Visible ideas: information patterns of conceptual sketch activity

Alistair McGown and Graham Green, Department of Mechanical Engineering, University of Glasgow, University Avenue, Glasgow, G12 8QQ, UK
Paul A. Rodgers, Engineering Design Centre, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, UK

The successful design and manufacture of today's increasingly complex engineering products relies to an ever greater extent upon the production and communication of information. The majority of design research to date has concentrated on supporting the information-rich latter stages of design and concerned itself with the distribution of product descriptions for the embodiment and manufacture of products. The conceptual stages of design, typified by vague knowledge and shifting goals, have been excluded from the research investigation. While computer processing power, storage facilities and organisational capabilities could prove useful within the early stages of design what tangible evidence do designers produce that could be captured by digital techniques? This paper studies designers at work in the early stages of design, concentrating on the visible sketching component of the design activity so that it might be understood and its efficiency subsequently improved by computer support.

The present engineering design environment is typified by shortening life cycles and growing product complexity. These two factors among many others have resulted in a cumulative increase in the amount of knowledge to be considered during design. In addition, greater accountability in terms of product liability is putting pressure on engineers to change their working practices[1,2].

The design research community has spent much of its effort in recent years developing information support systems that will capture relevant knowledge and experience needed in current product design and development. The emphasis has shifted from attempting to discover an algorithm for

1 **Hollins, B and Pugh, S** *Successful Product Design* Butterworths, London (1990)
2 **Wallace, K M** *Product development and design research* Keynote speech, ICED 97 Conference, Tampere, Finland (1997)

0142-694X/98 $—see front matter *Design Studies* **19** (1998) 431–453
PII: S0142-694X(98)00013-1

automated design and moved towards developing software to support designers[3]. The latter approach reaffirms the importance of the human element in design.

Most researchers have chosen however to ignore the earlier stages of design including the conceptual phase, in favour of developing expert systems for supporting the latter stages[4]. These latter embodiment and detail phases utilise an enhanced quality of information[5] that is more amenable to computer support than that available in the ill-defined and complex conceptual stages. Work has also been carried out into improving the evaluation of conceptual design[6–9] but little effort has been expended in developing a recording mechanism that will provide conceptual synthesis input to such evaluation systems.

Knoop et al agree that computer support of the latter stages of design is easier to achieve since the product description is already well known. They contend that technology push coupled with a poor understanding of the design process has led to the current lack of support for the conceptual designer[10].

As a result the conceptual stages of design, typified by indeterminate knowledge and evolving priorities, have been largely excluded from the digital environment and thus any digital record of the evolving design. This paper's aim, then, is to study designer activity so that it might be better understood and to suggest how this understanding might be applied via the creation of more suitable computer support that will improve the efficiency and effectiveness of conceptual design activity.

1 *Concept descriptions*

The onus for formal information delivery during engineering design has, to date, fallen upon written specifications[11,12]. Some of the drawbacks inherent in current specifications—including misleading requirements and ambiguous statements[4,13]—stem from the almost exclusive use of text-based information. Bearing in mind the experimental finding that 67% of the marks made on paper during conceptual activity are sketches[14] then distributed specifications should accommodate visual material in addition to textual information.

Sketching is a direct action within conceptual design but sometimes the drawings produced can be difficult for any observer other than the original 'artist' to understand. The design is often more easily understood when words are added to help explain the drawing's meaning, context or scale. Notice how it is quite difficult to ascertain what is represented in Figure

3 **Fischer, G and Nakakoji, K** 'Beyond the macho approach of Artificial Intelligence: empower human designers-do not replace them' *Knowledge-Based Systems* Vol 5 No 1 (1992) pp 15–30

4 **Hurst, K and Hollins, B** 'Improved product design specification compilation' in *Proceedings of ICED 95* Heurista, Prague (1995) pp 584–589

5 **McGown, A and Green, G** 'Recording the design process in real time: innovative design concept synthesis' in *4D Dynamics Conference Proceedings* De Montfort University, Leicester (1995) pp 127–130

6 **Green, G** *Evaluation activity within the conceptual phase of the engineering design process* PhD dissertation, University of Glasgow (1994)

7 **Rodgers, P et al** 'A formal method for assessing product performance at the conceptual stage of the design process' in *Advances in Formal Design Methods for CAD* **J Gero** (ed) Chapman and Hall (1996) pp 137–164

8 **Cziulik, C and Driscoll, J** 'Conceptual design evaluation based on function metrics' in *ICED 97: Proceedings of the 11th International Conference on Engineering Design* Vol 1, WDK and Tampere University of Technology, Finland (1997) pp 411–416

9 **Kuhnapfel, B** 'Simulation-based evaluation in conceptual design' in *ICED 97: Proceedings of the 11th International Conference on Engineering Design* Vol 1, WDK and Tampere University of Technology, Finland (1997) pp 133–136

10 **Knoop, W G et al** 'Towards more effective capturing of empirical data from design processes' *Proceedings of 1st conference in descriptive design*, Istanbul (1996)

11 **Pugh, S** *Total Design* Addison Wesley, Wokingham (1991)

12 British Standard 7373 Guide to the preparation of specifications (1991)

13 **Bucciarelli, L** *Designing Engineers* MIT Press, Cambridge, MA (1994)

14 **Hwang, T S and Ullman, D G** 'The design capture system: capturing back of the envelope sketches' *Journal of Engineering Design* Vol 1 No 4 (1990) pp 339–353

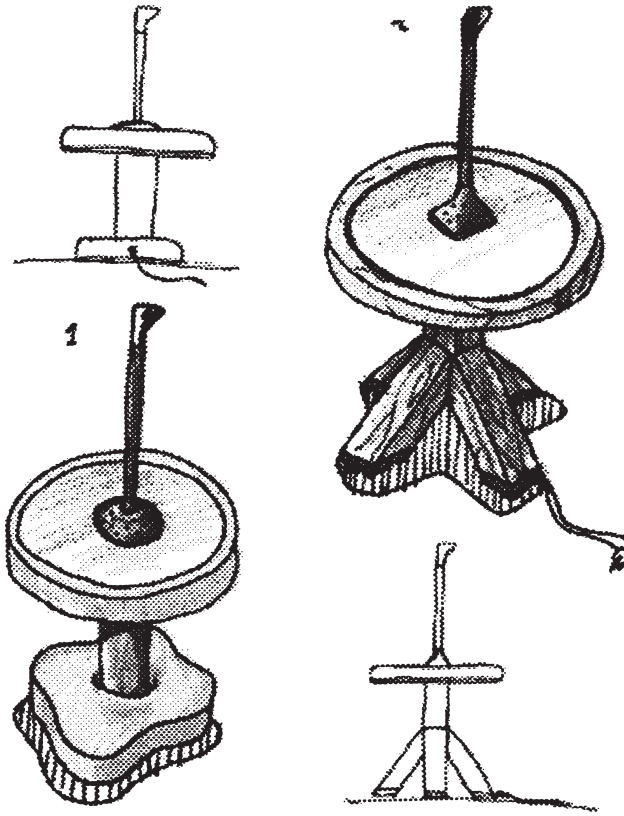


Figure 1 Sketch: Internet cafe table

1, without the aid of the caption. Figure 2 is easier for an observer to understand since it carries additional text annotations to provide context and also 'mannikins' that provide a sense of scale.

