Eckert, C.M., Blackwell, A.F., Stacey, M.K. and Earl, C.F. (2004). Sketching across design domains. In Proceedings of the Third International Conference on Visual and Spatial Reasoning in Design (VR'04).

SKETCHING ACROSS DESIGN DOMAINS

C M ECKERT, A F BLACKWELL
University of Cambridge, UK

and

M K STACEY, C F EARL
De Montfort University, UK, Open University, UK

Abstract. Sketching research so far has focused on sketching in a particular phase in specific design domains. This paper draws on descriptions of design processes given by designers from a wide variety of domains, as part of a research project on comparisons across design domains. A comparison across design domains draws attention to the multiple roles and forms sketching can take in idea generation and communication. Sketches are used as depictions of potential objects in idea generation, but also as thinking aids for reasoning about abstract concepts. They are used in those domains, such as software design, where there is no pictorial description of the product, but also in more visual design domains such as engineering design, to sketch out abstract properties. Sketches are a vital means of communicating design ideas. This paper also looks at the way the functions of sketches are performed by other media in those domains that don't produce visual products, as well as additional media in those that do.

1. Introduction

Sketching is a vital part of the public image of design. A designer sitting at a desk, fluidly drafting an impressionistic rendering of a new idea, is a popular picture of the designer at work. However while many designers do engage in this type of sketching activity, such sketches are only a small part of the entire design process. Other designers never sketch, either because they generate ideas in their heads or because they work in design domains too abstract for pictorial representation. However every designer needs a way to express imprecise and provisional information. This paper looks at sketching in a range of different design domains and analyses the different roles a

sketch can have, including ways in which the main functions of sketches may be carried out by other representations.

The word ‘sketch’ is used in two related senses. First: to create a drawing on paper that depicts something in an informal way, where decisions are to some extent provisional and details approximate. (Informality is relative: engineers reserve the word ‘drawing’ for precise formal depictions with exact measurements; anything less formal is a sketch, even precise-looking pictures that non-engineers would never call sketches.) Second, by metaphorical extension: to describe something in a quick informal imprecise way, in which details are inexact, provisional or missing. This paper focuses mostly on sketches as marks on paper, which might be called *drawings* by architects or *thumbnails* by graphic designers. But we are interested in how the functions of sketches are met in other ways. Occasionally people talk metaphorically about sketches when they mean vague verbal descriptions, but this meaning will be highlighted whenever it occurs.

Sketching research so far has primarily been conducted from the viewpoint of a particular domain, so that our understanding of sketching is influenced by the use of sketching in a particular domain at a particular time in the design process. For example, sketching has been intensively studied in early architectural design, where solitary designers begin to develop the conceptual design for a building by sketching out a floor plan or a view of the building. An extensive body of research on how architects and other designers use sketches, notably by Goldschmidt (1991, 1994, 1999) and Goel (1995), has focused on how designers reinterpret elements of their sketches (see Purcell and Gero, 1998, for a review). Schön (1983) views this interaction with the sketches as a conversation: the designers see more in their sketches than they put in when they draw them, and these insights drive further designing; designers alternate between *seeing as* and *seeing that* (Schön and Wiggins, 1992). Similarly Goldschmidt (1991) observed architects’ conceptual designing proceeding through an alternation between pictorial and non-pictorial reasoning.

In this paper, we offer some further evidence in support of this view of sketching (the section entitled “Imagery and Creative Discovery”), but we also consider many other ways in which sketches are employed in design processes, projects and organizations. These results are derived from a series of workshops and interviews with expert designers recruited from a wide range of disciplines within a large project called “Across Design”.

In the rest of this paper, we first describe the structure and methodology of the Across Design project, then present our findings grouped in areas of thematic interest with regard to the properties and function of sketches.

2. The Across Design project

The Across Design project is a multidisciplinary project with researchers from engineering, computing and architecture. The researchers on the project have conducted detailed observational studies of design practice, conducted experiments, and interviewed hundreds of designers in the course of their own past research. The aim of this project is to investigate similarities and differences between designing across industries, and seek ways in which best practice can be transferred. One possible theoretical perspective on how to do this is described by Stacey *et al.* (2002).

2.1. ACROSS DESIGN WORKSHOPS

The project is composed of a series of workshops in which designers with more than 10 years' experience talk about their design processes to an audience of three to five expert designers from other fields and a small number of interested observers as well as members of the project team. By design, these workshops are intended to collect narratives and subjective views, while enabling an in-depth analysis of the experiences, opinions and presentations of one or two representatives of each field. The analysis is qualitative and grounded in the experience brought to the project by the team members. We have conducted five of these workshops, involving 20 expert witnesses from a very broad range of design disciplines, as shown in table 1. All presentations are videotaped and recorded, exhibit material is photographed (or copied from presentation files), and recordings are fully transcribed.

Before the workshops, the designers were provided with a framework of design issues, as a briefing document, see section 2.3. The designers were asked to give presentations of around 30 minutes, and spoke for between 25 and 70 minutes, taking questions from the academic and industrial participants alike. After each presentation the academic participants asked clarifying questions and encouraged a discussion amongst the participating designers. These discussions were generally free and enthusiastic. The academics asked questions related to specific areas of the framework, in cases where the speaker did not appear to have addressed that area. Several presentations were either preceded or followed by individual interviews with the designers, conducted by a smaller group of researchers.

2.2. WORKSHOP PRESENTERS

At each workshop we aimed to have presenters from a wide variety of industries so that they could observe and comment on the similarities and differences between them. The designers were selected mostly through personal contacts of the research team or through recommendations by other

workshop participants. The participants were paid only travel expenses and joined the workshops out of genuine interest in design practice in other fields. The group of participants is self-selecting for people sympathetic to academic research and interested in reflecting about design processes.

In our analysis later in this paper, the designers are grouped into the following categories according to the usual work practices of that discipline, into Prime Users, Occasional Sketchers, and Non-Sketchers.

