the properties of light absorption and scattering (Gratton et al., 2001). Optical imaging thus might allow combining measurements of BOLD-type signals and event-related neuronal measures (Gratton et al., 2001). In addition, optical imaging is portable and does not require a laboratory facility, so it can be used in natural working environments. Therefore, optical imaging is a promising area for advancing design-related brain studies. For example, 2D and 3D representations and spatial reasoning skills can be seen as the core of professional training in many design fields. Designers manipulate various 2D (e.g. drawings, garment patterns) and 3D representations (e.g. physical mock-ups, clothing) and mathematical relations, such as proportions (Ho, Eastman, & Catrambon, 2006). These authentic activities could be studied using optical imaging in natural working environments.

Electroencephalography (EEG) is the oldest brain research method and provides millisecond-scale temporal accuracy. EEG and event-related potentials (ERP) are fast methods not limited to laboratory settings. EEG signals are the result of the synchronous activity of neuronal assemblies which can be recorded at the surface of the scalp. EEG might be able to trace expert/novice differences in design-related brain activity (Alexiou et al., 2009), and the availability of portable, lightweight EEG instruments permits performing such investigations in the natural working environments of designers. ERPs are averaged fragments of EEG which indicate brain activity that is temporally related to events, such as the presentation of an image or the beginning of a sound, task or attempt. Visual, somatosensory and auditory components (peaks) of ERPs have been observed, and some features of their relationships to the cognitive functions of perception, memory and attention have been identified. As stated, previous research has revealed activation of the brain's sensor motor areas in response to the stimuli of seeing other people working (Borghi & Cimatti, 2010) or hand-held tools (Witt et al., 2010). Moreover, recently published neuroscientific studies analysing the effects of drawing on alpha activity (Belkofer, Van Hecke, & Konopka, 2014) and comparing brain activity during drawing and sculpting (Kruk, Aravich, Deaver, & deBeus, 2014) have used EEG to examine the brain wave frequency patterns of participants engaging in art-making conditions. Thus, the long tradition of ERP research provides a good basis for application to design research. Pursuit of design tasks, however, might pose challenges for the ERP method due to the different time courses of the consecutive sub-tasks in the process. A clear disadvantage of EEG measurements compared to fMRI is the difficulty in identifying the brain areas, especially deeper regions, that contribute to the elicitation of responses. Thus, the strengths and weaknesses of the methods complement each other. In the next section, we explicate in more detail our neuroscientific experiments on 1) skill learning; and 2) drawing and forming using EEG instruments.

Measuring skill learning, drawing and forming with EEG

Our first neuroscience laboratory experiments examined the neural foundations of novices' process of acquiring new skills. We conducted an EEG study on how specific craft skills are learned. The participants were first-year university textile student-teachers and adults from Martta organization who voluntarily participated in the study. None had previous knowledge of the techniques learnt during the experiment. Modelling, coaching and scaffolding are traditional ways of learning specific craft skills during apprenticeships. Observation, guided practice (Collins, 2006), careful imitation and deliberate practice (Ericsson et al., 1993) play crucial roles in this process. Learning a new craft skill should activate the sensory motor areas of the brain when the participant receives certain stimulus (i.e. photos of hand positions during the craft technique). Thus, our laboratory experiment examined the neural foundations of novices' process of acquiring new skills and was aimed at answering the following research questions: 1) What brain activations are observed when participants look at instructions for craft techniques which they know and do not know? 2) How does skill learning change these activation patterns? 3) Does skill learning change the timing of the brain activity? In particular, we were interested in the role of motoric training in the skill learning process and its neural basis, as well as the brain organisation and large-scale memory systems of self-paced, intensive skill learning.

Figure 1 shows the research setting of the skill learning experiment. EEG measurements were performed before and after learning a specific textile craft skill. Electrodes were placed at various locations on participants' scalps to measure the voltage of synchronous electrical activity of neurons at those locations. During measurements, participants' brain responses were recorded using a NeurOne EEG-instrument (Mega Electronics Ltd, Finland) with 32 EEG and EOG channels. The EEG procedure enables illustrating brain activity during real-time viewing and action and is non-invasive and much less cumbersome than other brain imaging systems.