The above suggests a twofold need, which if addressed may improve the efficiency of communication at the conceptual stage. The hypothesis presented in this paper, then is:

That the media used must provide quicker communication and retrieval at the early stages of design, by providing combined visual and textual descriptions for improved evaluation and concept selection.

In addition to addressing the hypothesis this paper also shows that efforts made to study sketching activity in the conceptual stages of innovative product design can provide a worthwhile benefit in the form of improved speculative computer support tools.

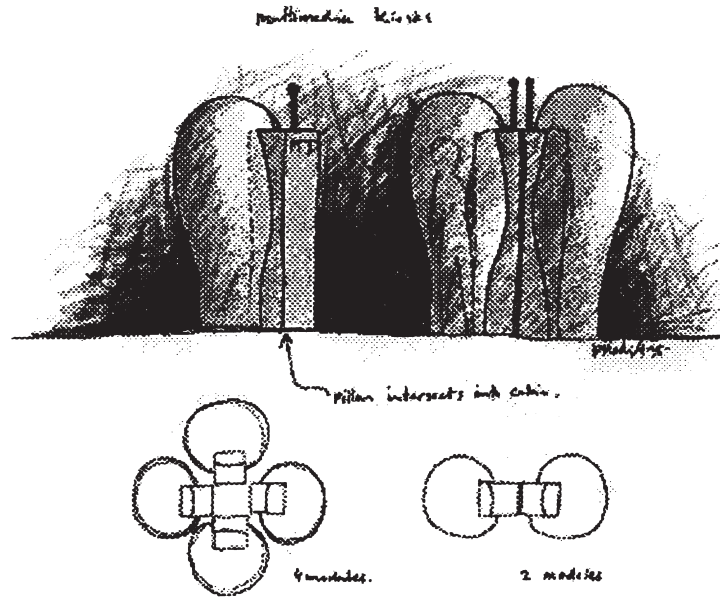


Figure 2 Sketch: Street furniture; multimedia kiosks (1 and 2 from project carried out by Philips Design, Eindhoven, The Netherlands)

2 *Sketching in conceptual design*

The designer's sketch is an integral part of the early phases of product design engineering. The majority of designers appear to have adopted freehand sketching as an invaluable part of the process[15,16]. Drawings are still lost and thrown away without much care or thought for future use however[13,16]. In recent years attempts have been made to support aspects of the sketching process using computer methods[14,17–20].

2.1 *Functions and types of sketching activity*

Visual representations are omnipresent throughout the design process, from early sketches to CAD-rendered general arrangement drawings. Cross uses drawings from each stage to illustrate the type of work that goes on as a design progresses[21]. The example concerns the design of a small cement mixer. In the order shown these drawings illustrate increasing degrees of concretisation and detailing[22]. (Figures 3–5)

Within the earliest stages of design the sketchpad is used to express ideas and has been referred to as the medium of reflection-in-action[23]. Schon suggests that through drawing, designers construct a 'virtual world' where the drawing reveals qualities and relations unimagined beforehand. Sketches are representations which will often allow the designer to 'try out' a new idea on paper, quickly and cheaply. Schon also notes that while drawing can be rapid and spontaneous, its residual traces are stable and can be subsequently examined by the designer at his or her leisure.

15 Lawson, B *Design in Mind* Butterworth Architecture, Oxford (1994)
16 Pipes, A *Drawing for 3-Dimensional Design: concepts, illustration, presentation* Thames and Hudson, London (1990)
17 Lakin, F 'The electronic design notebook: performing medium and processing medium' *Visual Computer* Vol 5 (1989) pp 214–226
18 Van Dijk, C G C 'New insights in computer-aided conceptual design' *Design Studies* Vol 16 No 1 (1995) pp 62–80
19 Gross, M D 'The electronic cocktail napkin—a computational environment for working with design diagrams' *Design Studies* Vol 17 No 1 (1996) pp 53–69
20 Tovey, M J 'Styling and design: intuition and analysis in industrial design' *Design Studies* Vol 18 No 1 (1997) pp 5–31
21 Cross, N *Engineering Design Methods: Strategies for Product Design* John Wiley and Sons, Chichester (1994)
22 Andreasen, M M 'Modelling-the language of the designer' *Journal of Engineering Design* Vol 5 No 2 (1994) pp 103–115
23 Schon, D A *The Reflective Practitioner* Temple Smith, London (1983)

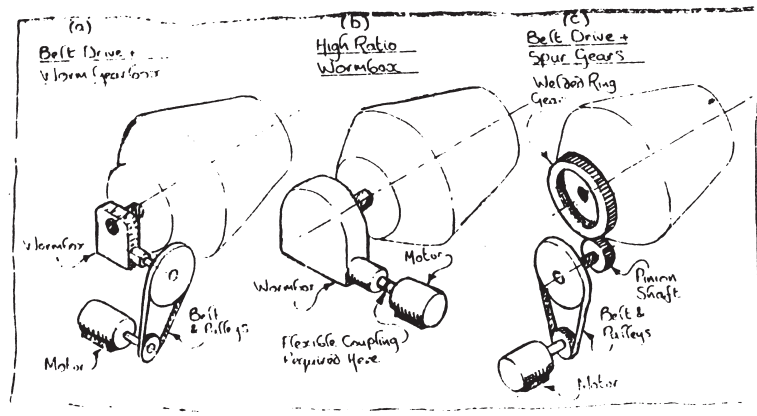


Figure 3 Drawings from the conceptual design phase, of three alternative solutions