TABLE 1. Participant Design Disciplines in Five Workshops

Oct 2002 (UK)	Diesel engine designer, Software designer, Product designer[1], Urban planner
April 2003 (UK)	Civil engineer, Web designer, Product designer, Drug designer
July 2003 (UK)	Graphic designer, Jet engine designer and senior manager, Film maker
Nov 2003 (UK)	Artistic fashion designer, Medical device designer, Food designer, Packaging designer, Architect
Jan 2004 (USA)	Architect, Technical fashion designer, Automotive designer and senior manager

2.3. PRESENTER BRIEFING

Prior to the workshops, the research team developed a framework of questions covering major issues of design in a fairly comprehensive way, based on their combined long term experience in different fields of design research. Participants were given a copy of this framework before each workshop in order to inform them of the issues that we were interested in, and provide some guidance regarding the scope of the discussion. Figure 1 shows an extract from this briefing material. The framework was partitioned into sections dedicated to *markets*, *organisation*, *requirements*, *process*, *data*, *complexity*, *representation*, and *evaluation*. Each of these sections was broken down into sub-issues. For example, *markets* was broken into *customers*, *intermediaries*, *market trends*, *diversity*, *consultation*, *inclusion*, *product ranges* and *innovation*. These summary terms were illustrated by specific questions. For example under customers, illustrative questions included “Who is your customer?”, “Is this the same person as the end user of your product?”, “Do you design for an individual, a market sector or a group of clients?”

[1] Product designer means a person or firm providing product design services for a variety of firms and product types

The participants were asked "to choose a *single* design project from your experience, and present it to the group as a case study to illustrate the design issues and challenges that arise in your profession", but were also told that "*We do not expect you to address all the issues that we have listed exhaustively*". They were encouraged to concentrate on those issues most pertinent to their own field. We recognise that the group of participants is self-selecting for people who are interested in reflecting on their design processes. In some of the domains we consider, this tendency to reflection might not be typical among the practitioners in that field.

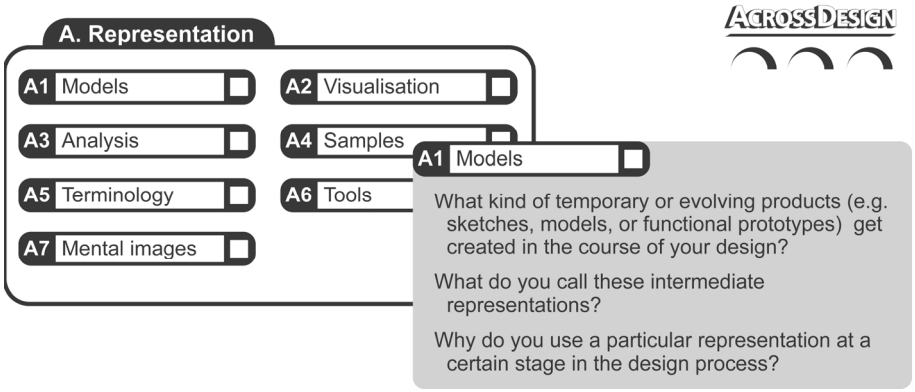

Figure 1. Extract from participant briefing material

Our analysis is qualitative and grounded in the experience brought to the project by the collaborating participants. We have chosen not to emphasise generality, or inter-rater reliability from our multiple inspections and coding of transcript material. Our intention is to make best use of the resource of experience among participating design experts, who draw on many years of experience and a rich context of design processes and products. The project aims to draw a rich picture of design and show through instances, where similarity and differences do lie.

For the purpose of this paper the first author has systematically gone through the completed transcripts and highlighted all discussion of sketches or other forms of provisional information, in order to gain an overview of the issues pertinent to sketching. The second author has collected all material that was coded as pertaining to sketching during the workshops. In the analysis framework all issues of *representation* are pertinent to sketching. In the paper we will discuss the role of sketching, as well as other ways in which this role is carried out. Specifically issues concerning *the phases of design*, *precedents* and *provisionality* are relevant, as well as consultation and *interaction with complexity*, both as *coping measure* and as way of *handling uncertainty* in design. *Formality* is also relevant to sketching.

3. The Roles of Sketches

Sketches, as marks on paper in various degrees of refinement, have multiple roles in the design processes. They are a means to generate or communicate ideas about the product, but also about the process itself. Some designers use sketches of design plans to do this, as illustrated by this web designer:

> "So, these steps in our phases, they came about initially at the planning workshop, I have a piece of paper somewhere where I sketched them by hand."

Here we will concentrate on sketches of products, where the same sketch can play multiple roles. In many design processes all these roles of sketches occur, although some are apparently missing in certain disciplines. In the following sections, we highlight several of these roles, summarizing previous research, followed by findings from our analysis of informants' contributions in Across Design.

3.1. MENTAL IMAGERY AND CREATIVITY

The nature of mental imagery is not yet fully understood, and debate continues about whether imagery is essentially pictorial, and associated with symbolic information about the identities and properties of the objects imagined (see Kosslyn, 1994) or is essentially symbolic, comprising information *about* imagined objects (see for instance Pylyshyn, 2003). Several cognitive accounts of sketching have focused on the use of an external representation as a tool for discovery of new content in images (Chambers & Reisberg, 1985; Finke & Slayton, 1988; Finke, Pinker & Farah, 1989; Finke 1996). According to these theories, mental images are relatively tightly bound to fixed semantic interpretations, whereas external percepts can trigger different interpretations. This means that people can facilitate the discovery of new information in a form imagined as a mental image by a process of externalizing that image (drawing a potentially ambiguous sketch of the imagined form), then inspecting the sketch to discover a creative new interpretation.

It seems that designers can readily find unintended configurations of sketch elements (Goldschmidt, 1999), although this ordinarily requires active interest in new possibilities, usually triggered by dissatisfaction with the current design (McFadzean *et al*., 1999), or forgetting of context. As shown by Finke's (1990) findings on how preinventive forms can facilitate creativity, using chance forms to meet design goals is often a fruitful idea generation strategy. For reinterpretation leading to creative insight, ambiguity is a benefit, regarded as important by both researchers and reflective practitioners.

