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ABSTRACT

A study was conducted to examine the observation that untutored Grade 7 students appeared to have tacit knowledge of how to solve problems in a technological context. Left to their own devices in an environment rich in three-dimensional materials, they frequently designed a solution to a problem in unique and creative ways. Based on experts' opinions, the literature describing the design process showed a model of designing as a set of procedures to be followed that did not seem to reflect what novice designers actually did. Ten Canadian Grade 7 students were paired into five single-sex dyads to reflect the real world of technology. Each dyad was provided with a design brief that described the technological problem to be solved. Analysis involved transcribing and segmenting subjects' talk during the problem-solving session and retrospective interviews. A coding scheme was developed to reflect the problem-solving nature of designing. The design strategy of each dyad was represented in the form of a computer-generated "map." Comparisons between the strategies used by the dyads and a theoretical model indicated four very significant differences: students' strategies were more complex than suggested by any of the linear models; subjects generated solutions serially rather than generating several at the outset; the preferred strategy for developing ideas was modeling in three-dimensional terms; and evaluating was an integral and ongoing activity during design. (Eight figures and 65 references are included.) (YLB)

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ED 401 491

THE PROBLEM-SOLVING STRATEGIES OF YOUNG DESIGNERS[1]

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Introduction

The study reported here derives from the observation of the researcher that untutored Grade 7 students appear to have tacit knowledge of how to problem solve in a technological context. Left to their own devices in an environment rich in three-dimensional materials, they frequently design a solution to a problem in unique and creative ways.

Childrens' experience of designing using materials begins in their earliest years before school. Their play with toys or the objects around them - wooden blocks, empty boxes, textiles - is used imaginatively to simulate the adult world. Witness the ingenuity of childrens' sand castles on the beach, tree houses, skate board ramps, all examples of designing and making in action (Breckon, 1995). Outterside (1993) has observed the emergence of design ability in a three year old child. She concludes that "it is evident that children enter formal schooling with a wealth of knowledge and experience relating to design ... which should be utilized and built upon by the teacher" (p. 49).

It is reasonable to suppose, therefore, that by the time students enter secondary school they have a very significant fund of experience with designing, that is, working from problem to solution. The steps they follow to achieve a solution, however, may not conform, either in number or in sequence, to those described in textbooks. Some of the elements of the "correct" process, such as sketching and investigation, are omitted by students. Others, such as testing and evaluation, are very evident but are not used in the sequence as described. Hence, the formal teaching of designing appears to conflict with the tacit strategies students bring with them to the technology classroom. According to Outterside (1993) "children ... use the process and process skills [of designing] unknowingly. We should try to raise childrens' awareness of these process skills ... in order to enable them to see and understand, what and how, they are thinking" (p. 49).

This paper begins with a summary of the literature relating to design process models, and a description of the methodology developed to elicit, capture and analyze the design strategies used by subjects. This is followed by discussion of an analysis of the way in which the strategies used by students differ from those in theoretical models of the design process. The implications of these findings for the teaching of designing and making complete the paper.

[1] Paper presented at the annual conference of the American Educational Research Association, New York, April 1996. The paper is based on the doctoral dissertation entitled "The Strategies Used by Ten Grade 7 Students, Working in Single-Sex Dyads, to Solve a Technological Problem" (Welch, 1996). My attendance at the AERA conference is made possible, in part, by funding from the Office of Research Services of the School of Graduate Studies and Research, Queen's University. The author would welcome suggestions and comments based on this paper. Address: Queen's University, Faculty of Education, Kingston, Ontario, Canada, K7L 3N6. Tel: 613-545-6262. Email: Welchm@Educ.Queensu.ca

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Models of the Design Process

According to Jones (1970) "all [models of the design process] are attempts to make public the hitherto private thinking of designers, to externalize the design process" (p. 3). This is nearly always accomplished by a diagram showing the steps in the process and the relationships between them. According to Siraj-Blatchford (1993) "providing a simplified model of the process of design which teachers may adopt heuristically provides for the student what Bruner (1986) has termed scaffolding" (p. 22). Vygotsky (1986) refers to this period when the teacher does for the student what they are not yet able to do for themselves as the "zone of proximal development" (p. 33), the gap between what an individual can do alone and unaided, and what can be achieved with the help of more knowledgeable others (Bennett, 1992). For as Schön (1987) has pointed out, one of the difficulties for the novice designer is that:

> Designing is a holistic skill [which] one must grasp ... as a whole in order to grasp it at all. Therefore one cannot learn it in a molecular way, by learning first to carry out smaller units of activity and then to string those units together in a whole design process; for the pieces tend to interact with one another and to derive their meanings ... from the whole process in which they are embedded ... [Nevertheless], it is true ... that design processes may be broken into component parts by strategies of decomposition useful both to practice and to coaching. (p. 158-159)

The literature describing design process models is based primarily on experts' opinions, on their thinking about design, rather than on systematic investigation or experimentally observing it (Lawson, 1990; Rowland, 1993). This literature, on the whole, shares a view of designing as a deterministic, essentially rational and logical process, a set of procedures to be followed. However, it is not clear that designers actually operate as this literature suggests. A few studies of expert designers engaged in the act of designing have been carried out (Akin, 1978; Cross, 1982; Darke, 1979; Eastman, 1970; Schön, 1983) and, as a consequence, empirical descriptions and models of the design process have been developed. Recent studies of novice designers at the elementary level (Johnsey, 1995a; Outterside, 1993; Roden, 1995), at the secondary level (Kimbell, Stables, Wheeler, Wosniak & Kelly, 1991), and at the university level (Elmer, 1996) are beginning to provide insight into their strategies.

Models of the design process are readily available in both the technology education literature and school textbooks. Yet it is by no means clear that these models reflect what designers, especially novice designers, actually do. Doubt may therefore be cast on their usefulness in teaching students to design.

Many of the models in textbooks depict designing as a simple linear, algorithmic process (Dodd, 1978; Engineering Council, 1985; Schools Council, 1982; Scottish Technical Education Modules, 1981; Shaw & Reeve, 1978; Williams & Jinks, 1985). Shaw and Reeve (1978, p. 7) described a "developmental sequence of four related areas of activity": Problem identification and definition, proposal of solutions, realization of design, and test/evaluate.