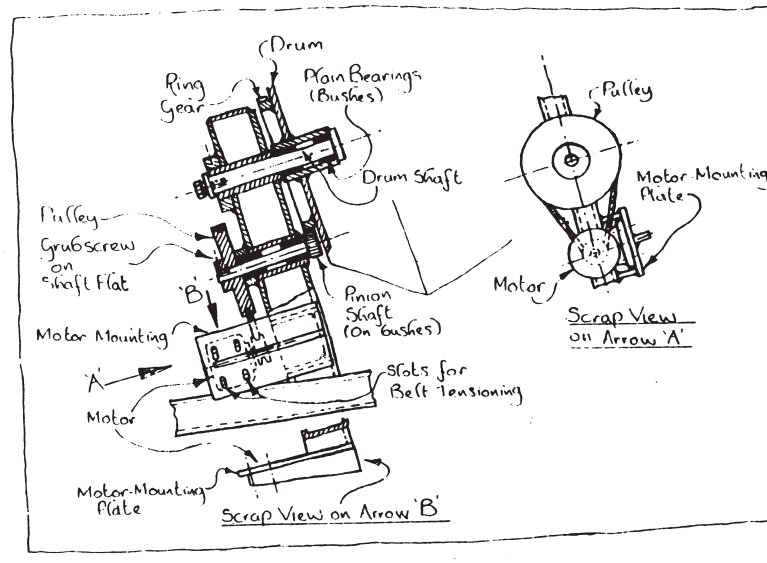


Figure 4 Drawing from the embodiment phase

Despite its importance in the design process, the sketch has a perceived low status, its true value hidden by the modesty of the designers[15,16]. Though it is one of the most tangible artifacts produced directly by conceptual activity[24], Schon's 'stable traces' may not be kept for subsequent use. When a project is over, early exploratory drawings are often destroyed and cleared away to make room for the next job[13,16]. The permanence of the sketch has perhaps been overlooked in favour of its spontaneity. The sketch may possess the potential to act as both facilitator *and* recorder of creative acts[25] presenting opportunities for improved evaluation and the re-stating of problems.

24 McGown, A and Green, G 'Multimedia product design specification: recording conceptual design activity in real time' in *ICED 97: Proceedings of the 11th International Conference on Engineering Design* Vol 2, WDK and Tampere University of Technology, Finland (1997) pp 701–704

25 Temple, S Thought made visible: the value of sketching, *Co-Design*, Issue No 1 (1994) pp 16–25

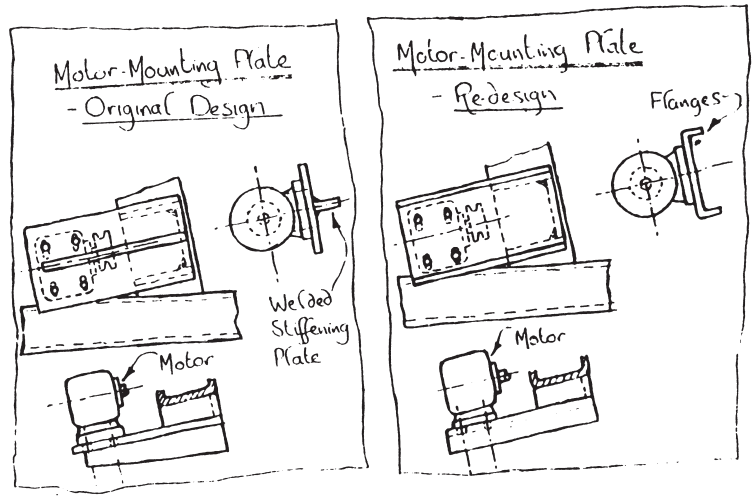


Figure 5 Two drawings from the detail design phase (3–5 reproduced from Cross 1994[21])

The flexibility of freehand methods mean that there are many different types of sketch, even within the conceptual phase. Some are of particular interest within the scope of this paper, others less so.

Ferguson sees the designer as using sketches to try out new ideas, to compare alternatives and—most importantly to his mind—to capture 'fleeting ideas' on paper[26]. He identifies three kinds of sketch:

(1) The *thinking sketch* which engineers use to focus and guide nonverbal thinking;
(2) The *prescriptive sketch* made by an engineer to direct a draftsman in making a finished drawing;
(3) The *talking sketch*, produced during exchanges between technical people in order to clarify complex and possibly confusing parts of the drawing. Ferguson recounts how a sociologist of his acquaintance observed designers actually taking the pencil from one another as they talked and drawing together on the same sketches. The talking sketch is a shared graphical setting which enables discussion.

The second kind of sketch does not concern us here as it is used almost exclusively within the latter detailing (pre-manufacture) phases of the design process.

Furthermore, a sketch is likely to be made for one of three reasons[25] and from one of three sources:

(1) To communicate the physical nature of an entity conceived in the imagination;

26 **Ferguson, E S** *Engineering and the mind's eye* MIT Press, Cambridge, MA (1992)

(2) To visually recall the physical nature of objects or environments from memory;
(3) To make a quick visual representation of entities or environments exposed to the naked eye.

The ability of the sketch to somehow make real an imagined object is of prime importance. The ability to communicate remembered objects is also of interest. In engineering this utility can often help to explain mechanisms like cams and gears to oneself or to another. This function is broadly similar to that of Ferguson's 'talking sketch'.

Figures 1 and 2 are from a speculative futures project carried out by professional designers and illustrate what a conceptual sketch may look like. The lines are crude and hasty, the hurried and indefinite quality expressing what is perhaps a necessary indecision.

2.2 *Scientific study of sketching*

One of the most detailed studies of the act of sketching was conducted by Goel[27]. He identifies two types of operation occurring between successive sketches in the problem-solving phases; *lateral* transformations and *vertical* transformations. In a lateral transformation, movement is from one idea to a slightly different idea. In a vertical transformation, movement is from one idea to a more detailed and exacting version of the same idea.

Figures 6–8 are sketches made as part of the architectural design of a post office counter. Figure 7 is a lateral transformation from Figure 6; three booths retain their location but have been internalised into the main core square. Figure 8 however is a vertical transformation from Figure 7. There