The cognitive science literature reports substantial controversy around these issues, with both sides of the debate supported by experimental evidence. It is therefore interesting to inspect the assertions of designers with regard to the relationship between sketches and mental images as a strategy for discovery or creativity. In the past we have found that even designers in detailed and technical disciplines (the software industry) report vivid mental imagery in experiential accounts of their own design process (Petre & Blackwell, 1997). Our own informant from the software industry confirmed those findings in reporting his own introspective insight that "Designing software is a visual process".

Several of our designers referred to mental images as somewhat ineffable sources of inspiration, for example a product designer saying that inspiration comes from "three gin and tonics and a hot bath", but many were intrigued by the imagery inherent in their own processes, grappling with a representation that can't quite be pinned down. Both fashion designers spoke of an almost mystical "feel" associated with the early creative stages incorporating impressions of force and movement.

Figure 2. Mood board for product design showing multiple sketches of the object and the sources of inspiration for it. While we don't know for what role the rough sketches have originally been drawn, they give a good impression of an idea generation sketch in product design.

3.2. THE PROCESS OF IDEA GENERATION AND RECORDING

This creative process can occur in a solitary situation. However joint sketching also plays a very important part in joint designing, where designers often draw on the same sheet of paper, and again benefit from reinterpreting ambiguous marks (Bly, 1988).

Sketches also play an important role in visualizing and capturing ideas during early stages of the design process. These sketches are often done very rapidly and not worked out in detail, but enable designers to get a feeling for the design space and to compare and evaluate their own ideas (see Figure 2). As one of our product designers put it: at the beginning of the design process:

> "We really need to get familiar with the product and that's done through those visits but also through understanding the products and brainstorms. And we will then start to initiate it here, the initial sketch freehand, and come up with quite a lot of ideas in three dimensions, drawings and sketches with a bit of colour on."

Another of our informants put the emphasis on capturing design ideas as they are developed through sketching. A senior jet engine engineer commented:

> "I am a great believer in sketching as well. I believe that sketching itself, not only is it able to capture the concepts, but it is also a way of being creative. Let your fingers do the thinking if you like. So I am a great believer – and I watch my guys when they are working, they do use sketching, and I am sure at the time they are being creative as well as recording."

In many instances it is difficult to draw a line between sketching to generate ideas and sketching to communicate these ideas. This is illustrated by the sketches in Figure 2 as well as the quote above. Designers need to record their ideas in order to develop them.

It has been noted in the past that introspective reports of mental imagery or "visual thinking" are correlated with personal assessments of creativity (Katz, 1983). It is not certain in which direction the causal relation lies for these reports. Several of our informants described their own sketches either as evidence for us of creative originality (in the case of fashion designers), as evidence for clients of the creative nature of the work (in the case of a product designer), or as a strategy for rejuvenating creative practice within a large corporation (in the cases of aerospace, automotive design, and

packaging design). In these latter cases, the sketch is seen as a generator of creativity, or possibly an outcome of creativity, with the exact status uncertain. This is the same ambiguity with respect to causal relationships that has been found in reports of mental imagery.

3.3. VISUALISATION OF ABSTRACT PROPERTIES

Several of our informants work in domains where the relationship between the design parameters and the physical configuration of the product is extremely complex. In drug design, the relationship between the shape of a molecule and its physiological effects is hard to predict. In ice-cream design, the microstructure of fats and emulsifiers contributing to mouth-feel and visual appearance is also extremely subtle. In these domains, designers reported that they use an abstract multivariate design space to describe the desired properties of the end product. The drug designer specifically creates sketches of desirable regions within these spaces (see Figure 3) However there is no direct relation between the abstract space and drawings of a molecule structure or micrographs of phase structure.

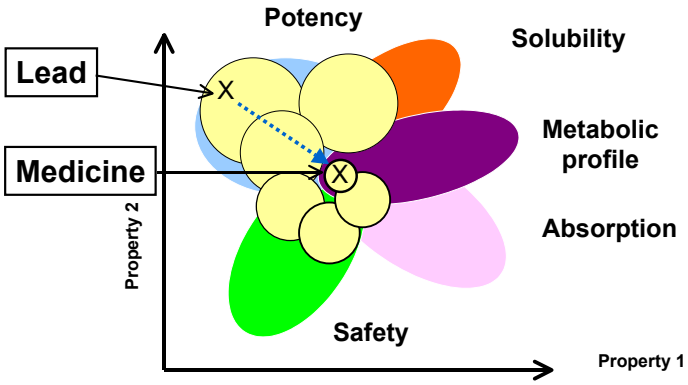

Figure 3. Computer drawn version of a problem space sketch, taken from our drug designer's presentation

Similar visual representations of abstract design spaces are used in large organizations with highly quantified and parameterized iterative design processes such as aerospace and automotive design. Some of our informants were senior designers in these fields (vice-president level), and their perspective of the design process was gradual change in a large number of performance parameters over successive model introductions. This multi-variate space was more similar than might be expected to the property spaces considered in drug or food design, despite the physical dissimilarity between the products themselves. At this level of analysis, design managers make sketches of desirable regions within the abstract performance space that

complement the sketches they might encounter presenting proposals for the physical form of new models.

In the case of software design, the space is necessarily abstract. In these cases, it is configuration rather than form that is perceived in sketches. Our software designer described the way that inter-linkages, when viewed within the Gestalt of an overall system design, can help the designer to re-conceptualise the structural core of the design. He was pleased with the fact that the standard sketch formalism in his discipline, the "universal bubble and stick diagram", was in fact completely free of prior semantic associations.

> "When I'm designing software, I like to draw sequence diagrams with pencil and paper …. I couldn't find a piece of paper on my desk that didn't have a diagram on it."

Recording ideas plays just as important a role in abstract domains as it does in the more visual design domains.

