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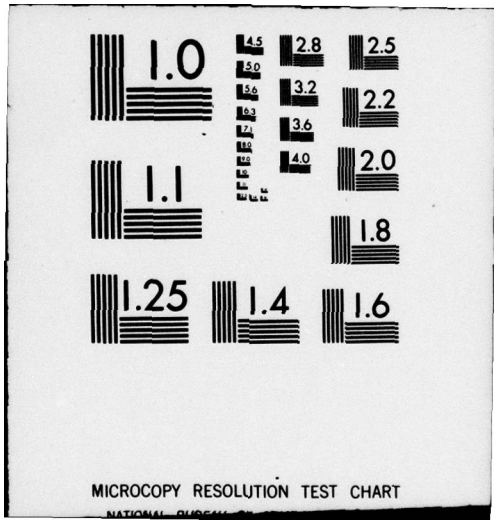
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An Experimental Investigation of the Design Process

John C. Thomas, Ashok Malhotra, and John M. Carroll

IBM Thomas J. Watson Research Center

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College students were given a complex design problem: to design a restaurant in a building that used to be a church. A diversity of background information-sources and problem constraints were given, mirroring the situation for software design. The study was also concerned with the effects on the design solution of gradations in the modifiability of pre-existing structures (ranging from exterior walls of the

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20. Abstract (cont.)

building to furniture and architectural detail). After completing the design, using a format of their choice, participants filled out a questionnaire concerning their strategy, goals and information sources. The primary difficulty in evaluating these designs is the same as in software design: the solution is essentially conceptual and cannot be directly tested. Although a common design-evaluation method is peer-ratings, in the current study we developed two objective methods. Practicality was measured as the ratio of functional requirements satisfied in the design to all requirements (the latter derived from an a priori elaboration of design goals). Originality was based on an information analysis of the features of each person's design relative to all designs. Within groups having similar SAT scores, there was a negative correlation between originality and practicality. Both measures were partially predicted by the participant's expressed goals but not by expressed strategy or stylistic differences between participants. A word list found to improve design on simpler problems in an earlier experiment was given half the participants, who subsequently had significantly higher practicality scores (no effect on originality was found). Modifications to existing structures differed but still formed a perfect linear ordering: no participant modified any higher level structure without also modifying lower level structures. In general, participants tended to design in a top-down, planned approach. The results of this experiment produced a detailed picture of structural design which seems very similar to software design.

An Experimental Investigation of the Design Process

John C. Thomas, Ashok Malhotra, and John M. Carroll

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Abstract

Twenty-nine college students were given a complex design problem: to design a restaurant in a building that used to be a church. Participants were given extensive background data on the expected clientele for the restaurant, the cost and spatial requirements for various items, the floor plan of the church, site information, equipment costs, remodeling costs, and typical customer complaints about similar restaurants. Such a diversity of information-sources and constraints mirrors the situation for software design. The study was also concerned with the effects on the design solution of gradations in the modifiability of pre-existing structures ranging in this case from exterior walls of the building to internal stuctural walls, to non-structural walls, to movable partitions, to furniture and architectural detail. Participants were free to present their ideas for the design in any format. After completing the design, participants were asked to fill out a questionnaire concerning their strategy, goals, and information sources. The primary difficulty in evaluating these designs is the same as in software design; *viz.*, that the solution is essentially conceptual. It cannot be directly tested. Although one common method of evaluating design in such situations is to have them rated by peers, in the current study we attempted to develop more objective methods. In particular, an a priori analysis of the design goals resulted in an expanded tree of possible functional requirements. Practicality was measured as the ratio of functional requirements satisfied to all requirements. Originality was based on an information analysis of the features of each person's design relative to all designs. Within each grouping of participants with similar SAT scores, there was a negative correlation between originality and practicality. Originality and practicality were both partially predicted by the participant's expressed goals. The measures were uncorrelated with any expressed strategy variables, or with any noted stylistic differences between participants. Half of the participants were given a word list that had been found to improve design on two simpler problems in an earlier experiment. Participants given this unstructured aid had significantly higher practicality scores but no effect on originality was found. The original floor plan of the church contained various structures which might or might not be changed by the participants. Participants differed in the degree to which they modified the existing structures. However, the structures that participants chose to modify formed a perfect linear ordering: no participant modified any higher level structure without also modifying lower level structures. Strategy differences between participants and implications of the findings for design aids are discussed. Generally, participants tended to design in a top-down, planned approach. The results of this experiment produced a detailed picture of structural design which seems very similar to software design.

