Using concept sketches to track design progress

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Sketching is one of the most important activities in the design and development of new products. Designers produce sketches, from concept design ideas through to highly detailed representations of product artifacts, product sub-assemblies and so on, to communicate with themselves and with others. To this end, the focus of this paper is the description of a study of student designers at work in the early stages of design, with particular emphasis on the visible sketching component of the design process. The study has been carried out to firstly investigate the sketching activity and secondly to explore methods or techniques which might improve the efficiency of this activity. In particular, the paper describes a technique, based upon three types of operation, namely lateral transformations, vertical transformations and duplication, that occur between designer’s sketches. These transformations can be used to help track the designer’s thinking mode which, it is envisaged, will increase the efficiency of the sketching activity. © 2000 Elsevier Science Ltd. All rights reserved

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The designer’s sketch is an integral part of the early phases of new product development (NPD) and designers appear largely to have adopted freehand sketching as the main method of communicating their ideas during these stages. Although integral in the NPD process, design sketches are often lost and thrown away without much care or thought for future use. In recent years, however, attempts have been made to capture and store certain elements of the sketching process using a number of different methods and technologies.
Designers utilise various types of media during their concept design sketching activities. From observations of designers in action\textsuperscript{9,10}, it has been found that it is common for designers to generate many ‘quick’ sketch ideas using traditional media, such as pens, pencils and paper. Concept design ideas are generated quickly and are used to frame not only the designer’s early ideas, but also to try and better understand the problem.

Visual representations are omnipresent throughout the NPD process, from early sketches to CAD-rendered general arrangement drawings. Usually, as the design progresses, the drawings illustrate increasing degrees of concretization and detailing\textsuperscript{11}. To this end, the conceptual sketch is very different from the other types of drawing employed by designers, such as the presentation drawing and the drawing for manufacture.

1 Sketching in conceptual design

During the early (conceptual) stages of design, the sketchpad is used widely to express ideas and has been referred to as the medium of reflection-in-action\textsuperscript{12}. In his work, Schon\textsuperscript{12} 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.

Despite their importance in the design process, sketches are often perceived as having a relatively low status. The sketch’s true value is often hidden by the modesty of the designer responsible\textsuperscript{2}. Though it is one of the most tangible artifacts produced directly during the conceptual activity\textsuperscript{13}, Schon’s ‘stable traces’ may not be kept for subsequent use. Typically, when a project is completed, early exploratory drawings are often destroyed and cleared away to make room for the next job\textsuperscript{4}. The permanence of the sketch has perhaps been overlooked in favour of its spontaneity. The sketch also possesses the potential to act as both facilitator and recorder of creative acts presenting opportunities for improved evaluation and the re-stating of problems\textsuperscript{14}.

The flexibility of freehand methods means that there are many different types of sketch, even within the conceptual phase of designing. Some are of particular interest within the scope of this paper, others less so. For instance, Ferguson\textsuperscript{15} sees the designer as using sketches to try out new ideas, to compare alternatives and to capture ‘fleeting ideas’ on paper. He identifies three kinds of sketch, namely the thinking sketch (which design-
ers use to focus and guide non-verbal thinking), the prescriptive sketch (made by a designer to direct a draftsman in making a finished drawing) and the talking sketch (which is produced during exchanges between designers and engineers in order to clarify complex and possibly confusing parts of the drawing). The second kind of sketch does not concern us here as it is used almost exclusively within the latter (detailed or pre-manufacture) phases of the design process. However, the ability of the sketch to somehow make real an imagined object is of prime importance in this work as is the ability to communicate design proposals to others.

2 Transformation typology

One of the most detailed studies of the act of sketching was conducted by Goel\textsuperscript{16}. He identified two types of operation occurring between successive sketches in the early stages of design, namely lateral transformations and vertical transformations shown in Figure 1.

