POSITION PAPER: ImagineD – A vision for cognitive driven creative design

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CAD systems are well suited to later design phases, but do not effectively support the early ambiguous, iterative, and creative stages of design. CAD is continually evolving, but only incrementally and by adapting to established design processes. We present a radically new vision for creative design – ImagineD – based on advances in HCI technology. In this vision, the designer is symbiotically connected to supporting computer systems via brain-computer and gesture recognition interfaces, and the design process is directly driven by the designer's cognition (via neural signals) and natural behaviour (via intuitive gestures). Realising this vision requires advances in scientific models of cognition, neural activity, and gesture interaction in creative design. The paper presents the work and visions of the University of Strathclyde, covering earlier CAD work before presenting ongoing empirical and theoretical research in the above areas by the ImagineD team. We conclude with key challenges.

Introduction

This paper is based on a keynote presentation by Alex Duffy at the 15th International DESIGN Conference 2018, in Dubrovnik, Croatia [1,2].

The term 'computer aided design' (CAD) can be traced back to Douglas T. Ross [3, p.iii], who envisioned a graphics-driven "man-machine system which will permit the human designer and the computer to work together on creative design problems." Through the work of pioneering computer scientists [4–6], CAD systems have evolved from purely 'number crunching' machines to sophisticated software, enabling the designer to visually represent their designs in 2D and 3D space and perform complex analysis and simulation virtually. CAD is considered to have increased the efficiency of design work, particularly in the later stages where there is a need for accurate design representation and information on artefact functionality [7]. It is now ubiquitous in industry, and CAD training is a common feature of design education.

Although modern CAD systems may be used to an extent throughout the design process, their greatest utility still seems to be in supporting the representation and refinement of artefacts during the detailing and testing phases. They are less useful in the early, conceptual phases of design for several reasons [7]. The majority of commercial CAD systems involve the stepwise, incremental creation of geometry using conventional keyboard and mouse input – this process is not conducive to the rapid iteration and evolution of abstract ideas that underpins creative design thinking. These systems also employ well-defined geometrical representations, and do not effectively support the ambiguous representations believed to be important for creativity. Additionally, modern CAD systems tend to employ relatively complex interfaces and have a steep learning curve, which diverts cognitive resources away from creative thinking towards system operation and control. From this perspective, Ross' [3] original vision has not been fully realised in design – CAD systems do not effectively support the early activities that are most fundamental to the production of creative design solutions.

Although commercially available CAD systems are continually advancing, they are doing so in an incremental manner and by adapting to long established design processes. This seems unlikely to yield the fundamental changes needed to better support creative designing. In this position paper, we outline a new vision – ImagineD – that considers CAD from a radically different perspective. Recent years have seen significant advances in brain-computer interfaces (BCI), which enable human-computer interaction via neural signals [8], as well as gesture interaction systems [9] and virtual/augmented reality environments [10]. These technologies open up possibilities for a completely new generation of design tools: systems that eliminate the keyboard and mouse, symbiotically connecting human and computer to realise ideas directly from a designer's imagination and seamlessly evolve them in sync with cognitive processing. Interaction with such a system will be virtually effortless, and the creative design process will be directly driven by the designer's cognition and natural behaviour. Achieving this long term vision firstly requires robust scientific models of gesture interaction, cognitive processing, and neural activity in creative design. This forms the focus of ongoing work by researchers at the University of Strathclyde and collaborators, as discussed in later sections.

The remainder of the paper presents work and visions from the University of Strathclyde, and is structured as follows. We firstly present an overview of earlier work on CAD systems at Strathclyde, to provide a background to the ImagineD vision and current scientific work. Next, the key elements of the vision are elaborated, and ongoing empirical and theoretical research in each of the above areas is discussed. We conclude by summarising some of the key challenges that must be overcome to advance scientific models of designer thinking and behaviour in creative design, as well as effective supporting technology.

Research background

CAD involves the combined attributes of human and computer, and may be viewed as a collaborative effort between the two. Each entity has their own particular characteristics that contribute to the design process. The human cognitive ability to create, make decisions, deduce, reason, and judge are crucial components in the success of the design [11]. The computer's ability to carry out fast reliable processing, with large memory storage, has provided the designer with greater freedom to investigate and explore a broad range of solutions [12]. Historically, due to these attributes, computers were largely used in design as 'super calculators', leaving it up to the designer to carry out the 'intelligent' tasks. However, the development of software techniques over the decades has enabled the computer to contribute more broadly to the design process, beyond just analysis – for instance, visualisation, providing guidance, and supporting model building and refinement.