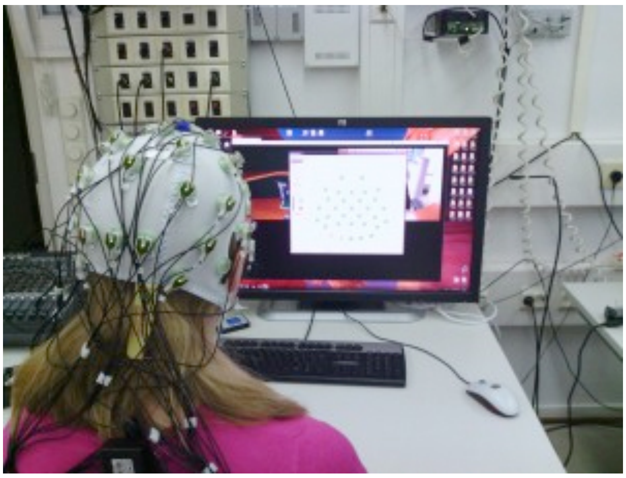

Figure 1. EEG equipment used in research on skill learning.

The 15 novice participants were shown 312 instructional photographs (i.e. working instructions) for three textile techniques. Most participants were familiar with one technique (crocheting), whereas the two other textile techniques (filet lacing and frivolite, or tatting) were previously unknown to or barely known by participants. Figure 2 shows examples of the photographs of the hand positions in the working instruction. These photographs were shown in a random order first before participants learnt a specific skill (textile technique) and then again after the technique was learnt and practiced. These participants were considered novices as, although they knew some textile techniques, they did not know the specific techniques used in this study (filet lace, frivolite). Brain responses to the photographs were averaged together across the sessions and across the participants.

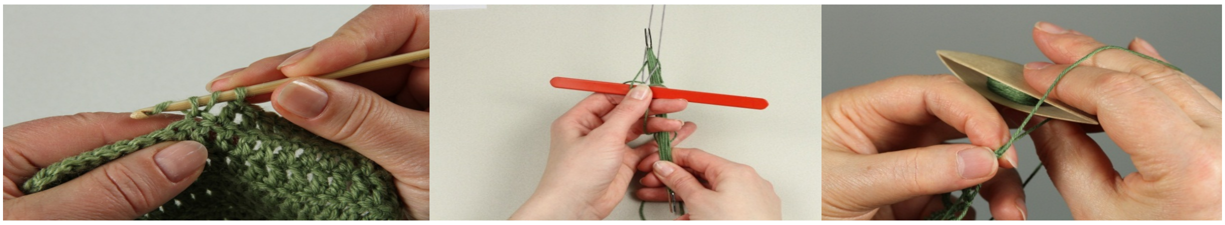

Figure 2. Photos of hand positions for textile techniques (from left to right): 1) crocheting; 2) filet lace; and 3) frivolite.

During a four-week period, the two groups of participants learnt one of two specific craft techniques: frivolite (tatting) or filet lace. After an expert taught these techniques in one session, participants independently practiced the skill and kept diaries of their own learning during the practice period. The EEG recording was then repeated, and the results from the first and second sessions were compared. After the experiment, the participants were interviewed. This kind of research setting is completely new in the design field, so we attempted to construct a rigorous, reliable research design. Figure 3 presents our brain research design to measure brain responses to images related to the three techniques.