3.4. COMMUNICATION TO OTHERS

Not all designers use sketches to generate ideas, but for many designers the most fundamental role of sketches is to communicate quickly with others, as expressed in this quote from an architect

> "When you draw you're trying to express something to somebody else. You're trying to reach across to someone else and to show them something. That quality of reaching across means that you can work with people who don't draw. I work with someone who draws really badly, awful. I'm embarrassed of his drawing, but he asks the right questions. He pushes the pen in a funny way and it's so ugly to look at, but his ideas are fantastic. So it's not about good sketching and bad sketching, it's about the quality of the vision to communicate and that's the crucial stage, of course you don't let them draw the picture for the client because that puts them off, but they know to share, is that true? There are lots of interesting different qualities of sharing in design. Very, very important."

Studies of sketching in engineering design, have mainly concentrated on using sketches to develop designs jointly in meetings. Tang (1989, 1991; Tang & Leifer, 1988), Bly (1988), Minneman (1991) and Neilson and Lee (1994) have shown that designers use speech, sketches and gestures in combination, using each mode to explain and disambiguate the others. Studies of solitary engineering sketching (Pache, 2001) have seen a wide variety of different sketching behavior and ability, with evidence for the reinterpretation of ambiguous notation in only a small number of cases. The key challenge for many mechanical engineers lies in expressing and visualizing movement of multiple parts through sketches.

An analysis of sketching behaviour in the knitwear industry (Eckert, 2001; Stacey *et al*., 1999) looked at the use of sketching to express design ideas at a handover point between different stakeholders in the design process. In the knitwear industry sketches, measurements and verbal descriptions were used together to form inconsistent, incomplete and inaccurate specifications. These ambiguous specifications were interpreted according to the recipients' personal experience, and the sketches were largely ignored.

3.4.1. Consultation and Concreteness

Sketches are often used as the intermediary objects in the communication between different groups of people. Several designers were concerned that their clients or customers have difficulty in understanding formal product specifications, so provide sketches and models to help achieve a concrete understanding of the design proposal. But sketches can also help users relate to the product concept in their lives, as when an architect makes sketches of a development as it would appear at different seasons of the year, so that participants in a public consultation meeting can imagine how it would be manifest in their own lives (see Figure 4).

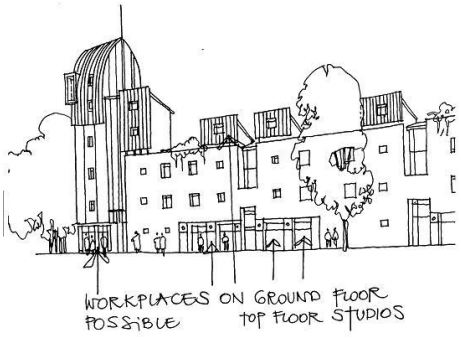

Figure 4. Architectural sketch

Architects often interact with official bodies, such as local councils, who have no specific understanding of the process of designing buildings, for whom they generate sketches throughout to document the process.

> "One of the things that happened – and I know this is very crucial in the design process, is we thought: 'we won't draw anything yet' but we actually we need to draw something really quickly – otherwise people don't believe you. It's no good drawing blobs and saying 'it'll be lovely later'. They want to see what it's like right away." (Architect)

3.4.2. Consultation and Fluidity

Our graphic designer used sketches to reinforce the fluidity of the design process when consulting with clients. She created pages of thumbnail-sized alternative renderings (produced using computer tools), bringing them to client meetings specifically so that she could "scribble" over her preparatory work. The packaging designer had experimented with this approach in a more formalized consultation process, by bringing a visual designer to a market focus group, and having that design produce sketches "live" during the focus group meeting, so that participants directly appreciate the opportunity they have to modify the proposals being discussed.

3.4.3. Consultation and Selection

Several informants described the way that sketches can be used to engage customers or clients with the design process. Sketches play an important part in the selection of design concepts, and designers preselect their sketches so as to guide their customers to the designs that they favour. Our car designer cynically described the practice of some offices as a "snow job" in which a wide range of design sketches are displayed on the studio wall to clients who might be sufficiently impressed by creative diversity (or simply distracted by the colours) that they relax creative control. One of the product designers guided the customers strongly through his selection of sketches:

> "In our case, I tended to present maybe two or three designs, and I would normally know which one I wanted the client to buy and I had good reasons for wanting him to buy, and so I used that approach."

While another product designers is less restrictive and shows his customers a wide range of sketches:

> "We have hopefully created a vision for the product in terms of a lot of sketches. Clients choose one or two, which we then have to work on in more detail for them."

Even where the client is open-minded, it is possible to get them more engaged in the process (according to an industrial product designer) through the use of freehand sketches that illustrate a creative product "vision".

3.4.4. Joint Designing

Designers routinely exchange sketches with their colleagues through the design process, as illustrated in this quote by a web designer:

> "The left-hand side shows the faxed sketches he sent to me. Once I had chosen one, middle black circle shows the worked-out image, also faxed, and then the last images show the final graphics."

In many case this is part of a dual negotiation processes: negotiation for understanding and negotiation for meaning. If designers do not understand the sketch, they then discuss this meaning using gestures and speech to

disambiguate the sketch (Bly, 1988; Tang, 1991). In doing so ideas are often developed further and designers gain new insights in the problem. Another form of negotiation occurs when people have different viewpoints that need to be resolved by a common compromise solution. Problems arise when different parties don't recognise that they have conflicting opinions, and assume that others will be able to interpret design information as intended by its originator (see section 7). Some of these issues are exemplified in the following quote from the graphic designer:

> Questioner: "*Do you find that people can interpret the sketches the way you would like them to interpret them or do you find that sometimes do they interpret them differently*?"
>
> "People generally speaking don't understand drawings. If we want to redesign something then you have to…then you get the right answers."
>
> Questioner: "*But even your colleagues, would they*?"
>
> "If not, then they don't have a job. Well, I think when you work in a small team like that you understand each others' ways. With clients there are just so many decisions."