Research on CAD at the University of Strathclyde has been ongoing for nearly four decades. This work has focused on supporting and optimising the collaborative relationship between human and computer, ultimately aiming to achieve more seamless and intelligent working between the two. The importance of this goal has been recognised since the earliest stages of CAD development, with Mann and Coons [13] stating:

> *"It is clear that what is needed, if the computer is to be of greater use in the creative process, is a more intimate and continuous interchange*

> *between man and machine. This interchange must be of such a nature that all forms of thought that are congenial to man, whether verbal, symbolic, numerical, or even graphical, are also understood by the machine and are acted upon by the machine in ways that are appropriate to man's purpose."*

Since 1984, research on CAD at Strathclyde has been driven by a vision to conceptualise an Intelligent Design Assistant (IDA) within an intelligent Integrated Design Environment (IDE). More recently, since 2010 the research focus has shifted to understanding the cognitive and neural processing of human designers, with the long term goal of enabling symbiotic interaction between the designer and computer in creative design. Each facet of the work is outlined below, before the new ImagineD vision is elaborated in the next section.

Intelligent Design Assistant (IDA)

In the 1980s, the computer's ability to do more than act as a sophisticated calculator was developed through artificial intelligence techniques [14]. Popularity grew during this period with a series of mainly bi-annual conferences in Artificial Intelligence in Design (AID) (e.g. [15]). The ultimate objective of the field of AID research was essentially to develop a computer that can emulate the reasoning capabilities of a human. The early stages of engineering design in particular were identified as a key area where the computer's role could be evolved from that of 'calculator'. It is within this context that the notion of an Intelligent Design Assistant (IDA) was conceptualised by MacCallum et al. [11].

An IDA is viewed as a computer system that emulates a design colleague, assisting and complementing the designer in all aspects of their design task (Figure 1). In this role, the system should assist in specifying the design solution, explain results and the reasoning behind conclusions reached, and provide flexibility in changing and altering the design model's definition and in actions taken. It should allow interaction through a user-friendly 'intelligent' interface, and in essence, perform in a comparable manner to a human design expert but with all the advantages that the computer can provide. To complement this, the designer should be able to define the design problem in the manner to which they are accustomed, check and validate results, make decisions, and control the progress of the design process. In short, the abilities of human and computer should complement one another, and at the same time be used to the full.

In the context of the IDA concept, the key tasks of the designer and computer system may be characterised under the following headings:

- ***Creation/definition:*** The designer defines the problem and can create new design solutions, or modify existing solutions. The system represents the solution definitions and can operate on these definitions to assist the designer in his task.

- ***Interrogation/explanation:*** The designer can check and evaluate a design solution, and may interrogate the system to explain results and the reasons for actions taken during the design process. The level of explanation given by the system should satisfy any degree of the designer's curiosity and be easily understandable.

- ***Control/adaptation:*** Control of the actual design process, the system, areas and parts of the solution under consideration, and the definition of the design model should be in the hands of the designer. The system should allow modification to the solution throughout the design process, either as a direct result of changes made by the designer or through the refining process of design. In addition, the system itself must be open to modification and alteration, not only to different designers' needs but also to new techniques and approaches being developed. Thus, the system should be a flexible and adaptive tool that is utilised and 'tailored' by the designer.

- ***Decisions/guidance:*** The decision making process, the direction, and the control of the design should remain in the hands of the designer. The system should provide guidance that would be of benefit to the designer through the design process, such as the next best parameter to change, the best relationships to model the solution, and the likely areas in which a solution might lie. This guidance should be of such a form as to be readily understood and should meet all of the designer's requirements.

- ***Specification/calculation:*** The design solution is specified and controlled by the designer (parameter values specified) while the system carries out calculations to indicate the solution's envisaged performance (e.g. cost) with respect to the design goals (e.g. cost < n).

- ***Learning:*** The computer should provide the most up to date design expertise and knowledge. Hence, the system should be able to learn and update its own knowledge and expertise because of new and past designs. The system should also be able to evaluate the design process itself and possibly enquire from the designer reasons for particular actions taken. Consequently, the system should learn from the way the designer carries out design.

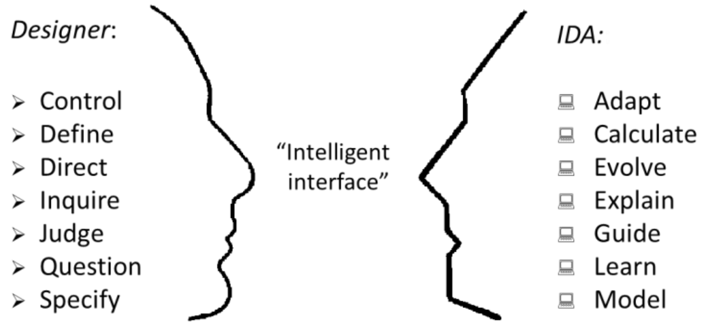

Fig 1. Roles of the designer and the computer [16]