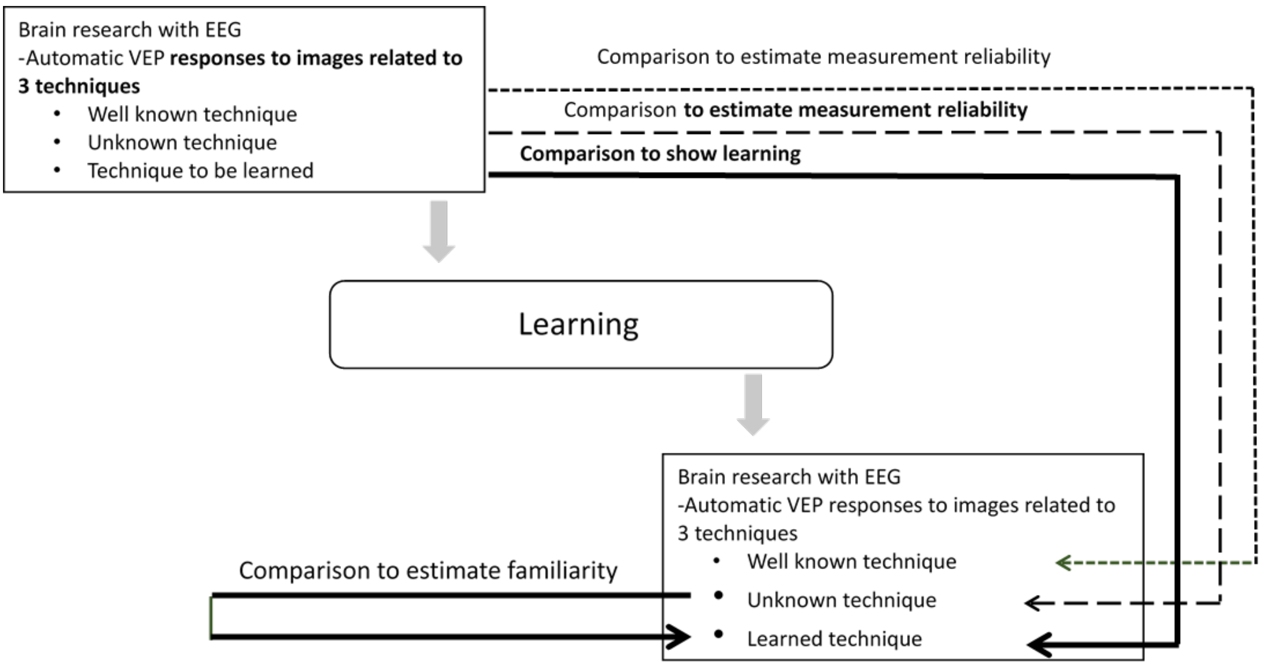

Figure 3. Skill learning research design.

We expected that, in addition to the visual processing, the motor or somatosensory areas would be activated while looking at the photographs. After learning the skill, this involvement likely would change, and some brain responses likely would become faster. Thus, by comparing participants' first and second recordings of the well-known technique (crocheting), we estimated the reliability across these two measurements. Similarly, comparing participants' first and second recordings of the unknown techniques provided another estimate of measurement reliability. Comparing the technique to be learnt in the first recording to the technique learnt in the second recording revealed the learning from the brain activity.

We report details of our results elsewhere but can conclude that we appeared to be able to capture the activated somatosensory areas and that the results indicated no differences in the known and unknown technique. These results confirmed that we measured the right phenomena. However, there were larger, positive changes in the brain responses to learned skill photos, indicating that participants more quickly recognised the photographs of hand positions related to the learned skill.

We conducted another neuroscientific experiment in which neurone EEG instruments and Faros (Mega) cardiac recordings were used to test hypotheses about the neural and physiological activity associated with producing visual representations (i.e. replicating drawings versus creating new designs) and material representations (i.e. replicating models versus creating new designs) (Leinikka, Huotilainen, Seitamaa-Hakkarainen, Groth, Rankanen, & Mäkelä, 2016). Only recently have some published neuroscientific studies analysed the effects of drawing on alpha activity (Belkofer et al., 2014) and compared brain activity during drawing and sculpting (Kruk et al., 2014). These studies (Belkofer et al., 2014; Kruk et al., 2014) used EEG to examine the brainwave frequency patterns of participants engaging in art making. In general, non-event-locked physiological and brain activity takes place in specific patterns related to cognitive processes and in responses to any stimuli present in the environment (Kruk et al., 2014). Theta waves were shown to be related to imaginative states and creative processes, alpha waves were detected in relaxed and normal conscious awareness, and beta waves were expressed during active thought and alert states (Kruk et al., 2014). Finally, gamma waves were correlated with cross-modal stimulus integration, synthesis and information-rich processing (Luck, 2005).