Our software designer, our food designer, a fashion designer and our architects, all referred to the development of a new language as part of the design process in interdisciplinary teams. While designers working in teams need graphical conventions with both semantics and syntax, the definitional aspect of language development is in conflict with the pragmatics of sketching behaviour, where the meaning of graphical elements can change without warning as the designer reinterprets or reuses them (Neilson and Lee, 1994). Where sketches are often ambiguous with regard to possible interpretive syntax, the syntax of language is predetermined among native speakers. Word morphology determines function in a way that visual form need not, and lexical assignment must carry semantic associations in a way that abstract graphical elements can avoid.

For these reasons, several designers stated that they tended to avoid verbalization during early stages of the creative process.

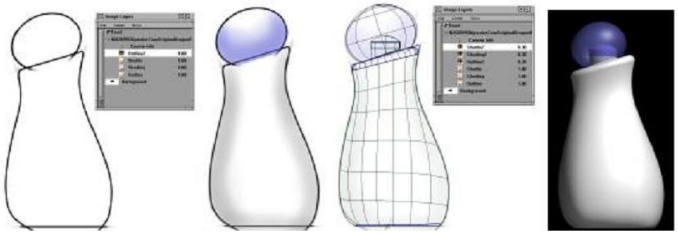

Figure 5. Hand Drawn Sketch, Computer Sketch and Computer Rendering

4. Sketches versus computer drawings

A constant theme in our workshops was concern with the way that younger members of the various design professions turn to computers too early in the design process, rather than working with pencil and paper (see Figure 5).

At first this might be seen as an appeal to craft traditions. However even design domains in which the computer itself is the traditional tool share this concern. Our software designer said that pencil and paper were essential to his work, and was also concerned that this might be a generational effect.

> "Yes, very much a sketch. Obviously computers are very very important, but there's nothing better than the right pen and the right pad. And they have to be that soft pencil and you sit there and you smoke and…Well, we all have different ways of doing it. And you sit there and suddenly, and so, the younger designers we use don't do that, they use the computers and straight in 3-D. We all do it differently." (Product Designer)

Hand sketches have qualities that computer sketches don't have. They are easier to share and easier to grasp by others, as they are portable or not scalable.

> "Sketching is crucial, and sometimes computer work is too private, because when you are sketching you become vulnerable. I've brought some sketches in case you don't know what sketches look like. They are just terrible things." (Architect)

A sketch does not have to be polished yet it can have detail where a computer model would not have it.

> "And they are primitive but somehow there's detail there. You can just see three people, nobody else can see that. It's your own little reference." (Product Designer)

In many cases, the computer was seen as a device that destroys uncertainty and provisionality. A sketch maintains its provisional quality where a computer model looks more final, therefore conveying that they

design might be more finalized than it really it. To recapture this uncertainty and provisionality, our graphic designer said that it was necessary to create many small pencil sketches, rather than turning too early to the computer, which she believed militated against creative work from her own graphic design students. On the other hand, one of the engineers commented in a follow-up interview that he had banned sketches from customer communication to avoid ambiguity and the appearance of provisionality in design handover. He instructed his designers to draw rough CAD models and use elements of past designs as placeholders for components that have not yet been designed.

5. Sketches in other Media

In domains where designers don't sketch on paper, the roles sketches fulfil need to be taken over by a different medium. Designers in many fields use other types of representations for thinking about and communicating skeletal, approximate and provisional ideas.

5.1. VERBAL SKETCHES

This was most salient in the presentation by the film maker. He talked frequently about sketches, but his sketches were verbal, not pictorial. He expresses the basic idea for his film in words:

> "One of the most important things to do when I reckoned I had the ideas and participants tied down was to write a 30-second version. Actually, no, it was about 15-second version of the programme that said: 'This is what it does'. I haven't got it, actually. I found a sort of copy but it was much later on and it's far too detailed. The fact is you really do do a little sketch. If that little sketch doesn't work, the programme isn't going to work."

The film maker makes documentaries. He depends on material that he can shoot on days he is on location. Because he can't control his material as much as a studio-based film maker, he does not see the point of making detailed story boards, but instead he says:

> "What you do is you write pseudo-scripts. So in a sense they are storyboards. You, to be plonking about it, you set up a table in two columns with sections so it's controllable. And then you put in a thought, pictures, a thought, pictures. It's not a storyboard. It's a sketch. A storyboard is more detailed than that. You get to the storyboard point, actually I never get to the storyboard point."

His verbal descriptions of the future film are at the same time plans for the recording he wants to make.

> "Now, we had a whiteboard. We didn't have any flow charts. All the whiteboard said was 'Kosovo, week 23'. It was really as basic as that. It was us talking that established what was going to happen, the flow. The future."

The non-sketchers amongst our informants were struggling with not being able to express and evaluate provisional information. The food designer conducted experiments. The project she described aimed to redevelop an artisanal ice cream on an industrial scale. The team went to the test kitchen and experimented with reconstructing the texture of the ice cream. Once they had succeeded in recreating the desired texture they analyzed their samples and transferred those to industrial processes. For drug designers it is important to evaluate the effect of their drug. They tried out many chemical combinations and applied standard evaluation strategies. The more promising ones were tested in standard batteries of in-vitro tests.

5.2. PHYSICAL MODELS

Several of our informants reported their collaborations with specialist designers whose "sketches" filled the function of design exploration, but were constructed in three dimensional or moving media. A traditional car body designer was reported as working directly in modeling clay, possibly interpreting concept sketches created by others, but mostly working with the clay itself. An architect with a particularly novel style of working created organic building forms by hanging catenary roof shapes from a support frame, in order to work directly with force distribution structures. Our film-maker created film segments as the only adequate representation of the product itself (in fact, these segments are the raw material of the final product, created via the process of editing), and organized the structure of the overall design in a textual table that simply referred to the original segments. In product design rapid prototyping is used to generate a physical model (see Figure 6).