Williams and Jinks (1985) describe designing as "a journey" (p. 37) and use a "design line" (p. 37) to separate the journey into a number of stages: problem need, first ideas, chosen idea, making, and testing and evaluation. They note, however, that "at the end of our journey ... it may be necessary to 'back track' to make modifications and, occasionally, we have to start all over again from the original problem" (p. 38). Burton (1986) advocated a linear approach since it "is logical and systematic ... and can be broken down into a developmental sequence consisting of a number of related areas of activity" (p. 241).

These linear models went through a considerable amount of development. Many authors recognized the iterative nature of the activity and so added any number of feedback loops to the basic outline. Barlex, Read, Fair and Baker (1991) describe the steps in a "design strip" (p. 3), but note that it "is not a straight jacket to be slavishly and linearly followed" (p. 3). Sellwood (1991) presents a design process consisting of a complex figure-of-eight shape, comprising two distinctive stages: (a) the thinking-sharing and interactive stages, and (b) the making and doing stages. However, the accompanying text describes a clear linear route through the model.

Kelly, Kimbell, Patterson, Saxton,and Stables (1987) identify two problems with describing a design process as a set of stages to be followed in a linear way. The first lies in attempts to identify "appropriate activities for each stage" (p. 16). As the authors point out, the activities of sketching or modelling or recording results may each be appropriate during a number of stages. A second difficulty lies in the interdependency of the activities. As Kelly et al. (1987) point out "[when] a pupil chooses to use 'modelling' as an aid to generation and development ... ideas that emerge must be evaluated instantly for the idea to develop [and] the developing idea may require a new line of investigation to see how useful it might be" (p. 16). Lawson (1990) identifies a further problem, when he demonstrates that there is no natural end to a design process. Frequently it is time or cost which terminate design activity.

The next generation of design process models described the activity as an open-ended loop (Department of Education and Science, 1987; Midland Examining Group, 1988). While these models remain linear there was an increasing acknowledgement that "designing seldom proceeds by way of a series of clearly recognisable stages to a neat solution" (Department of Education & Science, 1987, p. 9).

These models have been helpful guides to the sorts of activities that need to occur in Design and Technology classrooms. However they have also imposed limits by prescribing "stages" of the process that need to be "done" by students. As the Department of Education and Science in the UK noted in 1987:

> Used unsympathetically, the approach can reveal a greater concern for "doing" all the stages of the process than for combining a growing range of capabilities in a way which reflects individual creativity and confident and effective working methods. (p. 11)

Yet at the same time teachers recognized the need for a model that illustrated "the activities which play a part (emphasis added) in moving from the recognition of an area offering scope for activity to the completion of an end product" (Department of Education and Science, 1987, p. 9). It is also noteworthy that the loop ends with an arrow head pointing to a dashed arrow. This suggests that the process never really ends, but is brought to a conclusion which satisfies a set of requirements at that moment in time (what Simon (1969) refers to as "satisficing").

The next development further closed the loop and showed that the elements were more interactive. In a guide for teachers of General Certificate of Education courses in Craft, Design and Technology (Secondary Examinations Council, 1986) a process, described as "the design loop", is shown in the form of a closed circle with stages of the process distributed around the circumference, to provide "a visual guide to a generalised design procedure" (p. 9). However, as the guide cautions "it does not follow that students have to mechanically work their way around it ... There may well have to be a great deal of jumping about across and around the loop" (p. 9).

This model more closely reflects the ideas of Lawson (1990) who wrote that "the map of the design process must allow for an infinite number of return loops" (p. 27). And Baynes (1992) reminds us that "the processes involved in designing are not linear, ... and they do not always proceed in an orderly way. They are reiterative, spiralling back on themselves, proceeding by incremental change and occasional flashes of insight" (p. 1).

A quite different model of designing has resulted from research by the Assessment of Performance Unit, set up within the UK Department of Education and Science in 1975 to "promote the development of methods of assessing and monitoring the achievement of children at school" (Kelly, Kimbell, Patterson, Saxton & Stables, 1987, p. i), and later "to analyse the constituent parts of the [design] activity [in order to] make it possible to teach and assess it" (Kimbell, Stables, Wheeler, Wosniak & Kelly, 1991, p. 19). First described as the "interaction between thought and action" (Kelly et al., 1987, p. 14) and later as the "interaction between mind and hand" (Kimbell et al., 1991, p. 20), the model "reject[s] the idea of describing the [design] activity in terms of the products that result from it, and instead concentrate[s] on the thinking and decision-making processes that result in these products" (Kimbell et al., 1991, p. 20).

The essence of this model is that ideas conceived in the mind need to be expressed in concrete form before they can be examined to see how useful they are. In other words, "the inter-relationship between modelling ideas in the mind and modelling ideas in reality is the cornerstone of capability in ... technology" (Kimbell et al., p. 21). Yet as Johnsey (1995b) suggests "the model is essentially linear and (purposely) vague about what might be happening at any point in the process" (p. 207), reminding us of Lawson's (1990) observation that, in attempting to describe how designers design, "there is not a great deal of action to be seen ... it is what goes on in the designer's mind which really matters" (p. 24).

Perhaps it is because so much of the designer's work is hidden that few studies have attempted to investigate their actual practice. Yet if the teaching of designing is to become more effective then the strategies of untutored students as they design technological solutions must be examined. An understanding of these strategies would undoubtedly exert some good influence on teaching. Hence the next section of this paper describes a methodology developed to investigate the strategies used by untutored designers.

Methodology

Ten Grade 7 students (six boys and four girls) participated in the study. Subjects were chosen from a pool of volunteers using the following criteria: (a) they should be articulate, (b) they should be able to work cooperatively, and (c) they should have maintained average to above average performance in school work. These criteria were an attempt to ensure a reasonable degree of ability in order that subjects chosen were capable of demonstrating design and technological skills to a level which make detailed analysis possible and worthwhile.

Subjects were paired into five single-sex dyads. The decision to have subjects work as dyads reflects the real world of technology, in which most technological development occurs as the result of the efforts of two or more people working cooperatively. Additionally, previous research with dyads (Meyer, 1991) found that while those of mixed gender often do not communicate well or work cooperatively "the use of dyads ... encourage[s] students' conversation as a means to make students' thinking explicit" (Meyer, 1991, p. 14). Further, research has shown that the interaction in a dyad provides much richer data than when subjects work alone (Rahilly, 1991). Tobin (1990) argues that student collaboration "enables understandings to be clarified, elaborated, justified, and evaluated" (p. 407).