A previous EEG study by Kruk et al. (2014) showed that, compared to general movement, both clay sculpting and drawing increased gamma power in the right medial parietal lobe. In addition, clay sculpting decreased right medial frontal gamma power and elevated theta power. Also, Belkofer et al. (2014) indicated that alpha rhythm might play an important role in drawing. The results of both studies were discussed in the context of art therapy.

Thirty participants, both students and professionals, representing expertise in various design fields, participated in our study. Participants were regarded as experts in drawing from Aalto University. The question investigated was whether the brain responses to working with visual (drawing) or material (moulding clay) representations differed in the tasks of 1) copying; 2) creating novel designs; and 3) freely improvising. In the clay-moulding task, participants worked with clay material; otherwise, the tasks were similar. To measure participants' physiological responses to the copying, designing and free-improvisation tasks, we recorded their heart-rate variability (HRV) through the Faros and Aktigraph (i.e. pulse and movements) measurement.

In the drawing experiment, participants individually constructed three drawings: 1) a copy of a line drawing of a cup (copying task); 2) a creative design of a cup (design task); and 3) a creative drawing of a self-chosen topic (free improvisation task). The experimental setting consisted of 2 time blocks: a fast block and a slow block. Before drawing (or moulding clay), participants looked at the picture of the cup for 5 seconds and then a fixation cross for 10 seconds. This fixation cross was important for physiological measurements. In the fast block, the time for drawing or moulding was restricted to 45 seconds, but in the slow block, the time was extended to 3 minutes. Each block and each task was randomly assigned to participants and repeated 5 times. The same setting was conducted for 8 selected participants using a NeurOne EEG-instrument with 32 EEG channels that recorded participants' brain activity and tracked their HRV, which were all recorded in time synchrony with the tasks. In these experiments, we expected that the brain responses during the 10-second period of preparation to perform the tasks would differ according to the task. We assumed that the visual areas would be mainly activated in task 1 (visible through the suppression of the alpha rhythm), while motor areas would be more active in tasks 2 and 3 (visible through the suppression of the mu-rhythm). As well, the activity in the frontal areas of the brain would differ between tasks 2 and 3 due to the level of creativity required (see also Belkofer et al., 2014; Kruk et al., 2014). The experiments contribute to a novel understanding of the creative process compared to the copying task. Already in the physiological recordings, we observed a physiological response to the materials (drawing vs. forming clay) in the HRV parameters (Leinikka et.al, 2016).

Conclusion

Academic research on art, craft and design involves the analysis of design activities, creative processes and their consequences for the human mind and wellbeing. Learning through designing and constructing craft products appears to play an essential role in human development and facilitates the development of cognitive, spatial, motor, social and aesthetic skills. In addition, the artistic processes integral to crafts are central to emotional expression and regulation of human well-being and flourishing. Thus, success in the art, crafts or design fields depends on mastery of the entire design and craft process, from the generation of ideas to the learning of techniques and the production of visual and material artefacts. Participants must manage the procedures of planning, making and integrating mental representations into the surrounding material, physical and societal conditions, as well as reflecting possibilities and testing the boundaries of self-fulfilment.

In this article, we have reviewed research on the design cognition and competencies that constitute design expertise, and we have highlighted the importance of embodiment for skill learning. We also introduced our neuroscientific experiments to capture the neuroscientific basis of skill learning and to work with materials, that is, drawing and forming. The present examination reveals that the methods of neuroscience might open many interesting lines of design research. A limitation of traditional cognitive research on design is an overemphasis on deliberate the within-mind processing of conceptual or visual information. However, practitioners' accounts of their design experiences have tended to be subjective descriptions of their practices that are difficult to systematise to allow the accumulation of research design knowledge.

The rapidly advancing methods of neuroscience provide new possibilities to experimentally trace the interrelations between brain activity and design cognition. The brain changes and forms according to different physical and mental activities. Further, an exciting, new trend in neuroscience is to compare the brain structures of various professionals. It is an inspiring challenge to design an experimental setting to study the functional and structural changes of the brain related to learning and practicing special design skills.