27 Goel, V *Sketches of Thought* Bradford-MIT Press, Cambridge, MA (1995)

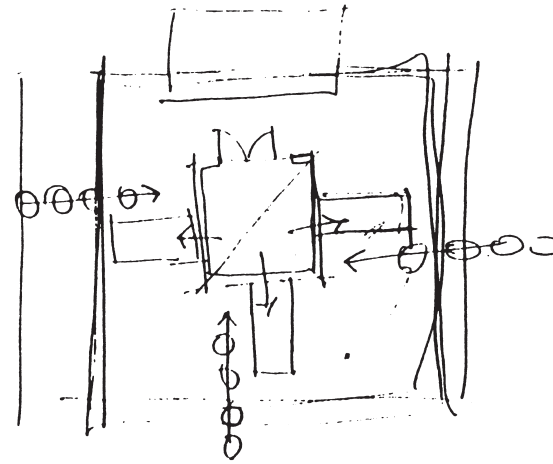


Figure 6 Sketch of post office floorplan

DST: DESIGN STUDIES (PAGE 7) 08-10-98 10:41:45 REV 14.02X ZDST$$136H

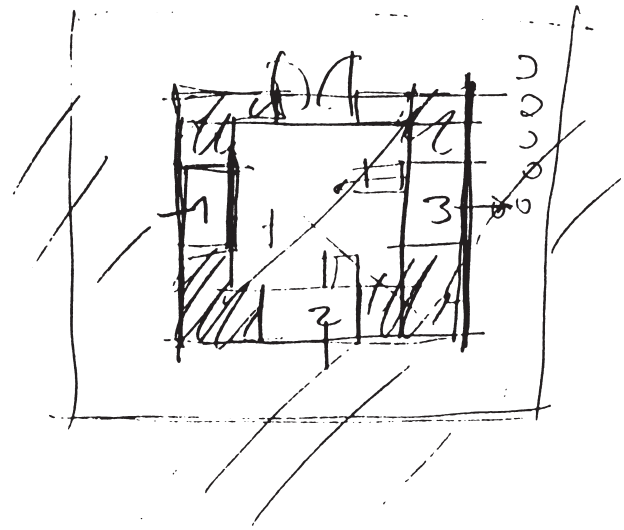


Figure 7 Sketch of post office floorplan

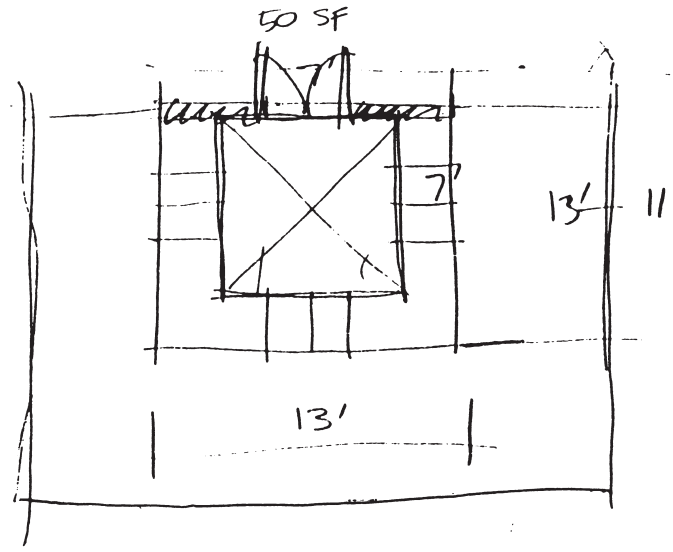


Figure 8 Sketch of post office floorplan (6–8 reproduced from Goel 1995[15])

is no modification of the idea of the booths in the central core; there is only the clarification of neater lines and the addition of dimension detail.

Goel concludes that freehand sketches—by virtue of being syntactically and/or semantically dense and/or ambiguous—play an important role in the creative, explorative, open-ended phase of problem solving. He believes that the properties of the freehand sketch facilitate lateral transformations and prevent early fixations.

Lawson[28] supports the above, maintaining that the computational theory of mind which underpins much of cognitive science falls some way short of being able to communicate the richness and diversity of thinking implied by freehand sketching activity.

2.3 Attempts to support sketching activity

Warburton assesses the use of available digital technologies during the design process, with particular attention paid to their appropriateness in modelling activities[29]. She concludes that at present:

- there are no apparent reasons why digital technology should be used for its own sake during the conceptual activity;
- digital and non-digital methods are equally appropriate in the development stages;
- computer support becomes more important during the latter stages.

Efforts have been made to affect the transition from paper-based, conceptual stage sketching to a digital environment. In the main these follow two main schools of thought. Firstly there are those that transform selected freehand-sketched concepts to digital input, via scanning or other methods. Secondly, there are those that attempt to mimic the natural sketching activity with computer-based methods.

2.3.1 Bridging paper and digital domains

The Fast Shape Designer (FSD) system[18] is used for making quick 3D sketch models from, and in addition to, 2D sketches. It does not try to replace traditional sketching. The system produces 'three-dimensional' sketch models from 2D sketches. The resultant model can then be milled to obtain a physical hard copy.

Tovey's prototype system[20] attempts to link freehand sketches to CAD models and is intended as a quick and convenient way of moving from concept sketches to a computer model. The system concentrates on the stage in the process that Tovey believes overlaps engineering design and CAE. He feels that CAD has much more application at this stage of the process than in attempting to support sketch activity directly.

Blessing's PROSUS support tool facilitates the capture and storage of early sketches[30]. It utilises a table/stylus interface to input freehand sketches to the system. Most notably, the stylus in use is an adapted nib-type pen. A thin sheet of paper can be placed between stylus and tablet and allows the user to see marks on paper, as in true freehand sketching. The output (on paper) is not one step removed from the input, via a monitor device for example, and it is this immediate response that is psychologically important

28 **Lawson, B** 'Book review' *Design Studies* Vol 18 No 1 (1997) pp 129–130

29 **Warburton, N** A heuristic model for Digitally Integrated Design, *Co-Design* Double issue Nos. 7 & 8 (1996) pp 22–27

30 **Blessing, L** *A process-Based Approach to Computer-Supported Engineering Design* Black Bear Press, Cambridge (1994)

to the designer. The secondary, electronic input is saved via the tablet as a bitmap image and entered to PROSUS' design matrices.

These systems demonstrate some of the utility of adapting paper-based sketches to computerised forms. A fully working system would mean that even early concepts could be linked to proprietary computer tools.

2.3.2 Sketching in a digital environment

Possibly the first study into drawing freehand on computer was published as far back as 1963[31]. More recently Lakin's VMACS system[17] helps provide recognition routines which identify graphic 'pieces' as expressions in notational symbol systems. VMACS recognises such diagrammatic representations as rigid body diagrams, bar charts and finite state automata to allow for more meaningful processing. Hwang and Ullman's Design Capture System (DCS)[14] is similar in that it is a draw-to-computer set up that does not use paper and pen.

The Electronic Cocktail Napkin system[19] adopts a 'paper and pen'-like interface. The Electronic Cocktail Napkin has capabilities for recognition and parsing of visual expressions and this is probably its most outstanding feature. Parsed diagrams are compared with diagrams already stored in the index and those that match can be pulled from the database and displayed. The system is intended to augment the architectural, case-based design aid ARCHIE[32]. Case-Based Reasoning (CBR) systems apply experience stored in computerised form to solve similar problems in slightly different contexts. The electronic cocktail napkin's ability to query by diagram is added to ARCHIE's concept-related and keyword processing capabilities.

Recently there has been an apparent shift from the established Artificial Intelligence approach towards one supporting directed exploration through the design case base. This reflects a shift from automating design towards supporting design through better access to relevant knowledge and information[33].

Hwang and Ullman have talked of 'back-of-the-envelope' sketches[14] while Gross talks of his 'cocktail napkin'[19]. Both invoke the immediacy of such 'whatever is to hand' media, an immediacy which current methods of computer capture are unlikely to offer. The systems of Lakin, Gross and Hwang and Ullman all offer optional support to designers and their freehand methods. None really intend to completely replace freehand sketching at the conceptual stage.