A number of key requirements for an IDA that facilitates more intimate human-computer collaboration may be derived from the above characterisation of roles. Essentially, the system should 'understand' the design problem and act upon this understanding or knowledge to aid the designer in carrying out their design task. That is, the system should:

- Accept and represent a designer's description of the design problem.
- Allow the problem and its solution to be altered or modified during the design process.
- Assist the designer in describing and evaluating solutions.
- Guide the designer during the design process. This guidance should be presented in an easily understandable manner and meet all the designer's requirements.
- Explain results and the reasoning behind conclusions reached. This explanation should satisfy any degree of the designer's curiosity and be easily understood.
- Be open to modification, development, or 'tailoring' by the designer.
- Update and develop its own design knowledge and expertise because of new and past designs, or new techniques and approaches.

- Interact with the designer. This interaction should allow all the abilities of the system to assist the designer in the most effective manner possible.

Integrated Design Environment (IDE)

The IDA concept has driven research on CAD at Strathclyde since the 1980s. Up until the mid 2010s, the focus of this work was primarily on supporting the design process in complex engineered to order systems. In this context, the early vision was that there should be many different IDAs providing specialised assistance to teams of designers, as well as varied discipline-specific support and later life-phase expertise (e.g. production, assembly, and manufacture). Such a variety of IDAs needs to be integrated and co-ordinated through a virtual 'team manager' (the Virtual Integration Platform, or VIP) within an Integrated Design Environment (IDE) [16], as shown in Figure 2.

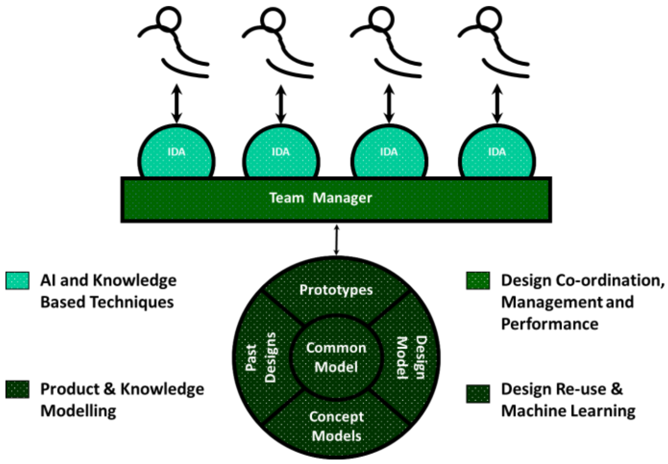

Fig 2. Intelligent Integrated Design Environment (IDE) [16]

The vision for the IDE and VIP was not only to integrate and co-ordinate multiple IDAs, but also to call upon a rich background of knowledge to facilitate the design development process. As shown in Figure 2, this repository of knowledge consisted of five main elements:

- The *design model*: A model of the design itself, not only geometric but reflecting different knowledge (e.g. design rationale), information, and data. This represents the design documentation/solution.

- *Prototypes*: 'Exemplars' that could be adopted at the early stages of design as a starting point for design exploration. These represent specific previous design solutions that can be adopted and adapted to suit new requirements, as well as general classes of solution types.
- *Past designs*: A repository of previous design solutions that can be interrogated and used in part or as a whole.
- *Concept models*: Similar to prototypes but at a more general level of abstraction and reflecting a specific solution type but general class of solutions. Generally at a high level of abstraction that would cover a wider potential solution space.

To develop the IDE and IDA concepts, research up until the early 2000s had a particular emphasis on: the fields of Artificial Intelligence and knowledge based techniques; design co-ordination, management and performance; product and knowledge modelling; and design re-use and machine learning. Research pre-millennium focused mainly upon developing IDA techniques, understanding, tools, and methodologies (Figure 3). As shown in Figure 3, this included product and knowledge engineering and management (core timeline), spatial and geometric modelling (top half), system configuration (top), knowledge re-use and learning (bottom half), and process management and process optimisation (bottom right).