However, all neuroscience methods have their limitations for addressing the research questions. Most neuroscientific equipment cannot be removed from the laboratory, and measuring brain activity requires expertise in neuroscience. As stated, neuroscience studies typically investigate very simple, repeatable cognitive processes, whereas designing and making crafts are complicated, multi-faceted activities. Therefore, it is difficult to create reliable, valid experimental settings in which to identify and determine the specific interrelations between design cognition and brain activity. Although we recognise the limitations of the cognitive neuroscience methods, we suggest that it can be seen as an alternative tool for design studies, appropriately accompanied by more traditional design research.

In Table 1, we summarise the pros and cons of the neuroscience methods in the context of design studies. Moving from the right to left column are the method name, parameters measured, temporal resolution (accuracy in time) and spatial resolution (how well the active brain areas are located). The strengths and weaknesses of the methods are described. As indicated in Table 1, some methods (fMRI) in the sequence of design activities are difficult to study, whereas EEG offers a long tradition of well-controlled experiments that can be applied in design studies. NIRS is a portable instrument but is not yet widely used in cognitive studies.

Table *1. Pros and cons of neuroscientific methods for design studies.*

Neuroscientific method	Parameters measured with this method	Temporal resolution (accuracy in time)	Spatial resolution (accuracy of locating active brain areas)	Pros for design studies	Cons for design studies
fMRI (functional magnetic resonance imaging)	BOLD-signal (blood-oxygenation-level-dependent signal), changes in blood flow after increased neuronal activity	Block design studies: several seconds to minutes Event-related studies: hundreds of milliseconds	From several millimeters to sub-millimeter accuracy	Some fMRI study protocols are quite well suited for design studies	Equipment cannot be removed from the laboratory; sequence of activities is difficult to study
EEG (electroencephalo-graphy)	Electric potentials from scalp, directly resulting from neuronal activity	Less than a millisecond	Problematic due to distortion of electric potentials, less than 1 cm in good conditions	Portable instruments, natural environments, some EEG study protocols are quite well suited for design studies, measurements of several hours are practically possible	Location of brain activity is difficult to determine
MEG (magnetoencephalo-graphy)	Magnetic fields outside the head, directly resulting from neuronal activity	Less than a millisecond	Less problematic than EEG, in good conditions clearly less than 1 cm	Some MEG study protocols are quite well suited for design studies, long tradition of well-controlled experiments stemming from EEG, optimal time-space-resolution	Equipment cannot be removed from the laboratory; location of brain activity is quite difficult to determine
MRI (magnetic resonance imaging)	Structures of the brain (structural MRI), neural tracts (DTI, diffusion tensor imaging)	No accuracy in time	Less than 1 mm	Good for studies comparing groups of people	Equipment cannot be removed from the laboratory
PET (positron emission tomography)	Structural image of concentration of metabolically active tracer, usually oxygen	Contrast of two conditions: no accuracy in time	Less than 1 cm	Good for comparing groups of people or natural tasks	Radioactive tracer is injected into participants; equipment cannot be removed from the laboratory
NIRS (near-infra-red spectroscopy)	Diffusion and absorption of near-infra-red light in tissues, depending on hemodynamic and electromagnetic changes in brain tissue	hemodynamic NIRS: hundreds of milliseconds, electromagnetic NIRS: millisecond (according to some researchers)	Theoretically less than 1 cm	Portable instruments, natural environments, some NIRS study protocols are quite well suited for design studies, measurements of several hours are practically possible	Difficulties in determining the location of brain activity, not many groups yet using NIRS for cognitive studies

To conclude, research on distributed and embodied cognition has assisted in expanding design research beyond the focus on mind to consider bodily, materially and socially distributed processes critical in design. As demonstrated in the present article, neuroscience provides instruments and methods which can be applied to study design competencies. In this article, we have tentatively sketched some directions for neuroscientific research to study design cognition, and we have described our own neuroscientific experiments. However, much future research is needed to deeply understand designing and making crafts from the neuroscience perspective.

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