The Design Brief

Each dyad was provided with a copy of a design brief that described the technological problem to be solved. The problem, entitled "Paper Tower", read as follows:

> Using ONE sheet of 220 mm x 280 mm white paper and 100 mm of clear tape, construct the tallest possible tower.
> You will also be given pink paper. This you may use in any way as you develop your solution. However, NONE of the pink paper may be used in the tower you submit as a final product.
> Limitations:
> There is a time limit of one hour.
> The tower must be free standing. It cannot be taped to the floor nor to anything else.
> When you have finished, the tower must stand for 30 seconds before having its height measured.

This particular task was selected for five reasons. First, the task contains the three elements which Cross (1994) describes as common to all design problems: "(a) a goal, (b) some constraints within which the goal must be achieved, and (c) some criteria by which a successful solution might be recognized" (p. 10). Second, the definition of the design process adopted as one of the bases for this study includes the following steps; understanding the problem, generating possible solutions, modelling a solution, building a solution, and evaluating a solution. Successful completion of the "Paper Tower" task requires each of these steps. Third, informal pilot testing in a variety of educational settings over a number of years by the researcher has demonstrated the task to be one which students enjoy. Fourth, the task does not require any equipment or skills beyond the abilities of Grade 7 students who have received no formal technology education. Finally, the task does not involve the use of dangerous equipment or materials.

Each problem-solving session was audio and video recorded by the researcher . Subjects were encouraged to talk normally during the session. Within three days each dyad returned for a retrospective interview. Subjects watched the video of their problem-solving session. A video camera was positioned so that both the screen and the students could be video taped, enabling the researcher to document the segment of the task referred to by the subjects. The researcher started, stopped, or rewound the tape as subjects engaged in a semi-structured interview.

Following Hayes, Flower, Schriver, Stratman, and Carey (1985) concise, clear and consistent instructions were developed to ensure that all sessions were as uniform as possible. The instructions for the problem-solving session were in three parts. Part 1 consisted of a warm-up activity. Ericsson and Simon (1984) demonstrated that when subjects are engaged in tasks involving oral information a warm-up activity is important. Further, the warm-up task should be similar to the main task. Part 2 of the instructions for the problem-solving sessions described the intent of the research, role of the subjects, and how the session was to proceed. The reason for the audio and video taping was reemphasized. Subjects were reminded that they should talk normally and naturally during the session. Part 3 of the instructions, used at the end of a problem-solving session, included a 'thank you' message, a reminder of the date and time for the retrospective interview, and a request to not discuss the design brief with friends until the data collection period was at an end.

The instructions for the retrospective interview also began with a welcome. As a warm-up subjects were asked to describe, from memory, the problem they solved in the previous session. The researcher then informed the subjects that they were going to watch the video tape of their problem-solving session, during which they would be asked to comment upon some of their actions. In an effort to minimize the response effects (Borg & Gall, 1983) subjects were made comfortable with the idea that if they could not answer a question it was legitimate to say "I don't know" or "I can't remember". The retrospective interview ended with a 'thank you' and a reminder not to discuss the interview with friends.

Preparing the Data for Analysis

Analysis involved transcribing and segmenting subjects talk during both the problem-solving session and the retrospective interviews. Segmenting, or unitizing, is, according to Holsti (1969) a process whereby "raw data are systematically transformed and aggregated into units which permit precise description of relevant content characteristics" (p. 94). According to Lincoln and Guba (1985) units " are best understood as single pieces of information that stand by themselves, that is, are interpretable in the absence of any additional information" (p. 203).

In this study transcripts were first segmented into "speech bursts" or chunks (Miles & Huberman, 1994, p. 56). A speech burst was defined as "a complete portion of text uttered by a subject without interruption from that subject's partner". Each speech burst was typed on a new line, with the speaker identified by a code name at the left. The start time, in minutes and seconds, of each segment was added to the left margin. Finally, a description of the subjects' actions was added to the right of each segment. Transcripts were then segmented a second time, each new segment delimited by a change in the actions of the subjects. Each segment of action was indicated using a square bracket. Figure 1 shows a sample of a segmented protocol.

S9: 26,04	So its going something like that?	621 622	Holds up two cylinders into teepee style framework.
S10: 26,07	Yeah. To make some smaller ones too.	624 625	Both continue to roll cylinders
S9: 26,18	Here, I'll roll while you tape.	627	
S10:	OK.	629	Fits 2 cylinders end-to-end
S9: 27,08	Like 20 minutes more.	631	Looks at clock
S10:	Go ahead. ???	633	Rolling & joining cylinders

Figure 1. Sample of a segmented protocol

Development of a Coding Scheme

A coding scheme was developed to reflect the problem-solving nature of designing as described in the technology education and human problem solving literature (Department for Education, 1995; Ericsson & Simon, 1984; Kimbell, Stables, Wheeler, Wosniak & Kelly, 1991). Codes were designed to describe the actions of the subjects, that is, the manifestations of their design thinking. The naturally occurring conversation between subjects as they engaged in the problem-solving task, and responses made during a semi-structured interview were used to inform this coding of actions.

According to Miles and Huberman (1994) "a provisional 'start list' of codes [may be created] prior to field work. [This] list comes from the conceptual framework, list of research questions, hypotheses, problem areas, and/or key variables that the researcher brings into the study" (p. 58). This approach is further supported by Tesch (1990) who adds that start codes may also be derived from the literature and tacit knowledge that the researcher brings to the study.

In this study "start codes" were developed by analyzing the design process, that is, problem solving, models described in twelve influential technology education documents spanning the years 1968 - 1992. Identical stages in the process were aligned horizontally. From this review a generic "sequence of actions" (Steps) and a start list of codes were developed.

A second approach to the derivation of a code set was then adopted and used to modify and extend the start list. Glaser and Strauss (1967) and Strauss (1987) advocate an inductive approach to the development of a code set. Grounded theory (Glaser & Strauss, 1967) states that codes should be "grounded", that is, derived from, the data. Strauss (1987) describes the process as "open coding", defined as "the unrestricted coding of the data aimed at providing concepts that seem to fit the data" (p. 28). Tesch (1990) refers to "empirical indicators", that is, actions, events and words which could be used to develop additional codes.