In all of these cases, the designers are exploring possible solutions, but are limited by the availability of appropriate tools for provisional representation. Two-dimensional sketches are not adequate to express the combination of force and form in a roof structure, or pace and composition in film segments. Subtle three-dimensional forms, although potentially expressible in perspective renderings, must be viewed from various angles. This can be problematic not only for the designer exploring creative forms, but for the client reviewing a design. One of our architect informants justified the expense of creating a three-dimensional model as a supplement to sketches of an interior space because she felt that clients never properly apprehended the configuration of a space from perspective renderings.

Figure 6. Rapid prototyping model

The expression and apprehension of complex constraints and multiple views poses a challenge to the methodological requirements of sketches as provisional, ambiguous and fluid. In all these cases, the material properties of the final product have been subverted in some way to establish the status of models as sketches: clay rather than metal, cardboard rather than wood, and verbal labels rather than video extracts.

5.3. MENTAL IMAGERY

Especially in those domains with extensive visual sketches, designers often also develop exceptional mental imagery. These designers can develop their ideas through visualisation and might only resort to sketches to communicate. For example the knitwear designers the first author has interviewed commented without exception that they can visualise garments, rotate them mentally and recolour them (Eckert and Stacey, 2003). A senior knitwear designer once commented that the most important skill of a knitwear designer was to visualise garments. Often they refer to their memories of existing objects, instead of sketches, as reference points that they mentally modify. Objects are also used as reference points in communication. As Eckert and Stacey (2001) argue, this works highly efficiently in communication within peer groups that share the same reference objects, but it poses problems in communication with technicians and customers, who do not know those reference objects. However the technicians and customers would also need the context information derived from other objects to disambiguate sketches. Communication through objects is also frequent in engineering design, where it has great creative potential to enable the listeners to reframe their thoughts through new reference objects, while it poses problem in expressing exact specifications (Eckert *et al*., 2003). It has this double-edged potential because it enables the listener to pick up on different aspects of the design from those the speaker might have intended. While designing purely through mental imagery can be

both quick and powerful, it has obvious limitations, such as the development process being unrecordable. Mental imagery is also limited by the amount of information people can keep in mind at any one time; Miller (1956) famously assessed the capacity of working memory as seven plus or minus two chunks. Even though expert designers can remember and manipulate large chunks, this is only a small fraction of the information required to create and describe a complex product (see Egan and Schwartz, 1979). Research on mental imagery (see Kosslyn, 1980, 1994; Logie 1995) shows that people can have a subjective sense that their mental representations are more complete and detailed than they really are, and that details are only filled in when people focus on parts of their mental images.

6. Sketching across domains

Idea generation and communication are absolutely central to any design activity; and need to be supported by some form of representation. Visual two dimensional sketching takes carries out these function to a varying extent in most domains. However in other domains, roles that are carried out by paper sketches are taken over by verbal description or physical models.

6.1. CLASSIFICATION OF SKETCHING

For the purpose of using paper sketches the design domains studied in the across design project can be classified in the following way:

- **Prime users** (product design, architecture, urban planning, fashion design, graphic design). The design domains in which the visual appearance of the product is central are prime users of sketching. In these domains ideas are generated through sketching. They are usually presented through visual storyboards, which often include sketches. In this domain only very exceptional designers would not sketch.
- **Occasional sketchers** (engineers, software engineers, system engineers and web designers). In these domains there is great variation between individuals. For example engineers typically sketch during early conceptual design and to communicate to their colleagues solutions to problems that crop up during the design process. Many software designers or system engineers draw blob diagrams to indicate parts of a system when developing system architectures. Their sketches are typically abstract and non-pictorial
- **Non-sketchers** (drug design and food design). Non-sketchers can typically be found in the design domains that are non-pictorial and which have standard encoding conventions. Among our informants, the drug designers and the food designer did not sketch, but used standard chemical notations to express their ideas, and used computer tools to

visualise the product ideas early. In both domains the design process was very lengthy, because to test the product a real prototype needed to be made.

7. Abstract Properties of Sketches

The literal meaning of the word sketch refers to marks on paper, quickly drawn in two dimensions. This section reviews some of the properties of sketches of visual sketches. These are exactly the properties of those representations that also function as sketches, as discussed in section 5.

7.1. SKETCHES AS DENSE SYMBOLS

Most fundamentally a sketch is a series of marks on paper. These marks form *dense symbols*, whose interpretation depends on both category information and exact spatial form (Goel, 1995). Their meanings lie in the combination of symbolic and geometric mappings from the sketch elements to the referent objects the viewer interprets the sketch to depict.

Sketch elements have *symbolic* meanings, defined by notational conventions and mediated by the recognition of abstract category memberships, mapping categories of mark-combinations to categories of objects or concepts. Sketch elements may be icons, or have shapes directly corresponding to the shapes of the object categories they represent. McFadzean *et al*. (1999) found that designers use a personal recurring set of graphical symbols to express abstract attributes of a design. These personal notations are based on the standard drawing conventions of the domain, but include idiosyncratic extensions and variations. Designers have recurring, idiosyncratic procedures for constructing symbols, that influence their final form. For example they would use the same curve to denote an arch, whenever they do not know the form of the arch.

Sketch elements often also have *geometric* meanings, mapping the exact forms of the marks and the spatial relationships between them, to the shapes and spatial relationships of the depicted objects. This geometric mapping is perceptual and non-symbolic, although interpreting pictures is to some extent a learned skill. The graphic notations for many spatial concepts embody direct mappings from their conventional shapes, so they convey geometric meaning even when only a category identifier is intended. Making geometric mappings involves recognising and exploiting drawing conventions. Recognising drawing conventions is especially important in understanding sketches of three-dimensional objects.

Viewers understand sketches by *perceiving* both the symbolic categories and the shapes of design elements – but shape perception depends on *what* symbols are seen. A sketch is ambiguous, as opposed to vague, when alternative ascriptions of symbols to sketch elements are possible.