An Experimental Investigation of the Design Process

1. Introduction

1.1 Importance of Design

The *New York Times* (12/26/76; p.34), contained the following item: "Design flaws were responsible for about two-thirds of the 52 million cars and trucks recalled in the last 10 years to correct safety defects, Federal safety officials say.... Recall campaigns not only are bad for public relations but they are also costly. The postage alone for certified letters to the most recent 770,000 owners of recalled vehicles cost General Motors and Ford about $400,000".

Design errors and their tremendous attendant costs are not limited to the automobile industry. In the field of software, for example, the cost of design is particularly important. By 1985, it has been estimated that software costs will constitute 90 per cent of total Data Processing system costs (Boehm, 1973). Design usually is estimated to account for about one-third of the time and cost of producing software (Wolverton, 1974). However, testing usually accounts for nearly half of the man-hours involved in software development, and about half to two-thirds of the errors in code originate during the design phase. Thus, improvements in software design could considerably shorten the development process, lower costs, and improve reliability.

The literature on software design is generally devoid of empirical work. Though the numerous heuristics for software design are useful in their own right, (e.g., Dahl, Dijkstra, & Hoare, 1972; Jackson, 1975; Yourdon, 1975) they do not explicate the cognitive processes operating in complex design problem solving. For its part, cognitive psychology has tended to focus on the analysis of simple, puzzle-like problems solved in short time periods by college students (e.g., Thomas, 1974). Some attempts exist to extend the theoretical work on simple, well-formulated problem solving to design problems (Reitman, 1965; Simon, 1973; Eastman, 1969; Freeman and Newell, 1971). Though empirical studies of design problems are rare, it

would seem that the study of applied psychology in this area could provide substantial benefits. The current study was designed to explore four issues in design: (1) the relationship of goals to the design product, (2) the production of design ideas, (3) the objective measurement of creativity and (4) the influence of strategy on performance.

1.2 Goals.

An excellent empirical case study by Mitroff (1972) illustrates the interactions of technical and social variables in a real-world design situation. An important finding of this study is that the client who calls for a design may either over-constrain the designer with requirements, making a design that fits ALL the requirements impossible, or under-constrain the designer so that a vast space of potential designs exists, probably only some of which will really satisfy the client's goals. The latter outcome will occur because the client may not be able to explicitly state all his goals.

Work on software design (Scott and Simmons, 1973; Walston and Felix, 1977) suggests also that communication problems between the client and the designer are frequent causes of design difficulty. One of the interests in the current experiment was the extent to which people would be aware of their design goals and the extent to which these goals would influence the design. If a better understanding of design goals and their relation to design products could be established, improved tools for communicating design goals might be established with resulting improvement in the design products. Thus far, the problems of communicating about purpose have been largely ignored in the software literature (But see Douglas, 1977).

1.3 The production of design ideas.

A second difficulty in design is finding the proper design elements (Malhotra, Thomas, Carroll, and Miller, 1978). In some cases, people have relevant information in long term memory but the information may not spontaneously present itself to consciousness. Apparent-

ly, information is only readily retrievable in a limited number of ways (Friendly, 1977) and it is unlikely that people can forsee all the possible uses to which information could be usefully put. Hence, they will later be able to retrieve the information only in a few of the potentially useful ways. A possible way to help the participant retrieve some of this information is to cue the participant with checklists, images, or, as in the present study, with words. Previous work (Thomas, Lyon, and Miller, 1977) indicated that an unstructured design aid consisting of an unorganized list of diverse, highly concrete words improved the design performance of college students on two simple design problems. One purpose of the present experiment was to extend this finding to a more complex design problem.

1.4 Product measures: originality and practicality.

Another difficulty in attempting to extend experimental results on solving simple problems to design problem solving is the appropriate choice of dependent measures of performance. Creativity is generally defined to imply both originality and practicality. For example, Bourne, Eckstrand, and Dominowski (1971) say "For behavior to be termed creative, it must be original (statistically infrequent), and in addition, a problem must be solved or some other criteria of relevance or practicality must be met." The present study defines more objective measures of both originality and practicality.