As a result of this open coding, new codes were derived. The coding scheme for this study contains six categories. The first five, requiring 24 discrete codes, describe the five stages of the theoretical model of the design process: (1) understanding the problem; (2) generating possible solutions; (3) modelling a possible solution; (4) building a solution; (5) evaluation. The sixth category includes eight miscellaneous codes, used to describe such activities as off-task talk and researcher instructions.

Mapping the Data

As noted earlier design process models found in the technology education literature are frequently depicted as a graphic model, often linear and frequently containing a number of feedback loops. In this study the design strategy of each dyad is represented in the form of a computer generated "map". Such maps make it possible to search for patterns in a single data set and for regularities in multiple data sets.

As described earlier the transcript of each dyad's problem-solving session was segmented, the start time of each segment recorded, and subjects' actions noted. The transcripts were resegmented into "periods of action" and coded. The time spent on each period was calculated. From this data four statistics were derived: (a) time on code, in seconds; (b) the percent of the total time spent on each coded period; (c) the total elapsed time, in seconds; and (d) the cumulative percent of total elapsed time.

The data were entered into a spreadsheet program, in which rows 2 to 25 each represent one of the codes developed to describe steps in the design process. Row 1 contains the cumulative percent of total elapsed time, one data point in each column. Additionally, each code in the coding set was assigned a number (e.g., RBRF=2, DPERF=3, DCONS=4), this number being identical to its row number in the spreadsheet.

Each cell in the spreadsheet was then filled with one of these assigned numbers. In the example shown in Figure 2 the subjects were reading the brief (RBRF) from time zero to 2.5

percent of total time. From time 2.5 percent to time 4.4 percent they were drawing (DRAW). The data were charted using an XY scattergraph with lines. Horizontal and vertical grid lines were added to assist with the interpretation of results.

	A	B	C	D	E	F	G
1	% data task 1	0	2.5	4.4	5.1	5.6	5.9
2	RBRF	2	2				
3	DPERF						
4	DCONS						
5	GEN			5	5	5	5
6	DRAW		6	6	6		6
7	PMU						
8	MANIP					8	8
9	MMU						

Figure 2. Data entry format

The final step in the analysis of data required the production of a series of empirical maps depicting the design process used by each of the dyads, and then the comparison of these to the theoretical design process.

The development of a theoretical map required reference to the technology education literature, in which the design process is depicted as a "characteristic sequence of actions" (Hayes, 1989, p. 3) containing six steps: (a) finding the problem, (b) understanding the problem, (c) generating possible solutions, (d) modelling a possible solution, (e) building a solution, and (f) evaluating the solution. However, to ensure that all subjects found a solution to the same problem, thus allowing a valid comparison of their sequence of actions, they were not required to find a problem to be solved but were provided with a design brief. An idealized map of a design process subjects might be expected to use in this study is shown in Figure 3.

The steps in the process are shown on the vertical axis. Time spent on each step in the process is represented by the bold horizontal lines. Having identified a problem to be solved students are expected to begin by sketching (generating) a number of alternative solutions, ultimately selecting the one which seems the most appropriate. Having selected a best solution, students would then be expected to spend considerable time modelling and making a solution, before evaluating the end product.

In Figure 3 the time spent on each step reflects a subjective interpretation based on a distribution implicit in a number of theoretical models. Step 1 (finding the problem) and Step 2 (understanding the problem) require the least amount of time. Steps 3 and 4 (generating possible solutions and modelling a possible solution) together require the greatest time. Step 5, building a solution, requires approximately the same time as either Step 3 or Step 4. According to theoretical models, evaluation (Step 6) occurs at the conclusion of Steps 3, 4 and 5.