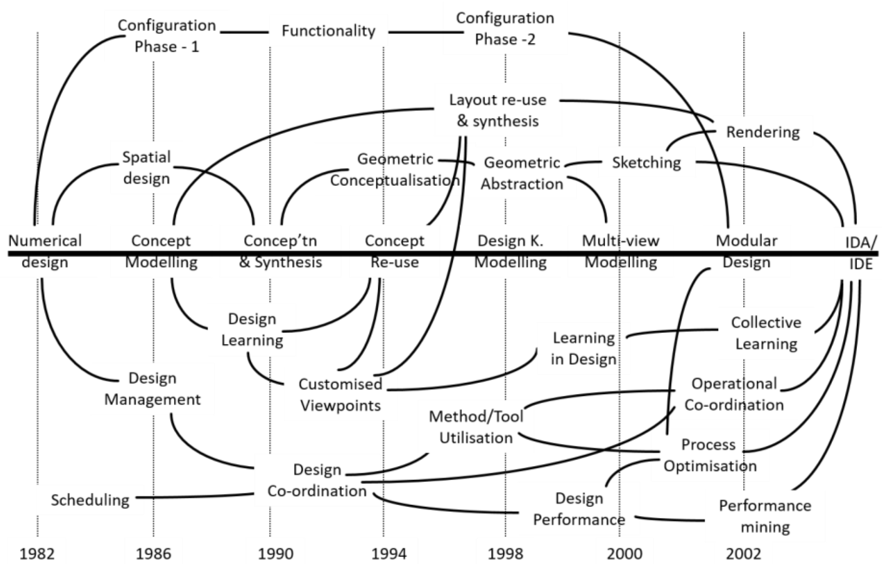

Fig 3. Focus of research pre-millennium

Post-millennium, the focus shifted to the integration aspects of the VIP, with research conducted across five projects [17–20]. As illustrated in Figure 4, these projects aimed to facilitate collaborative design and collaborative decision support, and promote collaboration through web-enabled design. The first prototype of the IDE vision of 1984 was realised in 2005 in the VRShips-Ropax 2000 project, and an evolved model tried and tested with industry in 2009/2010 primarily within the VIRTUE project.

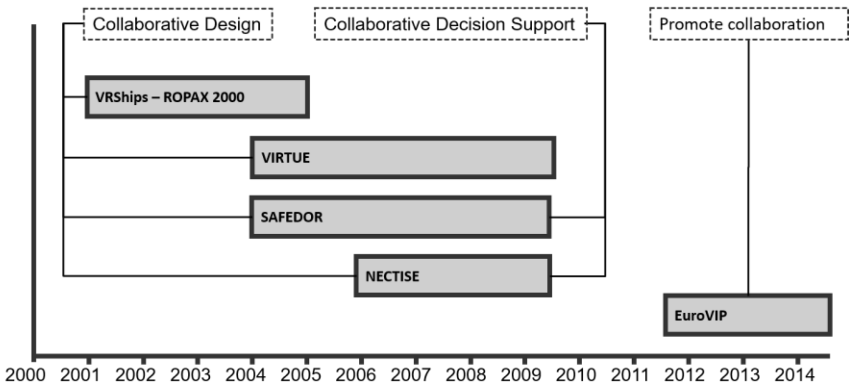

Fig 4. Post-millennium focus to mid-2010s

Towards a new vision for CAD

Although an IDE has been realised and significant progress has been made on IDA development since the 1980s, considerable research is still required to enable the kind of symbiotic interaction between human and computer that is needed in creative design. Fundamental modes of interaction are via the cognition, neural processing, and natural gestures of the designer; however, there is currently a lack of robust scientific models in all of these areas. Research will also be required to develop and integrate HCI systems to form an 'intelligent' interface, which can communicate the designers' thoughts and actions to the IDA and have the latter respond accordingly. Following completion of the IDE projects discussed above, the focus of CAD research at Strathclyde has shifted back to IDA and its relationship with the designer in order to tackle these challenges (Figure 5). This work is guided by the ImagineD vision introduced at the start of this paper, which is further elaborated in the next section along with current research activities.