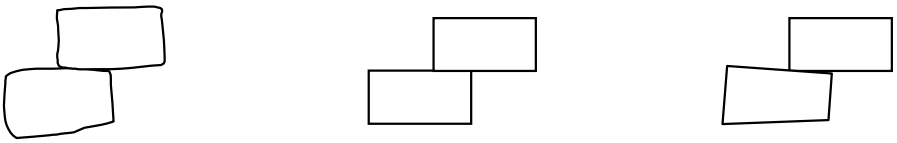

Figure 7. A sketch and its possible interpretations

For each viewer, a design sketch has a perceptual interpretation space: its meaning is the range of designs that it perceptually affords (see Figure 7). Beyond this, it has a deductive interpretation space: this is the range of designs that the viewer reasons that it can cover. As sketched lines have definite shapes and sizes, they suggest proportions and magnitudes, so interpretation spaces typically have centres – the interpretation that is most strongly suggested - and fuzzy boundaries. The greater the appearance of roughness the wider and more qualitative is the perceptual interpretation space.

7.2. IMPRECISION AND AMBIGUITY

Designers typically sketch imprecise ideas, embodying tentative decisions and with purely qualitative elements, covering a space of possible designs. Such a design space is difficult to express in a pictorial form. Designers often draw a typical instance or a range of instances, which can either be typical of sub-categories, or mark the edges of the design space that they represent. This strategy for indicating spaces can be applied equally to rough sketches and precise representations. Figure 7 might represent the relative location of two houses. Any range between the two extremes would be acceptable, but typically only the middle instance would be sketched. As design sketches are necessarily imprecise, they introduce ambiguity and inaccuracy into the transmission of meaning. Designers draw their mental concepts with varying degrees of accuracy according to their own conventions, but the sketches are interpreted according to the viewer's conventions as a different space of possible designs. Different people have different conceptions of central or typical category members; this is important when design element categories can vary over time, as in knitwear design.

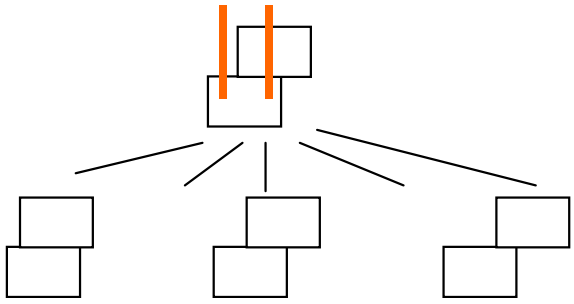

Figure 8. Sketch and its intended scope of vagueness

A sketch may be ambiguous; that is, it affords alternative symbolic interpretations. This can happen when a sketch element can be interpreted as a roughly drawn instance of one symbol or a more precisely drawn instance of another (such as a flared sleeve); or is on a fuzzy boundary between two category symbols (for instance, a slightly flared sleeve); or when marks can be grouped into symbols in different ways; or when the sketch is self-contradictory (for instance, a sweater with two different sleeves); or when alternative notational conventions are in conflict (a common problem in interpreting sketches of three-dimensional objects). A sketch element can be quantitatively ambiguous when it is unclear whether it is purely a category symbol or has a meaningful shape, or how wide the range of its geometric meaning should be. The degree of apparent roughness is a powerful signal of how wide the interpretation space should be, but the recipients cannot easily distinguish between intentional roughness and poor drawing. Roughness biases interpretation (for better or worse) towards simple shapes.

7.3. COMPARISON TO OTHER MEDIA

The imprecision and ambiguity of two-dimensional sketches are well recognized. While it is not clear what the scope of interpretation of a sketch is, nobody expects a sketch to be a precise medium or would use is as an exact specification. Other media lack this immediately visible sketchiness. While they might carry out the same role for the designers themselves, they might be received very differently by others. As our informants point out, a computer rendering or a model appear to be more defined, in the same way that a well laid out computer document looks more finished than handwritten notes. In the generation of other media, such are models, it is necessary to resolve some of the uncertainties that a sketch can carry, so that the balance between symbolic and depictive meaning is different. Often verbal references to other objects carry out the role of sketches. A sketch is always an abstraction of a potential object, where important characteristics are highlighted. In verbal references this abstraction is also implicit. This makes

them inherently more imprecise and ambiguous than sketches, while this is less recognized.

8. Discussion and Future Research

The current state of research on sketching in design is patchy, with researchers concentrating on particular phases in particular domains. Through looking at sketching behavior across a number of domains this paper examines the multiple roles that sketching can carry out:

- To generate and record ideas,
- To represent abstract properties pictorially,
- To communicate design ideas to others.

Our informants placed great emphasis on sketching as a means to communicate provisional design information both to customers and their peer groups. But these roles are not always carried out by sketches on paper. Some design domains use verbal descriptions. Existing objects can play a similar role to sketches, in that they support the generation of new ideas and serve as reference points in communication.

Our analysis of sketching behaviour across design domains is only a small part of ongoing analysis of the similarities and differences between design domains.

Acknowledgements

The Across Design project would like to thank the Cambridge MIT Institute for funding this research project (nmzh/013). But most of all we would like to thank all the participants in our workshops for giving us their time with such productive enthusiasm.

References

Akin, Ö: 1978, How do architects design?, *in* J.-C. Latombe (ed), *Artificial Intelligence and Pattern Recognition in Computer-Aided Design*, North-Holland, pp. 65-104.

Bly, SA and Minneman, SL 1990: Commune: A Shared Drawing Surface, *Proceedings of the Office Information System Conference*, Boston, MA, pp. 184 – 193.

Bly, SA 1988: A Use of Drawing Surfaces in Different Collaborative Settings, *Proceedings of CSCW'88*, Portland, OR: ACM Press, pp. 250-256.

Bucciarelli, LL: 1994, *Designing Engineers*, MIT Press, Cambridge MA.

Chambers, D and Reisberg, D: 1985, Can mental images be ambiguous? *Journal of Experimental Psychology: Human Perception and Performance* **11**(3): 317-328.