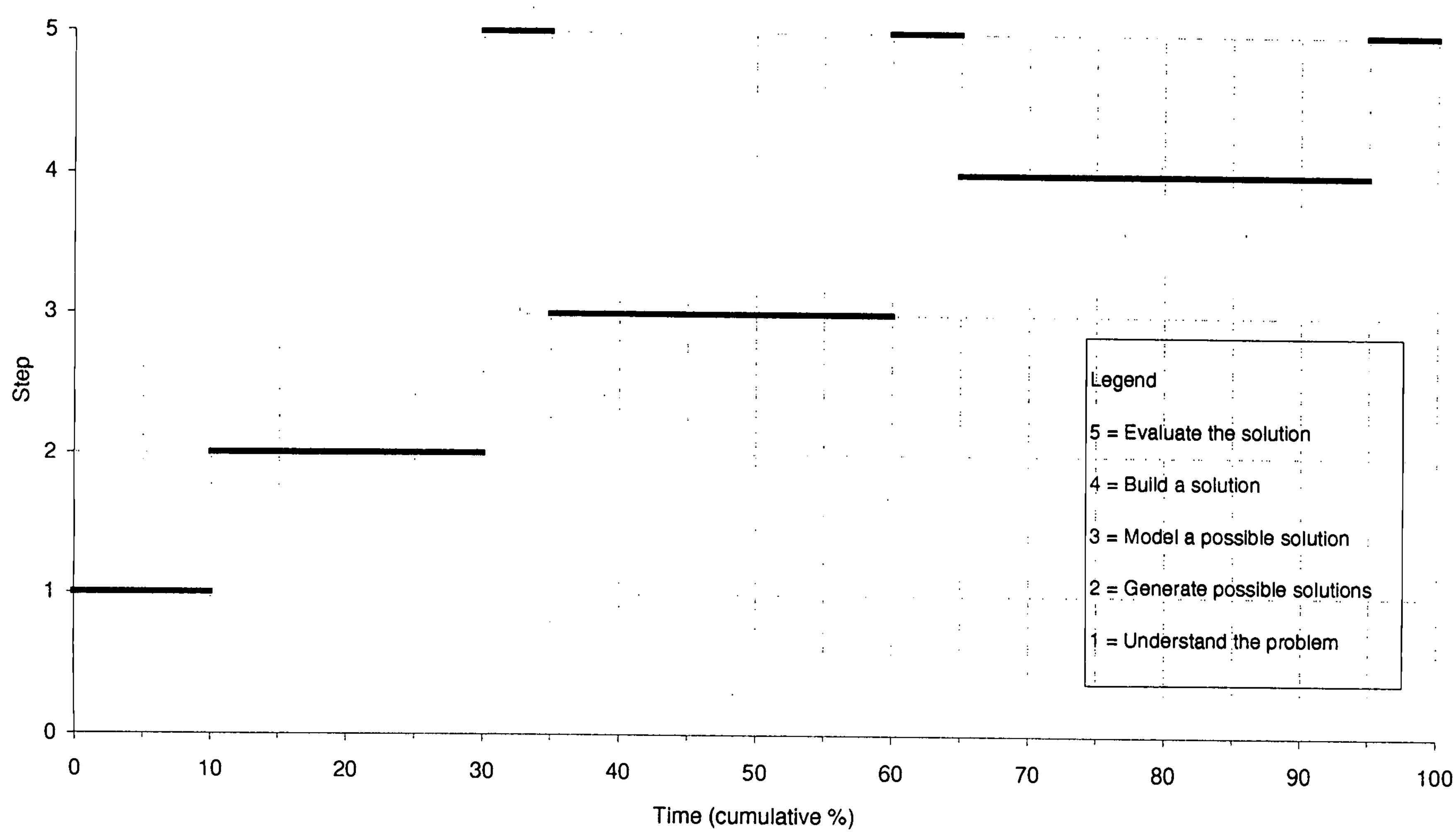


Figure 3. Map of the five-step theoretical design process used in this study

Results

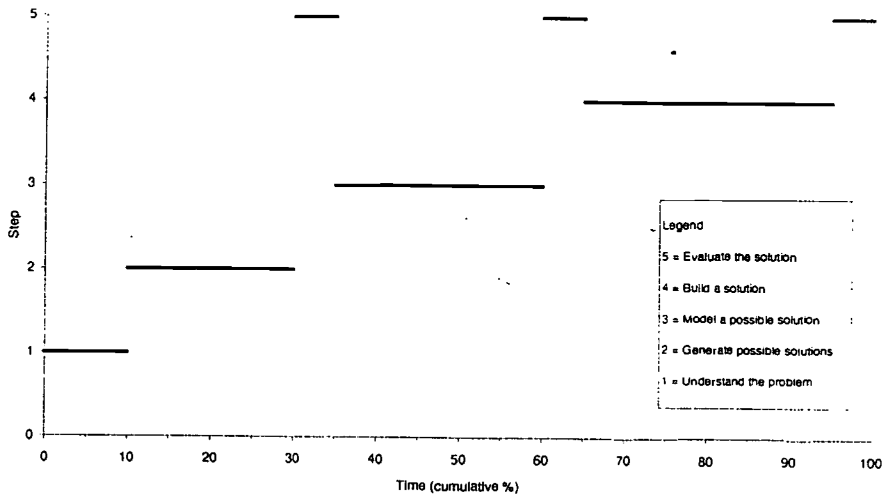
Figures 4-8 show comparisons between the strategies used by Dyads 1 to 5 and this theoretical model. Four very significant differences are evident. First, students' strategies are more complex than suggested by any of the linear models. Figures 4-8 show that subjects frequently do not work in a linear way through the steps identified in textbook models: understand the problem, generate possible solutions, model a solution, build a solution, and evaluate a solution. For example, understanding the problem appears to emerge from an exploration of solutions. Subjects moved very quickly to solution generation. Subjects did not appreciate the importance of analyzing and focussing on the problem before "jumping straight to design ideas" (Harding, 1995, p. 19). This finding is supported by research on expert/novice problem solving, which has shown that at the beginning of a problem-solving episode experts spend more time attempting to "understand" the problem, whereas novices move more quickly to solution generation (Chi, Glaser & Farr, 1988; Stewart & Van Kirk, 1990). Yet the designer needs to be sure of exactly what it is they are being asked to do. The fact that Dyad 2 did not model any solutions using the materials provided for that step, but moved immediately to using the materials intended for building a prototype provides evidence of the difficulties which may be encountered when the novice designer does not take the time to carefully read and thoughtfully interpret a design brief. Subjects did not sketch and evaluate several solutions prior to modelling but generated and modelled serially. Modelling itself was shown to be a complex activity, more accurately described by a model-test-refine-test iteration. This iteration itself appears to act as a source of inspiration for new solutions. Similarly, building a prototype involved an iteration, a constant toing-and-froing between building, testing, and refining. Evaluation occurred not as a summative activity after generating and modelling and building, but as an integral and ongoing activity.

Second, subjects generated solutions serially rather than generating several at the outset. Subjects in this study did not begin designing by sketching several possible solutions. Data has shown that no subjects attempted to sketch more than one solution at the outset, and that such sketching as did occur was perfunctory.

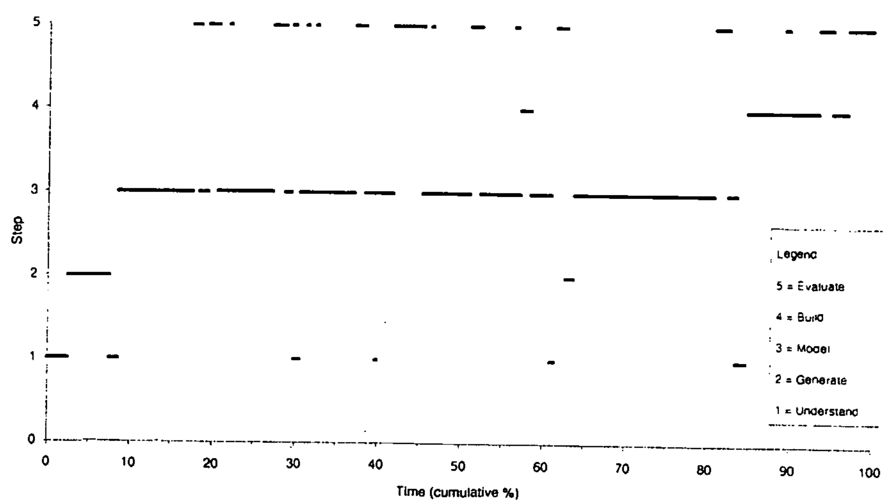
Third, it appears that the preferred strategy for developing ideas is modelling in three-dimensional form. Subjects moved to modelling much sooner than predicted by textbook models. The evidence suggests that novice designers are anxious to begin modelling, even before a solution has been fully worked out. This modelling served several purposes: externalizing ideas, providing a method of testing and refining and evaluating ideas, and stimulating new ideas. Modelling appears to be an essential stimulus to the ongoing development of ideas. The interaction with materials appeared to stimulate other design skills. It is important, therefore, for teachers to recognize when modelling is aiding students' other designing skills.