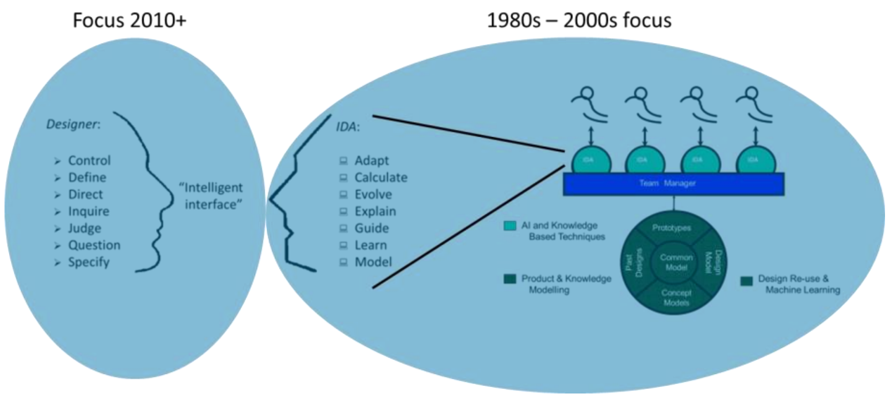

Fig 5. Overall research focus 1980s to present

The ImagineD vision and current research

ImagineD is a new vision for creative design: the designer is symbiotically connected to supporting computer systems, and the design process is directly driven by the designer's cognition and natural behaviour. The vision is illustrated in Figure 6. Advanced BCI technology will be used to seamlessly realise the contents of a designer's imagination as external representations in a virtual 3D environment, at various levels of abstraction and ambiguity. The designer will be able to intuitively interact with the virtual environment through their own natural gestures, using technology capable of instantaneously decoding intention from physical movement and enacting the required computational steps to realise it. Further intuitive control of the virtual environment will be possible through cognition via the BCI, which will also accurately respond to the designer's emotions (e.g. during evaluation activities). In the course of interacting with the virtual environment, the designer's internal conception of the design will change and evolve; in turn, the BCI system will seamlessly update the external representations in real time to reflect the designer's new understanding of the design.

Unlike existing CAD systems, the envisioned system will enable effortless, intuitive, and virtually unconscious interaction between the designer and computer systems, freeing up cognitive resources for creative thinking. It will also support abstract and ambiguous representations, as well as their rapid evolution and development, both of which are inherent to creative design. This will allow the benefits of computer-supported design [7] to be fully realised in the conceptual design phase for the first time. By significantly reducing (or even eliminating) the learning curve associated with CAD, design will be accessible to a broader range of people. This includes not only designers, but also non-expert stakeholders (e.g. users and customers) and even the general public. Computer-supported design could also become more accessible to the physically impaired, enabling people to enter/remain in the work force. From a social perspective, this could reduce care costs, enhance self worth, and perhaps also allow the ageing population to work later in life. In design practice, the system could support more efficient and effective collaborative conceptual design, by linking the cognition and behaviour of multiple distributed designers to shared external representations in a common virtual environment. At a basic level, it could lead to fundamental changes in the nature of the creative design process.

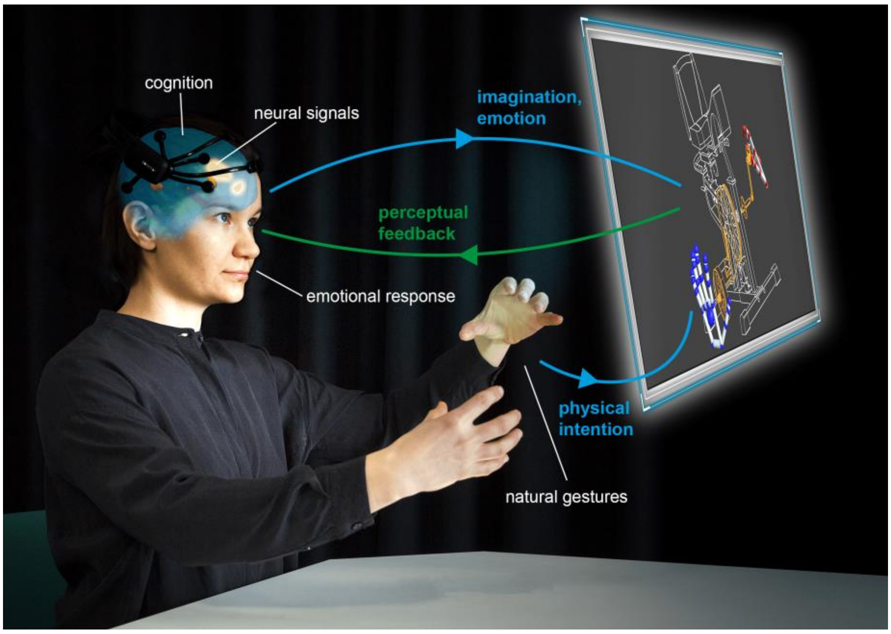

Fig 6. The ImagineD vision for cognitive-driven creative design

Achieving this long term vision requires scientific models and technological development spanning three main interacting areas, as shown in Figure 7: (1) intuitive gestures used by designers in 3D environments; (2) cognitive processes involved in creative design activities; and (3) the brain activity underpinning these cognitive processes. The following sub-sections provide an introduction to research in each of these areas that is currently being undertaken by the ImagineD team at Strathclyde, towards our vision for cognitive-driven design.