Tovey[20] suggests that there is little point in mimicking the sketch activity by computer methods unless the designer gains something over the tra-

31 **Sutherland, I E** 'Sketchpad: A man-machine graphical communication system' PhD dissertation, MIT, Cambridge, MA (1963) reprinted Garland Publishing, New York (1980)

32 **Domeshek, E and Kolodner, J** 'A case-based design aid for architecture' in *Artificial Intelligence in Design* **J S Gero** (ed) Kluwer, Netherlands (1992)

33 **Wood, W H and Agogino, A M** 'A case-based conceptual design information server for concurrent engineering' *Computer-Aided Design* Vol 28 No 5 (1996) pp 361–369

ditional method. Sketching by conventional means is extremely quick and effective.

Research indicates that the poor response and 'feel' of current computer tools are a source of annoyance and frustration for designers[18,25]. Freehand sketches are thought to possess the following advantages over computer sketch systems:

- greater speed
- greater ease of use
- greater immediacy
- better quality of response
- more expressive qualities
- they are constrained only by the designer's imagination

Thus, at present, there seems little reason to attempt to replicate freehand sketching by computer methods. Conversely, computer support of sketching activity can provide desirable features not offered by traditional 'paper-based' methods:

- storage facilities
- faster search for material held in storage, via meaningful processing techniques
- durability and permanence; sketches held on computer are not easily lost
- direct links to proprietary computer tools and networks

The research experiment described in the next section determines the volume and pattern of information produced by sketch activity throughout the conceptual stages of the design process. The research also aims to find whether sketches are indicative of the general progress of the design. Thirdly the experiment aims to find areas that will pave the way for effective computer support of freehand sketch activity.

3 *Methodology*

The study observed student designers in the final year of the M.Eng/B.Eng Product Design Engineering course at Glasgow School of Art between November 1996 and February 1997 and concentrated upon the sketching part of the design activity. The production of sketches was regarded as a measure of ideas and information produced.

In the past few years some work has been done in providing computer-based tools to support engineering and design at the conceptual phase[34–36], with the most credible of these based on descriptive rather than prescriptive

34 Hennessey, J 'Exploring enhancements for conceptualising' in *Automation-Based Creative Design: current issues in computers and architecture* **T White, and A Tzonis** (eds) Elsevier, Amsterdam (1994) pp 349–362

35 Ullman, D G 'Computer support for design team decisions' *VDI Berichte* Vol 1169 (1995) pp 83–95

36 Scrivener, S A R 'Designing at a distance via real-time designer-to-designer interaction' *Design Studies* Vol 14 No 3 (1993) pp 261–282

methods of research. It is difficult to predict the validity of developed tools without a firm basis in descriptive research methods.

Since engineering is essentially a human activity it has been proposed that the field research techniques developed in the social sciences could prove useful in helping to understand how and why design happens[37,38]. This study was intended as a careful and purposeful combination of both qualitative methods informed by social science research[39] and more traditional quantitative methods in relation to the same object of study.

3.1 *The experiment*

Four students were selected from a class of twenty-two by teaching staff. The selection was intended to illustrate a range of activity and varying scales of product. The students were not given specific tasks to do, nor strict time limits in which to do them. In line with an ethnographic stance[40], the students were observed at work on their individual, self-motivated projects. The projects constitute a major part of the eight-month, final year curriculum though they were interrupted by complementary core engineering lecture material and study. There are no intermediary submission dates in the project; only a final hand-in in May/June of the second session. The window for study was set to cover the conceptual phase period; fifteen weeks beginning in the fifth week of term.

Most of the material for quantitative analysis came from the students' sketchbooks, but qualitative observation was necessary to explain both trends and contradictions in quantitative results. Anecdotal material and assessments of the personalities of the students was obtained by placing the researcher in the participant-as-observer role[39]. This form of participant observation makes clear to the subjects that the observer *is* an observer and the researcher performs the dual role of observer and participator (in this case taking the role of a part-time tutor). The working environment is shown in Figures 9 and 10.

The four students worked on a wide range of products varying in many ways, most obviously in size. The students chose the following projects:

- computer hard drive swap system (Student W)
- ski-tow (Student S)
- mobile grandstand (Student A)
- mobile electricity substation (Student L)

37 **Wallace, K M and Hales, C** 'Engineering Design Research Areas' in *Proceedings of the ICED*, I.Mech.E., London (1989) pp 555–562

38 **Kennedy, P** 'Research in design using methods and ideas from social science research' in *ICED 97: Proceedings of the 11th International Conference on Engineering Design* Vol 2, WDK and Tampere University of Technology, Finland (1997) pp 449–454

39 **Robson, C** *Real World Research* Blackwell, Oxford (1993)

40 **Bucciarelli, L** 'Engineering design process' in *Making true ethnographies of high tech organisations* **Dubinskas** (ed) Temple University Press, Philadelphia (1988) pp 92–122

Figure 9 Studio environment

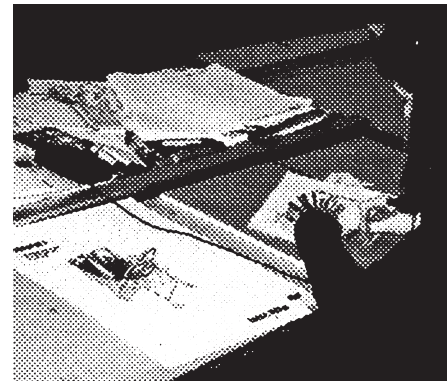


Figure 10 Studio environment

3.2 Rules and definitions

3.2.1 'Conceptual sketches'

The *Conceptual Sketch* is different from the other types of drawing employed by designers: the *Presentation Drawing* and the *Drawing for Manufacture*. Concept sketches and presentation drawings are sometimes confused since genuine concept sketches often perform a secondary function. They can be used to present ideas to clients and to those involved in a product's eventual manufacture, providing a kind of work-in-progress report.

Figures 11 and 12 are taken from one student's project. Figure 11 is a conceptual sketch that allows the designer to try out an idea on paper. It is about 100 mm by 100 mm seen in its original size. Figure 12 is a refined presentation drawing about the size of an A4 sheet made to give a quick impression of the product in use to a wider audience which, while it is a matter of judgment by an observer, differs little from that shown in Figure 11.