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. Figure 1 shows sketches

\begin{figure}
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Lateral (divergent)} & \textbf{Vertical (convergent)} \\
\hline
\begin{tikzpicture}
\end{tikzpicture} & \begin{tikzpicture}
\end{tikzpicture} \\
\hline
\begin{tikzpicture}
\end{tikzpicture} & \begin{tikzpicture}
\end{tikzpicture} \\
\hline
\end{tabular}
\caption{Lateral and vertical transformation examples (from Goel\textsuperscript{16}. Reprinted with permission)}
\end{figure}

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made as part of the architectural design of a post office counter. Figure 1(B) is a lateral transformation from Figure 1(A), in that the three booths retain their location but have been internalized into the main square. Figure 1(C) however is a vertical transformation from Figure 1(B) in that there is no modification of the idea of the booths in the central square; there is only the clarification of neater lines and the addition of dimensional data.

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.

3 Methodology
In the study described here, eight students were selected from a class of 22 by teaching staff. This paper will only describe the sketching activities of three of the eight students that were initially selected. This selection is intended to illustrate a range of activity and varying scale of project. In line with recent work on ethnographic methods\textsuperscript{17,18}, the students were observed at work on their individual, self-driven projects. These projects constitute a major part of the MEng. Product Design Engineering curriculum at the University of Glasgow. There were no intermediary submission dates in the project, only a final completion date. The window for study was set to cover the conceptual phase period totalling 15 weeks.

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 subjective assessments of the personalities of the students was obtained by placing one of the researchers (third author) in the participant-as-observer role\textsuperscript{19}. This form of participant observation makes clear to the subjects that the observer is indeed an observer. In this study, the researcher performed the dual role of observer and participator (in this case taking the role of a part-time tutor). The three students worked on a wide range of products varying in many ways, most obviously in size. The students selected the following projects, illustrated in Figures 2–4 below.

3.1 Definitions
3.1.1 ‘Individuating’ sketches in sketching episodes
The approach adopted in this study required the observer (third author) to ‘individuate’ (i.e. identify separate sketching episodes) and number each
sketch in order of their completion. Figure 5 shows a typical page from the sketchpad of one of the students involved in the experiment.

The observer first went through and identified separate (though still connected) sketching episodes. In Goel’s experimental work, subjects ‘individuated’ the output by drawing rectangles around each separate drawing and in some cases would number them in sequence. In this work the ‘individuated’ sketches in Figure 5 are shown by the overlapping rectangles, added afterwards by the observer.
3.1.2 Degree of transformation

Although Goel’s work recognises that transformation has taken place, no measure of the degree of transformation is proposed. Such a measure would be useful in helping to track design progress and, in particular, judging the
rate of design development. It may also help to measure the extent of lateral transformation, whether it is a small change or a complete conceptual shift. To facilitate a measure of each sketch’s degree of transformation, a practical and straightforward ‘complexity’ scale was developed during this study. The most simple of sketches, typically found in the students’ sketchbooks, was rated a ‘one’ and the most complex a ‘five’. A more detailed definition of the complexity rating is outlined in Figure 6.

4 Results and discussion

This section presents results of the three student designers’ sketching activities involved in the study. The results achieved have been separated into two elements. First the number and transformation balance (i.e. lateral against vertical percentage) of sketches produced during the observation period (section 4.1) and, second, a week by week record of the complexity and transformation progress of each student’s sketching activity is presented (section 4.2).

The observer (third author) studied every successive sketch of the three students’ sketching activity to decide which transformation had taken place in each case. An obvious change in thinking (divergence) is a lateral transformation, while if the change is instead to a more detailed version of the same idea then a vertical transformation (convergence) has occurred.

The observer encountered problems in sequencing the drawings within a page, and this often made it difficult to determine which drawings were actually successive. To this end, ‘successive’ was extended to mean ‘coming after’ in this study, rather than ‘consecutive’ which it is used to mean in Goel’s work. 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.