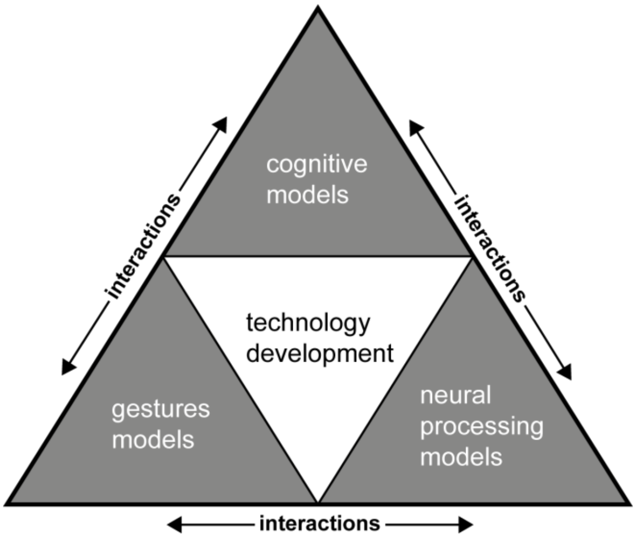

Fig 7. The scientific basis and technological development required for realising the ImagineD vision

Intuitive gesture interaction

Gestures are a natural and fundamental means through which humans interact with the world around them. They can be used for communicative purposes, to manipulate physical and virtual environments (ergotic gestures), and to learn from an environment through exploration (epistemic gestures) [9]. As demonstrated by our recent systematic review of the literature [9], the use of gestures in human-computer interfaces (HCI) has been widely researched across a variety of domains. Existing research has focused heavily on technology implementation, and gestures for use in HCI systems are frequently selected based on ease of implementation. Additionally, the majority of existing work focuses on the use of prescribed gestures that must be learned by the user, and leans heavily towards speech-related gestures as opposed to ergotic and epistemic gestures.

With regards to achieving natural, intuitive gesture interaction in cognitive-driven design, there are two shortcomings in existing work that must be addressed. Firstly, two key purposes of gesture interaction in this context are: (i) manipulating 3D representations in a virtual environment; and (ii) exploring the representations to support reinterpretation and decision making about the emerging design. Thus, there is a need to increase the intensity of research on ergotic and epistemic gestures in design environments. Secondly, achieving intuitive gesture interaction in creative design requires identification of the most appropriate gestures for different design activities – not just prescribing those that are easiest to implement technologically. However, little is currently known about the natural and intuitive gestures used by designers during the design process. There has been research on natural gestures used in collaborative design discussions [21], but not the manipulation and exploration of representations in a CAD context.

We have begun to address these challenges in ongoing work aiming to identify natural and intuitive in-air hand gestures for design. The research focuses on the natural, non-prescribed gestures used by designers to manipulate, interact with, and create digital object and product representations. An initial pilot study with 7 product designers reported in [22] showed both between-participant and within-participant repetition in the natural in-air gestures used to interact with and manipulate 3D objects. This suggests that a set of standard intuitive gestures could potentially be derived for design. Further investgation is currently under way in a large scale study of 80 designers.

Creative design cognition

Research on cognitive processes in creative design can be traced back to protocol studies by Charles Eastman in the late 1960s [23]. Since then, the field of design cognition has expanded significantly, with a sizeable body of literature and regular international meetings of the community (e.g. [24]) . However, systematically reviewing protocol studies on conceptual design conducted over the past 50 years reveals a lack of ontological clarity [25,26]. Due to inconsistencies in the concepts and terminology used to describe cognition by different authors, it is not clear what cognitive processes actually exist in the domain and how they should be defined for study.

The lack of a common and consistent design cognition ontology is problematic for two reasons. Firstly, it is difficult to formulate coherent research questions, interpret the results of different studies, and synthesise these towards the development of general models and theories of cognition. Thus, the scientific progression and maturation of the field is hindered [25,26]. Secondly, without robust and consistent scientific knowledge about cognitive processes, it is difficult to obtain meaningful and reliable results about brain activity from functional neuroimaging methods [27]. Cognitive neuroscientists aim to map clearly defined cognitive processes onto brain regions, through the use of experimental tasks that are carefully designed to elicit the processes of interest in a sample of participants undergoing brain imaging. In the study of design activities, we are currently unclear on what the processes of interest even are – never mind how to consistently elicit them across different designers in a brain imaging study. Neuroimaging (discussed in the next section) is fundamentally important for realising the ImagineD vision, and thus clarifying the design cognition ontology is a key challenge to be addressed.

Towards addressing the above issues, we conducted an initial mapping between cognitive processes studied in design cognition research and more established processes defined in the psychology literature. This resulted in the first generic classification of cognitive processes in conceptual design activities, providing the basis for future ontological development [26]. We have since applied this classification to support the design of several cognitive studies, which address another shortcoming highlighted by our systematic review: the tendancy for design cognition research to focus primarily on small-scale, exploratory studies using protocol analysis. Whilst this approach can provide a rich, in depth view on new or under-explored areas, there is a need for work that begins to build upon these intial findings through larger-scale, quantitative hypothesis testing. We are currently applying quantitative methods from psychology (e.g. behavioural experiments and standardised psychological tests) to study large samples of product designers, with the aim of characterising the cognitive processes involved in creative design activities in a more scientifically robust way. This work includes studies on cognitive abilities and unconscious incubation processes in ideation, and conceptual combination processes in design synthesis [1,2].