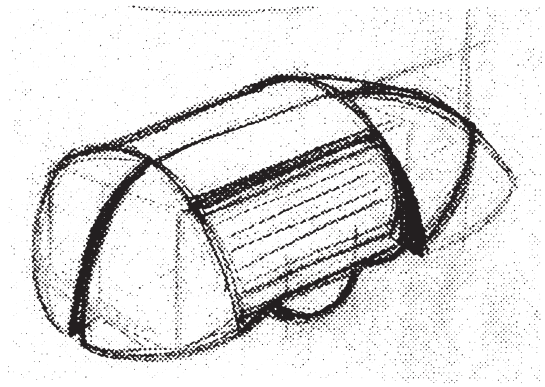


Figure 11 conceptual sketch

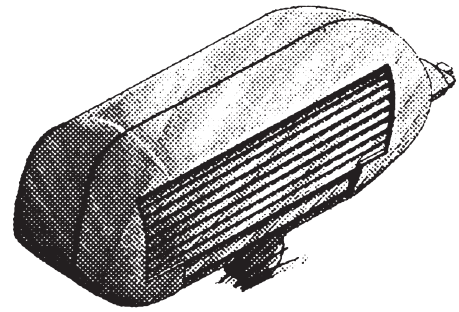


Figure 12 presentation drawing

Presentation drawings however are merely laboured reworkings of conceptual sketches, traced or more carefully rendered, perhaps with detailed graphics and text but not furthering the design. Such presentation drawings were disqualified from analysis.

3.2.2 *Individuating sketches on a page*

Figure 13 shows a typical page from the sketchpad of one of the students involved in the experiment. In analysing these pages each page must first be broken down into constituent sketches. The observer first identifies separate (though still connected) sketching episodes. Goel talks of 'individuating' when analysing sketches[27]. In his experimental work subjects individuated the output by drawing rectangles around each separate drawing and in some cases would number them in sequence.

The retrospective method used in this ethnographic experiment involves a degree of interpretation and the analytical process takes longer than if the student was asked to individuate and number each sketch in the first instance. From study of the sketchbook material it is obvious that the stu-

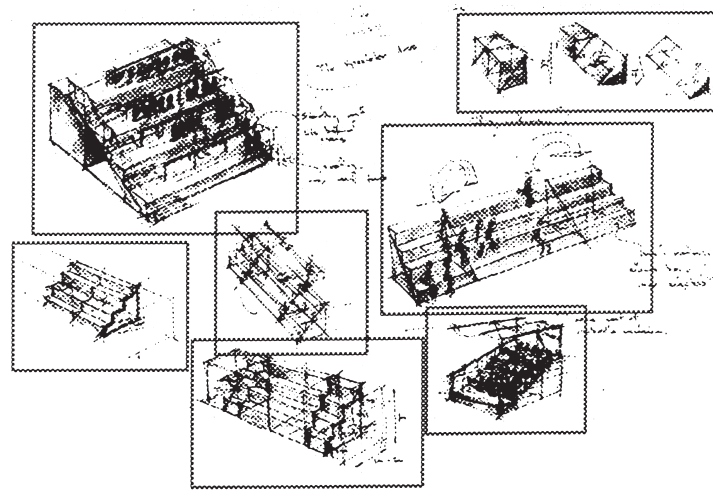


Figure 13 page from Student A's sketchbook

dents do not such a thing as part of their own practice—such a demand would have been an additional requirement over 15 weeks with possible influence on the experiment's outcomes. The individuated sketches in Figure 13 are shown by the overlapping rectangles added by the observer.

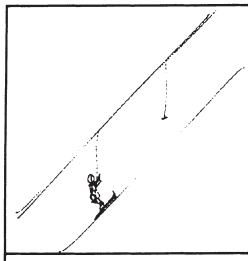
3.2.3 *Quantifying qualitative difference*

To be able to appreciate the pattern of information flow in the conceptual sketching activity, some quantitative measure of the activity is required. Furthermore a qualitative judgement of some attribute of the sketch needed to be classified in order to give some quantitative measure.

Each sketch on each sheet of the sketchbook was assessed for a measure of the information it communicated to the observer. To this end a simple scale of what has been termed 'Complexity' was constructed. The most simple of sketches typically found in the students' sketchbooks was rated a 'One' and the most complex rated a 'Five'. The scale was created by interpolating between the two extremes. Figure 14 includes the definitions which allow for the classification of each sketch.

Since the drawings have been marked with the date of their production, the qualities can be assessed chronologically to produce an information pattern of conceptual sketch activity in the early phases of design.

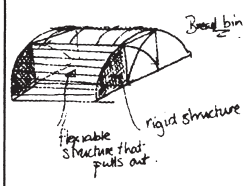
The amount of information is not only dependent upon the complexity of the sketch. That is to say the bigger a drawing becomes, the greater the space for discussion. Thus, an assessment of the amount of information in a drawing should include a factor of size.



Complexity Level One (Least complex)

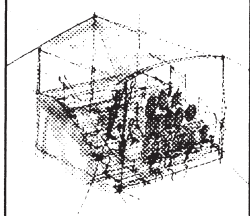
Monochrome* line drawing. No shading to suggest 3D form. No text annotations are used nor are numerical dimensions. Motion arrows may indicate moving parts.

* If a single colour is used then this also counts as monochrome (eg a drawing made in blue biro pen)



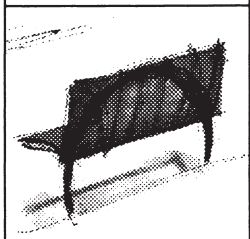
Complexity Level Two

Monochrome line drawing. There is no shading to suggest 3D form, but there is use of different thicknesses and pressures of line with a single medium. One or two brief annotations may appear not more than 6 or 7 words each. As in (1) motion arrows may be allowed.



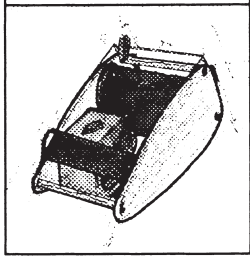
Complexity Level Three

Monochrome, with rough shading used to give suggestion of form. The drawing may be annotated to describe certain aspects of the idea. Dimensions might be apparent.



Complexity Level Four

Subtle shading is heavily suggestive of 3D form. The drawing will almost certainly be annotated. Colour, or gradation of monochrome 'colour' may be used to illustrate certain concepts or arrangements, but not to suggest the true colours of parts. NB The example used here is a colour illustration



Complexity Level Five (Most complex)

Colour is used to represent the actual colours of parts of the product. There is much use of shading (both highlights and shadows) to suggest 3D form. Annotations will be used to ask questions of the idea or to explain it. Generally a very busy drawing - many lines will be used in its construction. NB The example used here is a colour illustration

Figure 14 complexity scale

DST: DESIGN STUDIES (PAGE 16) 08-10-98 10:41:47 REV 14.02X ZDST$$136H

So let:

c = complexity of a sketch ($1 \leq c \leq 5$)
s = size factor of a sketch ($1 \leq s \leq 5$)
I_{ps} = Information held in an individual sketch, where

$$I_{ps} = (c.s)$$

and let:

I_{pw} = the information total per week
n_{pw} = the number of sketches made in a week
so that;

$$I_{pw} = \Sigma(c.s).n_{pw}$$

With an A3 sketchbook the largest sketch (size factor 5) must be considered a full page or near full page sketch, extremely rare as they may be. The smallest sketch was a thumbnail sketch—this was assessed from study of the students' material to be anything up to 50 mm by 50 mm. The other levels in the scale were assessed by interpolating.