Fourth, Figures 4-8 illustrate quite clearly how evaluating was an integral and ongoing activity when subjects in this study were designing. Evaluating occurred consistently from the earliest moments of designing. As Archer and Roberts (1992) have written:

> All design activity involves continual appraisal and reappraisal of the meritoriousness of existing realities and alternative propositions being handled. (p. 4)



Map of the five-step theoretical design process used in this study



Sequence of steps employed by dyad 1

Figure 4. A comparison between the strategy used by Dyad 1 and the theoretical model

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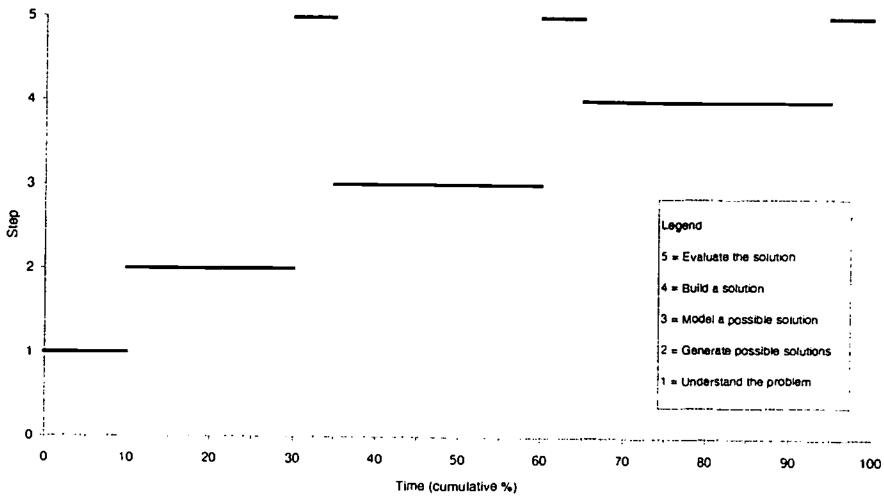
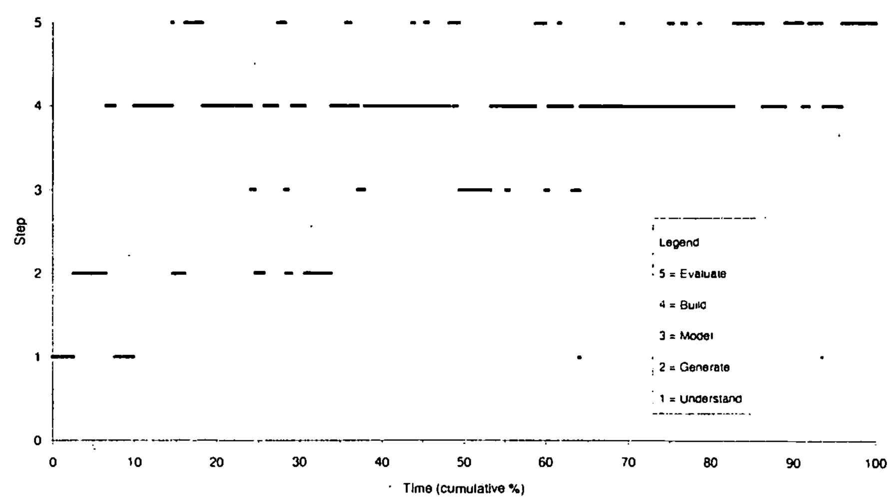


Map of the five-step theoretical design process used in this study



Sequence of steps employed by dyad 2

Figure 5. A comparison between the strategy used by Dyad 2 and the theoretical model

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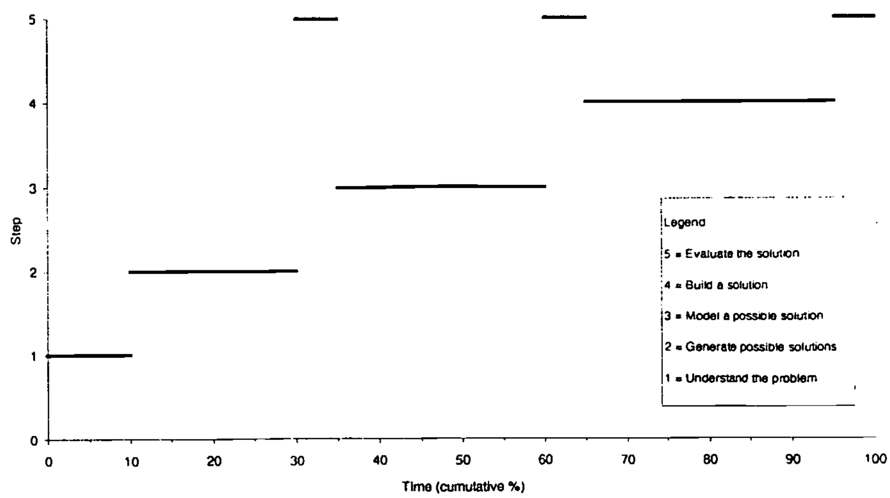
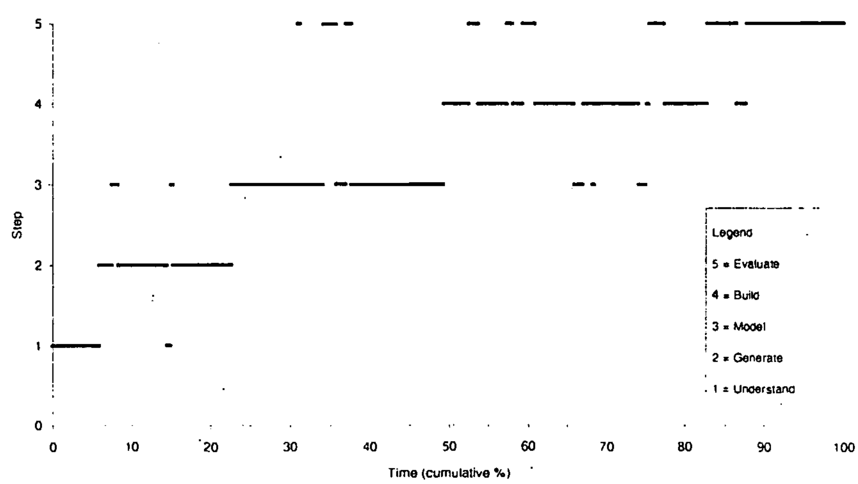