Neural activity

Central to achieving the ImagineD vision is developing the capability to directly capture and seamlessly realise the contents of a designer's imagination in a virtual environment. Alongside this, the designer must also be able to effortlessly exert control on the virtual environment and external representation through their cognition. This requires neuroscientific research to address three key challenges: (1) measuring neural activity to identify brain regions activated during creative design activities, particularly ideation/imaginative activities; (2) decoding imagined representations from brain activity and reproducing these virtually; and (3) decoding intention from brain activity and implementing the intended effects. Work towards challenges 1 and 2 is currently ongoing at the University of Strathclyde, with 3 forming a longer term focus.

Identification of activated brain regions:

Regarding challenge 1, functional magnetic resonance imaging (fMRI) is widely applied in cognitive neuroscience to map the brain regions associated with cognitive activities. Human creativity is a growing area of research in this domain; however, studies of domain-specific creativity and creative professionals are limited. Furthermore, whilst there are a small number of studies on design, none of these focus on professional product designers and/or engineers. To address this and provide an initial foundation for future neuroimaging work towards the ImagineD vision, we conducted an fMRI study of ideation in professional product design engineers [28,29]. We investigated the brain regions associated with ideation in response to open-ended and constrained problems in a sample of 29 designers, using an imagery manipulation task as the control condition. Key findings were:

- No significant differences in brain activation were observed between creative and innovative ideation, suggesting that these processes involve overlapping brain regions.
- Compared to the control task, ideation was associated with greater activity in the left cingulate gyrus, and preliminarily also in the right medial frontal and right superior temporal gyri.

fMRI studies of general creativity tasks have shown that the anterior cingulate cortex likely plays a role in inhibition and response monitoring. Thus, this region could support the inhibition of inappropriate/unoriginal solutions and solution evaluation in design ideation. The superior temporal gyrus has previously been associated with creative insight, which is a well documented phenomenon in design ideation. It is likely, however, that design ideation is a complex cognitive activity involving numerous interacting processes and brain regions [30,31]. Further studies are needed to build upon this initial work and develop a more comprehensive understanding. Nonetheless, with respect to the ImagineD vision, the observed activations in pre-frontal regions are encouraging, as BCI systems utilising intentionrelated activity within the prefrontal cortex are already in development [8,32,33].

Decoding imagined representations:

Regarding challenge 2 above, there is an emerging body of work on neural decoding using both fMRI and electroencephalography (EEG). Studies have focused on decoding of conceptual categories [34], visual perception [35], and mental imagery [8]. In terms of technology development, fMRI is currently not a particularly feasible route for enabling cognitive-driven design due to the large size of the scanner, the involvement of powerful electromagnets, and restrictions on human movement. However, EEG – which is more portable – is more promising, and EEG-based BCI headsets are slowly improving in performance and usability [36].

Whilst decoding conceptual categories may be an important component of a BCI system for cognitive-driven design, capturing the specific contents of a designer's imagination will fundamentally require the decoding of imagined shapes as well. A single EEG study in the literature has investigated the possibility of classifying imagined primative 3D shapes (e.g. cube, cone, sphere) from EEG signals [37], but suffered from low signal quality due to the use of a commercially available headset rather than the more advanced equipment typically used in a lab setting. To address this limitation, we have used a higher performance EEG system to investigate decoding of five primative 3D shapes. In an initial pilot study [38], 10 participants were presented with images of the shapes as a cue, and then asked to imagine the presented shape after the cue was removed while undergoing EEG recording. A machine learning-based classifier was then trained to decode the imagined shapes from the EEG signal. The results from this initial study suggest that there is separability between the imagined shapes in terms of their associated brain activity patterns, although this separability is lower than in other mental imagery tasks e.g. imagined motor actions. The classifier was able to decode imagined shapes with a maximum accuracy of 37%, which is significantly higher than chance level (20%). Further studies are under way and additional results will be reported in a forthcoming journal article [39].

Discussion

Since research on AI in Design in the 1980s, and the conceptualisation of the IDA, there have been significant advances in computing systems and HCI technologies. However, as discussed in this paper, commercial CAD systems are still not well suited to supporting creative design. They are advancing incrementally, without the radical changes needed to achieve more symbiotic and intelligent interaction with the designer during creative activities. We have outlined a new vision for creative design, where the designer and computer interact seamlessly and effortlessly and the design process is directly driven by the designer's cognition and natural behaviour. Realising this long term vision is still some way off, and will require numerous research and technological challenges to be addressed. Some of the key challenges are summarised below.