4.1 Number and transformation balance of sketches

As part of the study, each successive sketch of each student was assessed as either a lateral or vertical transformation. Figures 7–9 show the sketches evaluated as either a lateral or vertical transformation in comparison to their earlier sketches (as a percentage). From Figures 7–9, the tendency of students to produce work that is either laterally or vertically biased can, thus, be seen at a glance. This provides a quick insight into the thinking mode, week by week, of each student. One can also assess the switching between ways of thinking over the period of observation by looking at the results for each subject in turn. Each table breaks down, week by week, each student’s sketching activity and illustrates the amount of lateral and
<table>
<thead>
<tr>
<th>Complexity Level 1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Monochrome line drawing. No shading to suggest 3-D form. No text or numerical annotations are used.</td>
<td><img src="image1" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Complexity Level 2</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Monochrome line drawing. There is no shading to suggest 3-D form, but there is use of different thicknesses of line. One or two brief annotations may appear, but not more than 6 or 7 words.</td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Complexity Level 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Monochrome, with rough shading used to give suggestion of 3-D form. The drawing may be annotated to describe certain aspects of the concept. May include dimensions.</td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Complexity Level 4</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Subtle shading is heavily suggestive of 3-D form. The drawing will almost certainly be annotated. Colour may be used to illustrate certain parts of the concept or arrangement.</td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Complexity Level 5</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Extensive use of shading to suggest 3-D form. Annotations will be used to ask questions of the idea or explain it. Colour will be heavily used. Generally a very busy drawing - many lines will be used in its construction.</td>
<td><img src="image5" alt="Diagram" /></td>
</tr>
</tbody>
</table>

*Figure 6 Complexity scale*
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Figure 7 Week by week breakdown of Student A’s number and transformation balance of sketches

Figure 8 Week by week breakdown of Student B’s number and transformation balance of sketches
vertical transformations over the observation period of 15 weeks. Figures 7–9 also include the number of sketches produced by each student on a weekly basis.

Figure 7 shows that Student A opens with what is a possibly too brief a spell of lateral activity (Week 2). Although there is good balance between lateral and vertical transformations (i.e. 75:25%), in this week, the number of sketches produced (i.e. four) is too few for this stage of the project. This is followed by a spell of relatively balanced activity, and another short spell of lateral activity in Weeks 4 and 5. Student A’s work is typified by a fairly balanced approach overall. Even those weeks where there is a notable bias towards one type of thinking, it is relatively slight. The overall progress of Student A, shown here, is ‘slight lateral to balanced to vertical to slight lateral’, showing a dominant tendency towards very ‘mild’ alternating episodes. This indicates consistent, if somewhat unspectacular, progress.

Figure 8 illustrates that Student B opens her account with a late start. This is followed by a spell of predominantly lateral work (Week 4), immediately followed by a week of slightly vertically-biased activity (Week 5). A large spell without sketching ends with two weeks of vertical activity in Weeks 11 and 12. There is a switch to a period of intense lateral activity
(68 sketches) in Week 13 which is followed by a switch back to vertical thinking for Weeks 14 to 15. The week of lateral activity in Week 13 tends to make the overall activity look as though it is typified by alternate switching between thinking modes. There are some concerns here, however, in that the opening spell of lateral sketch work was too quickly overtaken by vertical thinking. This suggests early fixation.

In Figure 9, Student C produced a good number of sketches over the 15 weeks. The student displays an initial tendency to produce lateral work. Between Weeks 2 and 5 inclusive, three weeks show considerable lateral bias, although Week 4 shows an almost 50:50% split. Work done during the student break weeks (7 and 8) shows a brief vertically-biased episode followed by a laterally-dominant week. When Student C returns to his sketchbook in Weeks 10 and 11, there is another burst of laterally-biased activity. This is followed by a two week spell of very much vertically-biased work, however. Another two week spell of lateral activity comes at the end of the observation period. Overall, Students C’s work displays a predominantly lateral start with alternate switching between lateral and vertical modes thereafter.