Eckert, CM and Stacey, MK: 2000, Sources of Inspiration: A Language of Design, *Design Studies* **21** (5): 523-538.

Eckert, CM: 2001, The Communication Bottleneck in Knitwear Design: Analysis and Computing Solutions *Computer Supported Cooperative Work*, **10** (1): 29-74.

Eckert, CM and Stacey, MK: 2001, Designing in the context of fashion designing the fashion context, *in* P Lloyd and HHCM Christiaans (eds), *Designing in Context: Proceedings of the 5th Design Thinking Research Symposium,* pp. 113-129

Eckert CM and Stacey MK: 2003, Sources of inspiration in industrial practice: the case of knitwear design, *Journal of Design Research* **15**(4): 355-384

Eckert, CM, Stacey MK and Earl CF: 2003, Ambiguity is a double-edged Sword: Similarity References in Communication, *in Proceedings of 14th International Conference on Engineering Design*, Stockholm, Sweden.

Egan, DE and Schwartz, BJ: 1979, Chunking in recall of symbolic drawings, *Memory and Cognition*, **7**: 149-158.

Finke, RA: 1990, *Creative imagery: Discoveries and inventions in visualization*, Hillsdale, NJ: Lawrence Erlbaum Associates.

Finke, RA: 1996, Imagery, creativity, and emergent structure, *Consciousness and Cognition* **5**(3): 381-393.

Finke, RA and Slayton, K: 1988, Explorations of creative visual synthesis in mental imagery, *Memory & Cognition* **16**(3), 252-257.

Finke, RA, Pinker, S and Farah, MJ: 1989, Reinterpreting visual patterns in mental imagery, *Cognitive Science* **13**(1), 51-78.

Goel, V: 1995, *Sketches of Thought*, MIT Press, Cambridge MA.

Goldschmidt, G: 1991, The dialectics of sketching, *Creativity Research Journal* **4**: 123-143.

Goldschmidt. G: 1994, On visual design thinking: the vis kids of architecture, *Design Studies* **15**: 158-174.

Goldschmidt, G: 1999, The Backtalk of Self-Generated Sketches, *in* JS Gero & B Tversky (eds*), Visual and Spatial Reasoning in Design*, Cambridge, MA. Sydney, Australia: Key Centre of Design Computing and Cognition, University of Sydney, pp. 163-184.

Katz, AN: 1983, What does it mean to be a high imager? *in* J.C. Yuille (ed.), *Imagery, Memory and Cognition: Essays in honor of Allan Paivio*. Hillsdale, NJ: Erlbaum, pp. 39-63.

Kosslyn, S: 1980, *Image and Mind*, Harvard University Press, Cambridge, MA.

Kosslyn, S: 1994, *Image and Brain*, MIT Press, Cambridge, MA.

Logie, RH: 1995, *Visuo-spatial Working Memory*, Psychology Press, Hove.

Miller GA: 1956, The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information, *The Psychological Review*, **63**: 81-97.

Minneman SL: 1991, *The Social Construction of a Technical Reality: Empirical Studies of Group Engineering Design Practice,* PhD Thesis, Department of Mechanical Engineering, Stanford University, Stanford, CA.

Neilson, I and Lee J: 1994, Conversations with graphics: implications for the design of natural language/graphics interfaces. *International Journal of Human-Computer Studies*, **40**: 509-541.

Oxman, R: 1990, Prior knowledge in design: a dynamic knowledge-based model of design and creativity. *Design Studies*, **11**: 17-28.

Pache, M, Roemer, A, Lindemann, U and Hacker, W: 2001, Re-interpretation of conceptual design sketches in mechanical engineering, *Proceedings of DETC'01*, Pittsburgh, Pennsylvania.

Petre, M and Blackwell, AF: 1997. A glimpse of expert programmer's mental imagery. In S Wiedenbeck and J Scholtz (Eds.), *Proceedings of the 7th Workshop on Empirical Studies of Programmers*, pp. 109-123.

Purcell, AT and Gero, JS: 1998, Drawings and the design process, *Design Studies* **19**: 389-430.

Pylyshyn, ZW: 2003, Mental imagery: in search of a theory, *Behavioural and Brain Sciences* **25**: 157-237.

Schön, DA: 1983, *The Reflective Practitioner: How Professionals Think in Action*, Basic Books, New York, NY.

Schön, DA: 1988, Designing: Rules, types and worlds, *Design Studies*, **9**: 181-190.

Schön, DA and Wiggins, G: 1992, Kinds of seeing and their function in designing, *Design Studies*, **13**:135-156.

Stacey, MK, Eckert, CM, Earl, CF, Bucciarelli, LL and Clarkson, PJ: 2002, A Comparative Programme for Design Research, *Proceedings of the Design Research Society 2002 International Conference: Common Ground*, Brunel University, Runnymede, London.

Stacey, MK, Eckert, C.M. and McFadzean, J: 1999**,** Sketch Interpretation in Design Communication, *Proceedings of the 12th International Conference on Engineering Design*, Technical University of Munich, Munich, August 1999, volume 2, pp. 923-928.

Star, SL: 1989, The Structure of Ill-Structured Solutions: Heterogeneous Problem-Solving, Boundary Objects, and Distributed Artificial Intelligence. *in* L Gasser and MN Huhns (eds), *Distributed Artificial Intelligence 2*, Morgan Kaufman

Suh, NP: 1990, *The Principles of Design*, Oxford University Press, New York.

Tang, JC: 1989. *Listing, Drawing and Gesturing in Design: A Study of the Use of Shared Workspaces by Design Teams*. PhD Thesis, Department of Mechanical Engineering, Stanford University, Stanford, CA. Xerox Palo Alto Research Center report SSL-89-3.

Tang, JC: 1991, Findings from observational studies of collaborative work, *International Journal of Man-Machine Studies* **34**: 143-160.

Tang, JC and Leifer L: 1988, A Framework for Understanding the Workspace Activity of Design Teams, *Proceedings of CSCW'88*. Portland, OR: ACM Press, pp 226-232.