1.5 Process measures: the strategies of participants.

In the study of software particularly, but also in books on design in general, it is often assumed that the designer's effectiveness may be greatly enhanced by impacting his strategy (See, e.g., Jones, 1969 for an overall design strategy, as well as for a review of particular sub-strategies). We therefore assessed the strategies of participants by a post-design questionnaire as well as by characterizing stylistic features of the design product.

2. Method

In this experiment, an attempt was made to study as much of the design process as would be feasible in a single experimental session. To accomplish this, the particular design situation chosen was one for which college students have some relevant background information and some motivation to do well. The design of a restaurant fit these criteria. For versimilitude, a case study (Reagen & Stevens, 1972) of a Bonanza Steak House was used. In addition to material from the case study, numerous other information sources were provided to the participants.

Participants were told that the restaurant would be placed in an old church. They were provided with a diagram of the existing layout of the church. (See Figure 1). In many design situations, one must modify an existing procedure or structure. The existing church layout was designed by the experimenters to include a number of features of varying permanence. This was to allow us to test the variability between participants in how much they were willing to change the existing structure. The church layout contained external walls, internal structural walls, internal non-structural walls, internal movable partitions, and architectural details and furniture. It was hypothesized that these would form a hierarchy of modifiability.

Insert Figure 1 About Here

2.1 Participants

Twenty-nine paid volunteers from a small, nearby liberal arts college served as participants. These participants were generally above average in terms of their SAT scores.

2.2 Procedure

Participants were run as a group. Each participant was initially furnished with a folder containing the printed information sources (See section 2.3). Each participant was told that the task was to design a restaurant and that the folder contained potentially relevant information. They were told to read this information and, when they felt ready, to ask for additional materials in order to communicate their design. Participants were told that they could spend as long as they liked reading the material and as long as they liked designing the restaurant. They were also told that they were free to communicate their ideas about the restaurant in any format that they wished including pictures, floor plans, and written comments. Participants were also informed that they were welcome to take notes and that they would be allowed to refer to their own notes as well as the printed information during the design. The participants were requested to work alone. When a participant indicated that he or she was ready to begin designing, the experimenter noted the time and gave the participant a variety of types of paper (lined, plain, quad), a ruler, and several pencils of various colors. When a participant completed designing, a questionnaire was given the participant. The questionnaire asked for background information on the participant including SAT scores, and asked information about the participant's goals during design, the information sources used, and the strategy that the participant had adopted.

2.3 Information sources

The information sources given to the participant included four pages of typewritten background material on the owner of the restaurant, the Bonanza chain and the location and financing of the restaurant. In addition, participants were given a sheet of site information, a list of typical costs for various types of renovation, a list of costs for restaurant equipment, a floor plan of the current church, a written verbal description of the church, a list of common complaints of restaurant customers, a list of the spatial requirements for various aspects of

kitchen and dining equipment and furniture, and information on the expected business volume for various times and days.

2.4 Scoring procedures

A creative response is generally defined to be one that is both original and workable. In this study, an attempt was made to develop a universal method of defining originality and practicality. To this end, a mathematical definition of originality *O*, was calculated according to the following procedure. First, a feature analysis was performed on the restaurant designs. Every feature found in any design was listed. Second, every individual design was checked for each feature. The presence of a feature was coded as 1 and its absence by a 0. Third, by summing over participants, the probability of the presence or absence of each feature was calculated. Fourth, the information H(i) in each design was calculated (taking the sum of probabilities times the log to the base two of the reciprocal of the probabilities). Fifth, we calculated the information present in the most original possible design, given the distribution of features in the actual data H(max). (This was done quite simply. For each feature, a hypothetical, optimally original design had a feature if it was more commonly left out, and omitted a feature if it was more commonly included). Finally, each participant was assigned a ratio value by dividing the information in his or her design by the maximum possible information present in a design, given the data: O (i)= H (i) / H (max). This measure of originality has the theoretical advantages that it is closely related to information, it has an objective zero point, and exhibits other desirable properties (e.g., transitivity, and reflexivity).