Map of the five-step theoretical design process used in this study



Sequence of steps employed by dyad 3

Figure 6. A comparison between the strategy used by Dyad 3 and the theoretical model

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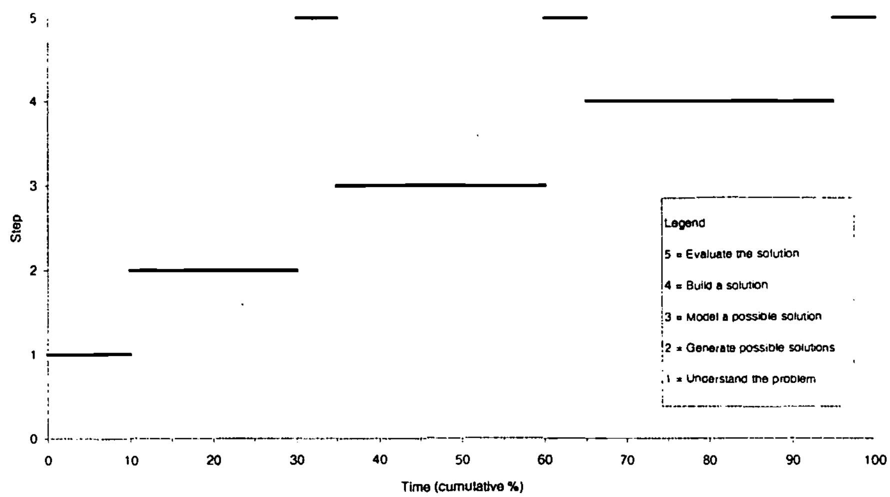
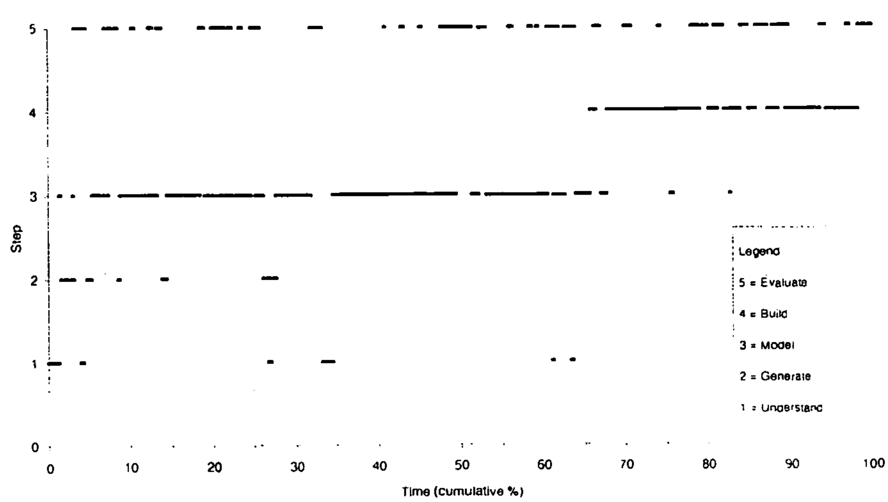


Map of the five-step theoretical design process used in this study



Sequence of steps employed by dyad 4

Figure 7. A comparison between the strategy used by Dyad 4 and the theoretical model

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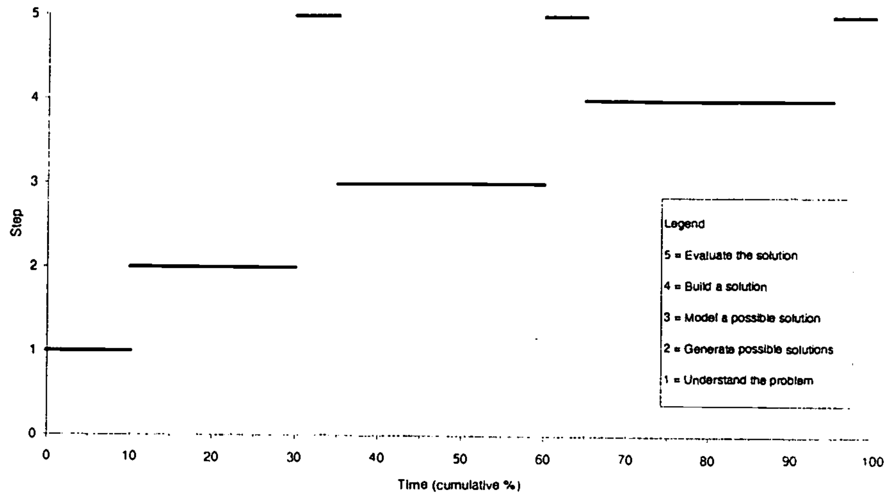
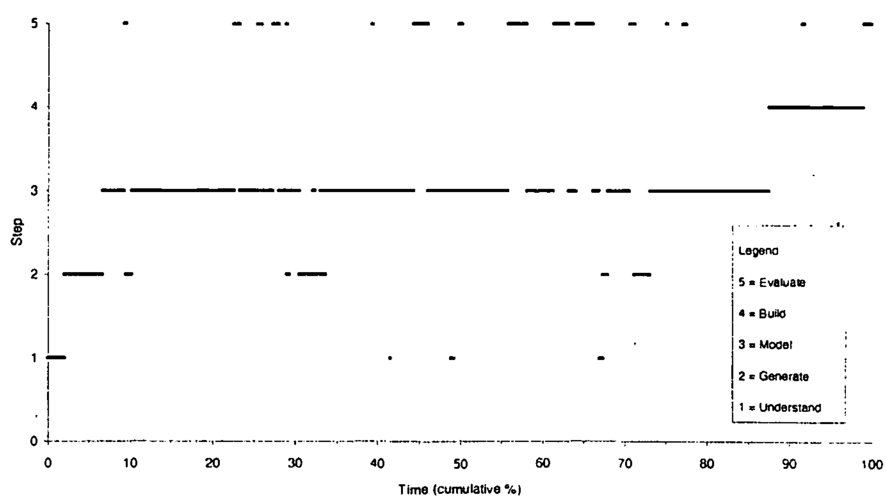


Map of the five-step theoretical design process used in this study



Sequence of steps employed by dyad 5

Figure 8. A comparison between the strategy used by Dyad 5 and the theoretical model

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Discussion

Because of its relatively recent introduction into the school curriculum, technology education has but a limited corpus of empirically derived research findings to support the development of curricula. This study adds to that corpus by developing and implementing a methodology for investigating the strategies used by novice designers. Both the methodology used and the findings of this study have implications for the theory and practice of technology education. In particular, they have implications for the way in which designing is taught to students. These implications will be discussed under the subheadings of "theoretical significance" and "implications for teaching".