3.2.4 *Size factor scale*

(1) thumbnail sketch up to 50 mm × 50 mm
(2) up to 100 mm × 100 mm
(3) up to 150 mm × 150 mm
(4) very large—up to an A4 page
(5) full page—drawing covers most of the A3 page.

A note was also made of the media used to produce each sketch. Particular interest was focused upon whether sketches were freehand or were drawn by computer methods and pasted in to the sketchbooks. It was felt that it might be useful to analyse the kinds of tools used and how the choice of tools changed with time, if at all.

3.2.5 *Qualifying transformations*

The observer looked at every successive sketch to decide which transformation had taken place in each case. An obvious change in thinking is lateral transformation while if the change is instead to a more detailed version of the same idea then a vertical transformation has occurred.

The observer found it difficult to sequence the drawings within a page, and this made it hard to determine which drawings were successive. To

this end 'successive' was extended to mean 'coming after' rather than 'consecutive' which it is apparently taken to mean in Goel's work[27]. Jumping opportunistically from one idea to a second different idea and then on to an expansion of the first idea can only be realistically defined to be a vertical transformation from the earlier idea, whether consecutive or not.

4 *Discussion*

4.1 *The freehand nature of sketching*

Table 1 illustrates that three of the four students involved in this study use almost exclusively freehand techniques for drawing. The table also illustrates that each student has a preferred medium of choice, with around 70% of drawings being made with one or two specific media. Note that Student W produced some computer-generated material—the print-outs pasted into his sketchpad meant it could be included in this analysis.

4.2 *Flow of ideas*

Figure 15a, Figure 15b, Figure 15c and Figure 15d are 'chronological' graphs which show how sketch information output, I_{pw}, varies over time. All four graphs show a slow start and sudden peak in information generated. This is followed by a lull or slackening off in activity, followed by another peak (slower this time than the first). In the case of Student A and Student S (Figure 15a and Figure 15c respectively) the second peak is significantly shorter in height than the first which may suggest convergence towards a more finalised concept solution.

In the case of Student A the information totals rise again in the last couple of weeks of the observed activity. This suggests the transition of a dominant concept to the embodiment phase.

Table 1 Media used for drawing in the conceptual phase

	Student			
Drawing media	*A (%)*	*L(%)*	*S(%)*	*W(%)*
Hard pencil	40	-	-	3
Soft pencil	11	69	4	69
Ballpoint pen	-	6	78	6
Fineliner pen	18	18	2	-
Colour marker	-	4	< 1	-
Mixed f'hand Media	31*	3	16	6
Computer generated	-	-	-	16

*Subject A produced 28% of drawings with a mix of fineliner and monochrome marker

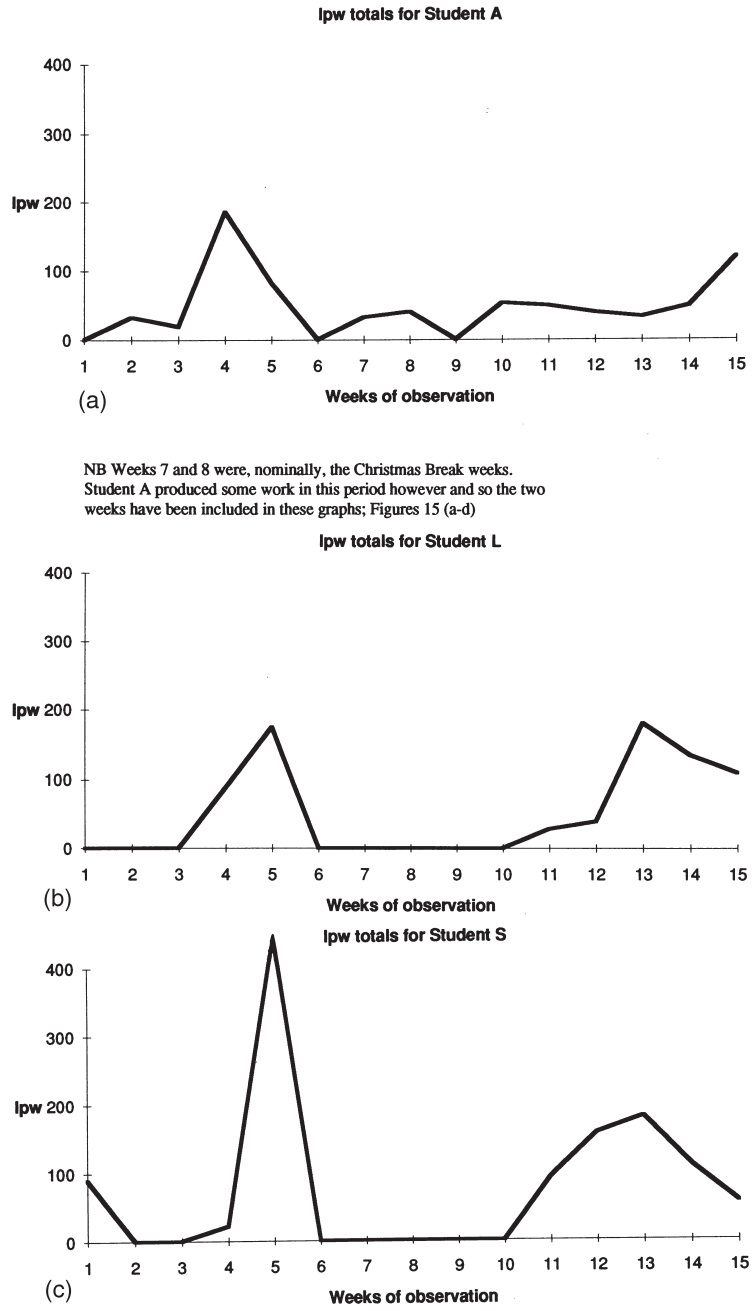


Figure 15 (a,b,c,d) I_{pw} *v. time*

4.3 Lateral and vertical transformations

Each successive sketch was assessed to be the result of either a lateral or vertical transformation. Table 2 illustrates that Student S shows notable bias towards vertical transformations in his sketch work, while Student A

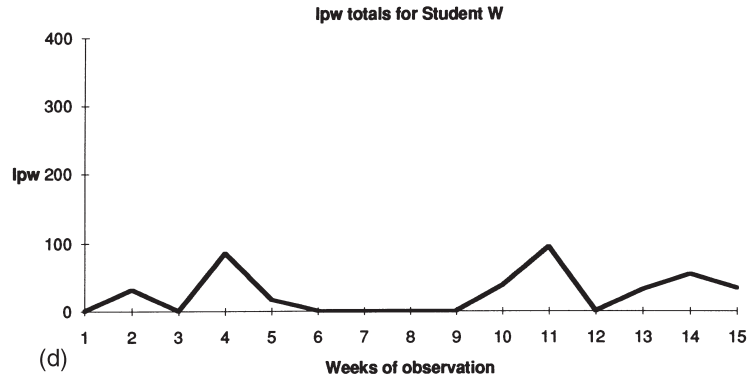


Figure 15 Continued

Table 2 Lateral and vertical transformations

Transformation Type	*Student* *A*	*L*	*S*	*W*
Lateral transformation (%)	59	48	36	51
Vertical transformation (%)	41	52	64	49

displays a slight lateral bias. Student L and Student W are split almost 50–50 between lateral and vertical transformations, in line with findings from a recent similar study of architects[41].