A similar measure ranging from 0 to 1 was defined for practicality. A thorough analysis of the goals for the restaurant layout was made on an a priori basis. Goals were refined to functional requirements. That is, higher level goals were broken down into successively more measurable, more specific subgoals. This resulted in a hierarchy of goals. Each participant's design was examined from the standpoint of each goal at each level of the hierarchy. If the participant's design was judged to have met that goal, it was assigned a 1; if not, a 0. Finally, each participant's practicality score *P*, was calculated to be the ratio of goals and subgoals satisfied to the number of goals in the entire goal hierarchy. (The goal tree is shown in Figure

2). In the present case, since participants were free to make their own decisions regarding the relative importance of various goals, weightings were not assigned to different goals. For some situations, a more appropriate variant could be developed which would include a weighting function.

Insert Figure 2 About Here

It was judged that two of the twenty-nine participants had not really accepted the basic goal of building a usable restaurant in the church and their designs were not given a value for *P* and were excluded from the analyses described below.

3. Results

3.1 Originality and Practicality.

On the questionnaire, each participant was asked to rate how important it was that the design was original, novel, complex, practical, workable, and imaginative. Participants tended to split into two groups: those whose emphasis was on being practical and workable versus those who were concerned with originality, novelty, and imaginativeness. The ratings of workability and practicality were positively correlated with each other and negatively correlated with the ratings of imaginativeness, novelty, and originality, which in turn were all positively intercorrelated.

Objective originality scores, as defined above, varied from .624 to .766 (See Figure 3). Objective originality *(O)* was not correlated with the objective measure of practicality *(P)* overall (r=.02). However, when participants were divided according to SAT scores into six categories, there was a negative correlation between *O* and *P* within each group. Although there were too few participants in each group for any of the six correlations to reach significance, a two-tailed sign test would make the overall result marginally significant (p=.03).

Insert Figure 3 About Here

Aside from this result, the only measure at all predictive of *O* was the participant's avowed concern with having a design that was workable and practical. The correlation between the sums of these measures and *O* was -.452, ($F(1,18) = 4.75$, $p < .05$). Participants who expressed high concern with being practical scored low on this objective measure of originality. The participant's other statements about strategy and SAT scores were both non-informative with respect to *O*.

Participants varied in the proportion of functions fulfilled *(P)* from .34 to .71. (See Figure 4). Objective *P* was unrelated to any measure of the participant's strategy or style. However, again, there was a significant relation to the sum of the participant's own ratings of the importance of originality, imagination, and novelty. Those participants who expressed high concern with these characteristics had designs that scored low on *P*.

Insert Figure 4 About Here

3.2 An aid to idea production.

Half of the participants were given an extensive word list but given no instructions to use it. Those participants who received the list scored significantly higher on *P* than those participants who did not use the list. By looking at whether or not the participant was given this aid, at SAT score, and at expressed goals, a multiple correlation of .84 in predicting *P* was obtained ($F(3,16) = 12.85$, $p < .01$).

An earlier study (Thomas, Lyon, and Miller 1977) had shown this aid to be effective in a simpler structural and a procedural design problem. The effectiveness of the aid was surprising in the current experiment however, since the participants were not required to use the aid and the result should therefore be replicated.

3.3 The Participant's Approach

Strategy. An issue of particular interest in software design is the strategy that a software designer uses. Specifically, it has often been argued that top-down design is advantageous (e.g., Kernighan & Plauer, 1976) but presumably people are not likely to spontaneously adopt this strategy. It was generally difficult to determine the participant's strategy from the design plans. Several questions on the post-design questionnaire were designed to assess the extent to which the participants felt that they had used a top-down strategy. Somewhat surprisingly, 19 of the 29 participants claimed essentially to have used a top-down approach to designing the restaurant. Only four claimed to have used bottom-up design and six claimed to have used some mixture of the two. In view of the admonitions to use top-down methods in programming, it seems odd that the majority of untrained college students would claim to spontaneously use a top-down approach in their design.