Robust scientific models of cognition, neural processing, and gesture interaction in creative design are fundamental for realising the vision. Without valid and reliable knowledge in these areas, it is difficult to identify and develop the HCI technology needed. A fundamental challenge in this area is the need for a common cognitive ontology of creative design [24], as outlined in previous sections. Such an ontology would provide a consistent framework for formulating hypotheses and research questions, designing studies, and interpreting results to advance general models and theories of cognition and neural processing. At the moment, it is difficult to compare, synthesise, replicate, and build upon studies due to fundamental differences in the cognitive concepts and terminology used. There is also a need for larger scale, quantitative and/or mixed methods research to build upon the plethora of small scale, exploratory protocol studies conducted to date. Although the latter are useful for exploring new or under-researched areas, we need to ensure we move beyond initial description to prediction, explanation, and theory-building/evolution.

From a methodological perspective, neuroimaging methods are necessary for advancing our knowledge of neural activity in creative design. However, they are challenging to apply due to the characteristics of designing (and in particular, creative design). For instance, sketching, verbalising, and gesturing are often key elements of design activities, but physical motion can negatively affect neuroimaging results and is therefore typically constrained or avoided completely. There are also temporal issues – creative design can unfold over minutes, hours, days, weeks, months, and even years, but most neuroimaging methods capture brain activity over short periods of seconds or minutes. The variability of creative processes compared with other kinds of processing is also problematic. As noted by Abraham [40], there is a difference between 'being creative' and 'trying to be creative', and it is difficult to 'turn on' creativity when required within the constraints of an experimental paradigm. This may impact upon the validity of results. Lastly, with respect to ecological validity – creative design is a complex activity that likely involves a broad range of interacting cognitive processes. It is also situated, i.e. affected by the environment within which it takes place. Considering this, alongside the constraints on physical activity discussed above, raises the question of whether we can develop experimental tasks for neuroimaging that actually reflect the natural thinking and behaviour of the designer, and what this means for the results obtained.

In terms of actually developing an interface and supporting systems to realise the vision, a key barrier at the moment is the immaturity and limitations of existing HCI technologies. For instance, the capability to accurately decode and reproduce externally the contents of the imagination is still a long way off. Developing an interface that is practical and commercially viable will likely require significant advancements in BCI technology over the coming decades (e.g. [41,42]), and research will need to progress in step with this. The ethical and social issues surrounding technology that can 'tap in' to the human mind and brain will also need to be considered and addressed (e.g. see [43]). In addition to the challenge of implementing and integrating suitable HCI technologies, it will also be necessary to ensure that broader requirements for computer support in conceptual design are met. As demonstrated in [7], these are complex and varied, spanning the initial ideation process, the digitising of design and translation of design requirements, and design review and evaluation. A key requirement is that any system developed for conceptual design can be seamlessly integrated with systems for downstream activities. Thus, the scope of research will need to be expanded again from the relationship between the designer and IDA to the Integrated Design Environment of the future.

Concluding remarks

To summarise design and conclude, it took 30 years to realise the initial 1984 Strathclyde vision of an Intelligent Design Assistant (IDA) operating within an Integrated Design Environment (IDE), with the first prototype IDE created in 2005. The focus of this ongoing work has now shifted to the new ImagineD vision: here, the designer is symbiotically connected to supporting computer systems via brain-computer and gesture recognition interfaces, and the design process is directly driven by the designer's cognition (via neural signals) and natural behaviour (via intuitive gestures). It is envisaged that this will be realised in the long term future, and will require significant research and technological challenges to be overcome. Currently, these challenges include:

- The development of scientifically robust models of cognition, neural processing, and gesture interaction in creative design.
- The development of a common cognitive ontology in creative design, to provide a consistent framework for hypothesis testing and theory development in cognitive and neurological research.
- Conducting larger scale, quantitative and/or mixed methods research to build upon the small scale, exploratory protocol studies currently favoured in design research.
- Addressing the limitations of neuroimaging methods for studying design, including: constraints on physical behaviour during data collection; the temporal nature of design versus short data collection periods; the variability of creative processes versus the need for highly controlled experimental conditions; and the trade-offs between neuroimaging constraints and the ecological validity of design tasks studied.
- Technological advancement of currently immature HCI technologies (e.g. mental imagery decoding and virtual reproduction), to the point where developing a cognitive-driven design interface is practical and commercially viable.
- Addressing the ethical issues associated with technology that can interface directly with the human mind and brain.
- Ensuring that broader requirements for computer support in conceptual design are met, including seamless integration with downstream activities.

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