Although the weekly totals are more important in monitoring and guiding the sketching activity, overall the total figures illustrate that Student C displays a slight lateral bias (59:41%) while Student B and Student A are split almost 50:50% between lateral and vertical transformations. These findings correspond well with findings from a recent similar study of architects20.

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 balance between lateral and vertical transformation at these early stages rather than an extreme lateral bias16. It is likely, however, that the balance will shift to an extreme (and finally total) vertical bias as the design representation progresses towards the embodiment and detailing stages. From his experiment, Goel16 mentions a third possible transformation type (duplication). This 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 Figures 7–9, a judgement was made as to whether each drawing was either a lateral or vertical transformation from the drawing before. Duplication transformations were not considered here. However, it is envisaged that future work will include duplication transformations and the impact they may have on progress made during concept design sketching activities.
4.2 Sketch complexity and transformation activity

From the results of the student designers’ sketching activities presented earlier, any effective support of concept design sketching must acknowledge the three main issues of Goel\textsuperscript{16}. That is, the support tool should be able to provide feedback to the designer with regards to whether s/he is generating sketches that are \textit{vertical} transformations, \textit{lateral} transformations, or \textit{duplications} of previous sketches. From the studies of the three subjects’ presented earlier, one can graphically represent each of their sketching activity (in terms of sketch complexity) against time.

Figures 10–12 illustrate the three students’ sketching activities, in terms of their complexity (section 3.1.2) levels 1–5 on the y-axis, over the same 15-week time period on the x-axis. Each weekly segment of sketching activity is represented either as a \textit{lateral} transformation represented by a triangle, a \textit{vertical} transformation by a square, or a \textit{duplication} by a circle. Weeks where there was no sketching activity are represented by a \cdot. Although it is possible that the student designer may have generated both \textit{vertical} and \textit{lateral} transformations during their weekly sketching activity, the type of transformation that was most prevalent in their sketchbook was the one selected and represented.

From Figure 10 it can be seen that Student A’s sketching activity contains mainly \textit{vertical} transformations. There are, however, a couple of \textit{lateral}
transformations with some *duplication*. This subject’s activity is also characterized by the complexity level staying at level 3 throughout the design process, with some progression into complexity level 4.

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In Figure 11 it can be seen that Student B’s sketching activity contains mainly vertical transformations. There are, however, a number of lateral transformations in the subject’s sketching activity towards the end of the process. These lateral transformations were mainly down to the subject generating a number of various layout detail changes. This subject’s sketches have progressed well in terms of the complexity level. That is, the subject’s early sketches contain little information (low complexity) as is expected, but as the process develops so do the subject’s sketches (the sketches develop, over time, from complexity level 1 to 5).

Figure 12 illustrates the sketching activity of Student C. This student’s activity is made up of a majority of lateral transformations, with some vertical transformations and duplication. This subject’s sketches have not developed well in terms of the complexity level. The total activity (15 weeks) comprises sketches with a low complexity rating (level 1–2). This suggests that the subject has been unable to decide on which concept to develop and move on to the more detailed aspects of the design problem, otherwise known as design fixation21,22.

5 Conclusions and future work
This study has confirmed that freehand sketching is prevalent in the conceptual phase of design and that the sketching activity has peaks and troughs of both lateral and vertical transformations over time. In this way, sketches can provide insight into the designer’s mode of thinking at any particular point in the design process. It is hoped that this reflexive analysis will provide a basis to support more effective and efficient use of the designer’s time and effort.

In addition, the work described here points the way towards providing effective metrics for design progress and development tracking during the conceptual design phase. More work is, of course, required to refine and validate such metrics.

Future research will extend this work to cover the use of sketches in group settings within our academic sample group. Also, a further plan is to continue this work in an industrial setting, which is characterized by greater sources of noise and greater amounts of information.

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