4.4 Ratios of effort

By assessing the complexity and size of each sketch, as in Section 3, a picture of weekly sketch activity was constructed. Table 3 illustrates sketch activity for each of the four students over a fifteen week period. The left hand column in each case shows n_{pw}, a count of the number of sketches produced in a week. The central column shows I_{pw}. The right-hand column in each case is an index of designer activity; a ratio of I_{pw}/n_{pw}.

Tracking this ratio on a week-to-week basis provides some indication of the industry of the designer.

The totals given at the foot of Table 3 show the performance of the designer over the conceptual phase as concerns sketching activity. They are calculated by dividing the sum total of I_{pw} by the total number of sketches over the period.

4.5 Issues raised

The reliance on ideas at the conceptual stage would not appear to result in an over-abundance of lateral transformations. Good design is a result of

41 Suwa, M and Tversky, B 'What do architects and students perceive in their design sketches? A protocol analysis' *Design Studies* Vol 18 No 4 (1997) pp 385–400

Table 3 Index ratios of weekly sketch activity

Week of Term	Student A			Student L			Student S			Student W		
	No. of sketches	*Information totals*	*Ratio, l/n*	*No. of sketches*	*Information totals*	*Ratio, l/n*	*No. of sketches*	*Information totals*	*Ratio, l/n*	*No. of sketches*	*Information totals*	*Ratio, l/n*
Week 5	0	0	0	0	0	0	33	90	2.73	0	0	0
Week 6	13	32	2.46	0	0	0	0	0	0	8	32	4
Week 7	7	19	2.71	0	0	0	0	0	0	0	0	0
Week 8	34	186	5.47	17	88	5.18	9	22	2.44	14	86	6.14
Week 9	13	82	6.31	34	175	5.15	174	445	2.56	5	17	3.4
Week 10	0	0	0	0	0	0	0	0	0	0	0	0
Break	7	32	4.57	0	0	0	0	0	0	0	0	0
Break	6	40	6.67	0	0	0	0	0	0	0	0	0
Week 11	0	0	0	0	0	0	0	0	0	0	0	0
Week 12	9	53	5.89	0	0	0	0	0	0	20	38	1.9
Week 13	13	49	3.77	5	28	5.6	36	92	2.56	12	95	7.92
Week 14	12	39	3.25	8	39	4.88	66	156	2.36	0	0	0
Week 15	12	33	2.75	69	181	2.62	34	180	5.29	8	32	4
Week 16	13	49	3.77	41	135	3.29	33	110	3.33	17	55	3.24
Week 17	43	120	2.79	35	110	3.14	12	57	4.75	7	34	4.86
Totals	182	734	4.03	209	756	3.62	397	1152	2.9	91	389	4.27

balance between lateral and vertical transformation at these early stages rather than an extreme lateral bias[27]. It is almost certain however that the balance will shift to an extreme (and finally total) vertical bias as design progresses towards manufacture.

From experiment Goel mentions a third possible transformation type. A *duplication* is, as the name suggests, a movement from one drawing to a type-identical drawing. These duplications could prove a key factor in ascertaining from a designer's sketches the design progress made.

In approximately 20% of cases, Subject S was repeating previous sketches but on the binary status scale used these were determined to be vertical transformations. From analysis of sketch evidence *alone* it was obvious that the student's project as a whole was not progressing; there was a lack of balance between lateral and vertical transformations and a tendency to duplicate earlier work.

Furthermore Table 4 shows how the overall ratios of total I_{pw}/n_{pw} correspond to the overall project performance of each student as assessed by an independent marking panel. Performance is based upon an examination of student process and practice and not just upon the final product. The sketchbooks themselves were considered as part of this assessment. For Student S the Information total (which had been reached by including repetitive sketches) was corrected for duplication and thus reduced by 20% to a new modified total shown in Table 4. The number of sketches considered for n_{pw} remained the same. Repetition is thus penalised by this approach.

5 *Conclusions and future work*

From the analysis and discussion above, the study confirms that freehand sketching is prevalent in the conceptual phase of design and that the sketching activity has peaks and troughs over time, with its highest peak near the beginning of the design process.

Table 4 Ratios of I_{pw}/n_{pw} corresponding to overall performance

Student	*Grade*	*Total ratio* I_{pw}/n_{pw}
W	A +	4.27
A	A	4.03
L	A −	3.62
S	D	2.61

If the dominant medium of the freehand sketch could be accommodated within a digital domain then an index ratio of the information in a sketch considered against the amount of sketches produced, could be used to provide a weekly track of the quality of the designer's effort. This would require parsing routines able to rate the complexity level of a sketch against a given scale.

A sophisticated parsing function able to distinguish between the three modes of *lateral transformation*, *vertical transformation* and *duplication* in the designer's sketches, checked against those held in a design record, would be advantageous in providing a warning to the designer, should s/he become 'trapped' in one mode. Parsing of visual material, such as suggested by Gross[19], may be able to recognise the same-ness of duplication between sketches and also the same-ness between vertical transformations. Current systems would be likely to confuse the two, so more work is needed in optical identification. Lateral transformation would be defined as a lesser degree of same-ness between sketches. Using these methods the designer's conceptual method of choice, freehand sketching, can be anchored to the advantages offered by computer support.

The additional parsing of inputted natural language text attributes in conjunction with the parsed visual material will be incorporated into an improved Product Design Specification to enable efficient distribution of product knowledge in the conceptual phase.

Future research will extend to cover the use of sketches in group settings within our academic sample group. The next step will be to continue this work in an industrial setting, which is characterised by greater sources of noise and greater amounts of information.

Acknowledgments

The authors would like to thank Philips Design, Eindhoven for giving their permission to reproduce sketch material used in this paper. We are also grateful to MIT Press for granting permission to reproduce figures from Goel's *Sketches of Thought* and to Addison Wesley Longman for allowing the use of illustrative material from *The Engineering Design Process* by B. Hawkes and R. Abinett (1984). This had previously been published in Cross (1994)[21]. Our thanks are also extended to the Product Design Engineering students at Glasgow School of Art for their co-operation and for the loan of sketchbook material.