Theoretical Significance

The review of literature on models of the design process to be used in technology education suggested a discontinuity between the theoretical models, that is, models derived by thinking about what designers ought to do, and empirical models, that is, models which describe what designers actually do. This discontinuity was further supported by the classroom observations of the researcher; that Grade 7 students, left to their own devices, do not design in the way prescribed by textbooks. Hence the research questions which drove this study were designed to lead to an understanding of how untutored designers go about the business of solving a technological problem. Therefore one particular contribution of this study has been to examine in detail the actual practice of a small sample of untutored designers.

Since the internal mental processing of a problem solver is inaccessible to direct observation the researcher, in order to obtain information about an individual's problem-solving processes, must find a method of requiring the subject to reveal the steps being followed so that an observable sequence of processes will be available for analysis. The resulting protocol is then available for analysis. While protocol analysis is being used increasingly for investigating various aspects of technology education (Elmer, 1996; Johnsey, 1995a; Roden, 1995) this study represents one of the earliest in which the subjects' actions and associated task talk were recorded and analyzed. A second contribution of this study has been therefore to substantiate protocol analysis as an appropriate methodology for the investigation of untutored designers' behaviour.

The set of assumptions about the general structure of problem-solving processes postulated by both Ericsson and Simon (1984) and Hayes (1989), plus design process models in the technology education literature provided a theoretical framework for the development of a scheme consisting of "start codes" to describe the actions of subjects in this study. This coding scheme was then refined using the inductive approach advocated by Glaser and Strauss (1967) and Strauss (1987). Codes "grounded", that is, derived from, the data were used to develop a more comprehensive, detailed and descriptive coding scheme. Thus this study provides the first detailed analysis of the actions of novice designers using a coding scheme grounded in the qualitative analysis literature.

Implications for Teaching

This study derived from the researcher's first-hand experience with attempts to teach designing and making using theoretical models of the design process contained in relevant textbooks. This study clearly shows that subjects' untutored design strategies do not match these models. Hence these results contain implications for teaching children how to design and make.

The most significant result to emerge from this study was the critical role of modelling in three-dimensional materials as an aid to subjects' thinking. Modelling was used to support a range of activities: increasing understanding of the problem, stimulating the generation of solutions, seeing what a design would look like, testing, and continuously incorporating modifications and improvements into a solution. This is perhaps no surprise, for as Hayes (1989) has written "much of our knowledge of solution strategies is acquired rather unsystematically through our daily experience in solving problems" (p. 52). The bulk of students untutored technological problem-solving skill will have been acquired in the material world: building sand castles, using commercial construction kits, constructing using found materials, and so on. Yet this result contradicts the strategy proposed by all design process models: that students sketch several possible solutions before moving to modelling in three-dimensional materials. Clearly the results of this study suggest that teachers should encourage modelling with three-dimensional materials early in the process. It appears important to provide students, early in the process, an opportunity to explore, develop and communicate aspects of their design proposals by modelling their ideas in three-dimensional form.

However, this may pose something of a difficulty for, as Hayes (1989) has described, there are significant disadvantages to moving too quickly to a "task environment ... the real-world context in which the task is to be performed" (p. 59), rather than operating in "a planning environment ... a symbolic representation that can substitute for the real world when we are thinking about the problem" (p. 59). For novice designers, there are disadvantages to working with three-dimensional materials, which will require the use of materials and tools, prior to planning and exploring ideas, which will require the use of a sketch pad and drafting board. Hayes suggests that designers must be taught to work efficiently in a planning environment before moving to the task environment. Yet previous research has shown how students with no prior technology education do not have the skills to represent in two-dimensional form an object which will eventually be made using three-dimensional materials (Constable, 1994a). There is often a mismatch between students' imaginative abilities and their representational skills (Anning, 1993).

The results of this study also reveal good reason to doubt the efficacy of requiring students to follow any form of linear or sequential design process model. The study has shown that untutored designers do engage in many of the sub-processes of theoretical models, but they do not prioritize or sequence these sub-processes as suggested by the models. For subjects in this study the design process was not a rigid framework to be applied strictly. It appears, as Wise (1990) has suggested, that "the design process is a set of reminders of what might be involved" (p. 27).

The results suggest that a simple draw it-make it sequence described in most models published to date may not be an appropriate way to develop design capability. Kimbell, Stables, and Green (1995) have suggested that "there is no overall, single form of design process" (p. 32). The results of this study support this finding. This, in turn, suggests that there may be no one way to teach designing to students.

The complexity of the process used by subjects in this study suggests a need for teachers to explicitly teach design process skills which will assist students' problem solving, but which do not impose a strict sequence in which those skills are applied. As Barlex (1995) has observed, it is "important to ... retain the spirit of experimentation in the design process ... [and] to encourage pupils to find their own methods and frameworks for thinking about problems" (p. 7). Yet at the same time, as Kimbell (1990) has described, students must be provided with a superstructure to designing. They must be able to think and work strategically, so that when time runs out at the end of a project they are where they want to be. Hence designing combines dynamic thinking within the project with the meta-cognitive task of being able to stand back and have an overview of the whole that will lead to a satisfactory conclusion.

This study also made evident the dominant place of evaluating as subjects were designing. It appears that teachers need to focus the attention of students on this activity and stress its importance. How ongoing evaluation is likely to increase the quality of both the end product and the ability of the student to design effectively. A recognition of the model-test-refine-test iteration so dominant in the strategies used by subjects should, as Johnsey (1995a) has also found, encourage teachers to take a broader view of the nature and role of evaluating when students are designing.

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