There are several possibilities for explaining this apparent discrepancy. First, it is conceivable that participants were simply incorrect in their self-report behavior. Only those aspects of their behavior that fit into an easily coded organizational pattern may have been recalled. However, more careful observation of some pilot participants as well as clues from the design plans themselves make this alternative unlikely. Second, it is possible that top-down design is fairly natural in the design of a structure but more difficult and non-intuitive in the case of designing a procedure (like programming). Third, perhaps programming top-down is not so rare as its proponents would have us believe. Fourth, participants may have perceived an organized approach to be more highly esteemed.

Another question of interest was how participants would change their behavior if they were to do the design task again. In response to such a question there were several categories of answers. Some participants essentially said that they would adopt a different strategy (4), some said that they would change the relative values of certain goals (11), while others said they would change specific features of the design (2). Six participants said they would not change anything while four gave no answer and three gave various miscellaneous answers. Among those who said they would change their strategy, two said they would be more logical and top-down, one said the goals should be more explicit, and one said the new approach would be "more dimensional." Among those who said that they would change their goals, seven said that they would be more concerned about money and three said that they would be less concerned about the existing church layout while one said they would keep more closely to the initial layout.

Apparently then, the changes that participants would make on the basis of their design experience fit into one of several categories: (1) a change in approach or strategy, (2) a change in the relative value given to various goals, (3) more or less attention to particular details. This finding suggests that, in this particular domain at least, a useful design aid may simply be a checklist based on this limited number of concerns. This would "remind" participants at the outset of variables they might not otherwise consider except in retrospect.

An alternative way of looking at answers was to perform a word frequency analysis on the answers to this question. The frequently occurring words could be classified according to: 1) financial considerations (expenses, cost, spend, money), 2) procedural changes (first, differently, start, approach, how), 3) quantitative changes (more, much), and combination or complexity words: (and, with, in). Again, the ways that participants would change their behavior include strategy changes, changes in the relative importance of various goals, and attention to particular details. In addition, it appears that some participants would do much the same things but in a different order or in different combinations.

Other questions concerning strategy revealed that the majority of participants claimed to have worked on the hard parts first (19 out of 29), and to have planned out their approach before beginning (19 out of 29). Neither of these answers was related to objective performance measures. These results again support the contention that participants were more systematic in their approach than one might have suspected on the basis of the folklore of software design.

Units of design. Participants were also asked essentially what their units of design were. The results were that 8 said areas; 4, ideas; 4, mixed; 2, rooms; and one participant each claimed the following: subrooms, specific features, kitchen first, 4' by 4' squares, and miscellaneous. A word frequency analysis of the answers to this question turned up the following in order from most to least frequent --- rooms, areas, (and), (the), ideas, area, tables. Participants seem to perceive a variety of units of design as appropriate even in this fairly simple design problem. A structured approach based on a pre-existing set of units might be difficult for some people to use, though this hypothesis requires direct test. Also suggested by the above results is the classification of alternate sub-designs by multiple, possibly over-lapping units. This would allow people who would spontaneously analyse the problem differently to access possibly relevant information.

3.4 Differences in the Modifiability of Existing Structures

Although the essence of design is that something new is created, the new is always within the context of some pre-existing structures, procedures, or units. In the present problem, participants were free to choose the extent to which they were willing to modify the pre-existing structure of the church. It was hypothesized that participants would be most likely to change furniture and architectural details, somewhat less likely to change the moveable partitions, less likely to change internal non-structural walls, less likely to change internal structural walls, and least likely to change external walls. If one sums across participants, this was certainly true. Only three participants changed the external walls, 12 changed the

structural walls, 16 changed the non-structural walls, 18 changed the partitions, and all the participants changed the furniture or architectural detail. With regard to the stronger hypothesis that such changes formed a strict hierarchy; among the 29 participants there was no case of a reversal of this hierarchy (e.g., a participant who changed structural walls but left non-structural walls alone). To do so *would* have been physically possible but participants never violated the hierarchy.

This consistency provides some indirect support for the notion that people share a consensus about the levels in a hierarchy, at least for the case of *structural* design. Such a consensus is a desirable feature if some of the potential benefits of communicability accruing to top-down design are to be realized.

There have appeared some experimental investigations of hierarchies in the literature in cognitive psychology. Generally, such studies have been more concerned with *what* the consensually determined hierarchy is rather than with the *degree* of consensus though there are some exceptions (Durding, Becker, and Gould, 1977; Friendly, 1977).

3.5 Dimensions of Style

In addition to looking at the features of the restaurant designs that participants included, the designs were also characterized according to style as defined below. First, participants could communicate their design choices via some combination of a price list, a verbal description, a floor plan, or pictorial views of the restaurant. The various plans were characterized for style according to whether the participant: 1) used color in the design, 2) evidenced concern with three dimensions, 3) included contextual description or pictures, and 4) showed asymmetry in the design. These particular stylistic variables were chosen because the use of color, three-dimensions, concreteness and scope, and a preference for asymmetry have all been claimed to be characteristic of creative people (Stein, 1974). It was hypothesized that such

styles would be found among those participants who scored relatively high on originality but not practicality.

With respect to the mode of communicating ideas, every one of the 29 participants included a floor plan. In addition, 20 gave verbal descriptions, 17 gave lists of costs, and 7 gave one or more pictorial views of some aspect of the design. These means of communication occurred in many possible combinations.

Twelve participants used only one color in the design plan, nine used two colors, six used three colors, and two used five colors. Only four of the participants gave explicit evidence of concern with the dimension of height. Seven participants gave diagrams that showed the surrounding context of the restaurant. Five participants showed symmetry in the overall design and 15 had seating primarily in rows.

These style variables were not, however, correlated with practicality or originality. As noted, it was expected that a correlation with originality would occur. The independence of stylistic features from the objective measures of originality and practicality may suggest that the act of *communicating* about the design is fairly separable in this case from the actual creation.

An incidental observation of potential importance to education is the extent to which these participants became *involved* in the design of the restaurant. This was evidenced by the fact that though the participants were all told that they would be paid for four hours regardless of the time they actually spent, only one participant attempted to hand in a design before three hours and twenty minutes. Giving complex design problems that require the application of knowledge is probably a very effective manner of teaching the knowledge. Educational research on this point may prove very fruitful.

4. Discussion.

4.1 Goals of Design.

Previous research (e.g., White, Terence, & Cecil, 1977; Terborg & Willer, 1978) indicates that explicit goal-setting influences performance. Although typically, performance has been measured uni-dimensionally, Terborg & Miller (1978) took several measures of performance.

The current experiment extends previous research to more creative cognitive activity and proposes two important dimensions of goals and performance. We found that the participant's assessment of where he or she stood on the tradeoff between practicality and originality was encouragingly consistent. The participants tended consistently to fall into two groups: those who stressed practicality and workability on the one hand, and those who stressed originality, novelty, and imagination on the other. Furthermore, there was some relationship of these questionnaire results to the objective measures of *O* and *P*. A participant of a given ability level seems to be able to control, or at least report on, the extent to which he or she will strive for originality at the expense of practicality or vice versa. If participants can tradeoff in this manner between originality and practicality more accurate assessments of an individual's abilities may be made if *both* factors are taken into account. Also, clients of designers should make more explicit their own desired tradeoff between originality and practicality. Extensions of the study of design problem solving should examine quantitative *and* qualitative goal-setting as independent variables.

4.2 Aids to Idea Production.

The fact that participants often failed to meet all of the functional requirements that we considered important for a restaurant suggests that a simple checklist of such requirements would have improved the practicality of the designs considerably. Even the presence of an unrelated list of words apparently acted as a cue to consider more possibilities. Collaboration can be thought of as another 'aid' to the design process in that two participants will probably consider more ideas than one participant. However, the literature on group problem solving

indicates that the value of collaboration will depend upon where in the problem solving process collaboration is introduced as well as the mechanisms for interacting (See Stein, 1975 for a review of group procedures for improving problem solving).

4.3 Measures of the Design Product.

There were significant correlations between the theory-based measures of originality and practicality and independent variables. Further development of these measures could provide an important tool for studying complex problem solving. An alternative procedure, explored in a number of more recent experiments (Carroll, Thomas, and Malhotra, 1977; Carroll, Thomas, Miller, and Malhotra, 1977) is to structure a design problem so that more objective measures are feasible.

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Figure Captions.

Figure 1. The layout of the church in which the participants were to design a restaurant.

Figure 2. Goal tree for a restaurant design.

Figure 3. The distribution of objective originality scores.

Figure 4. The distribution of objective practicality scores.

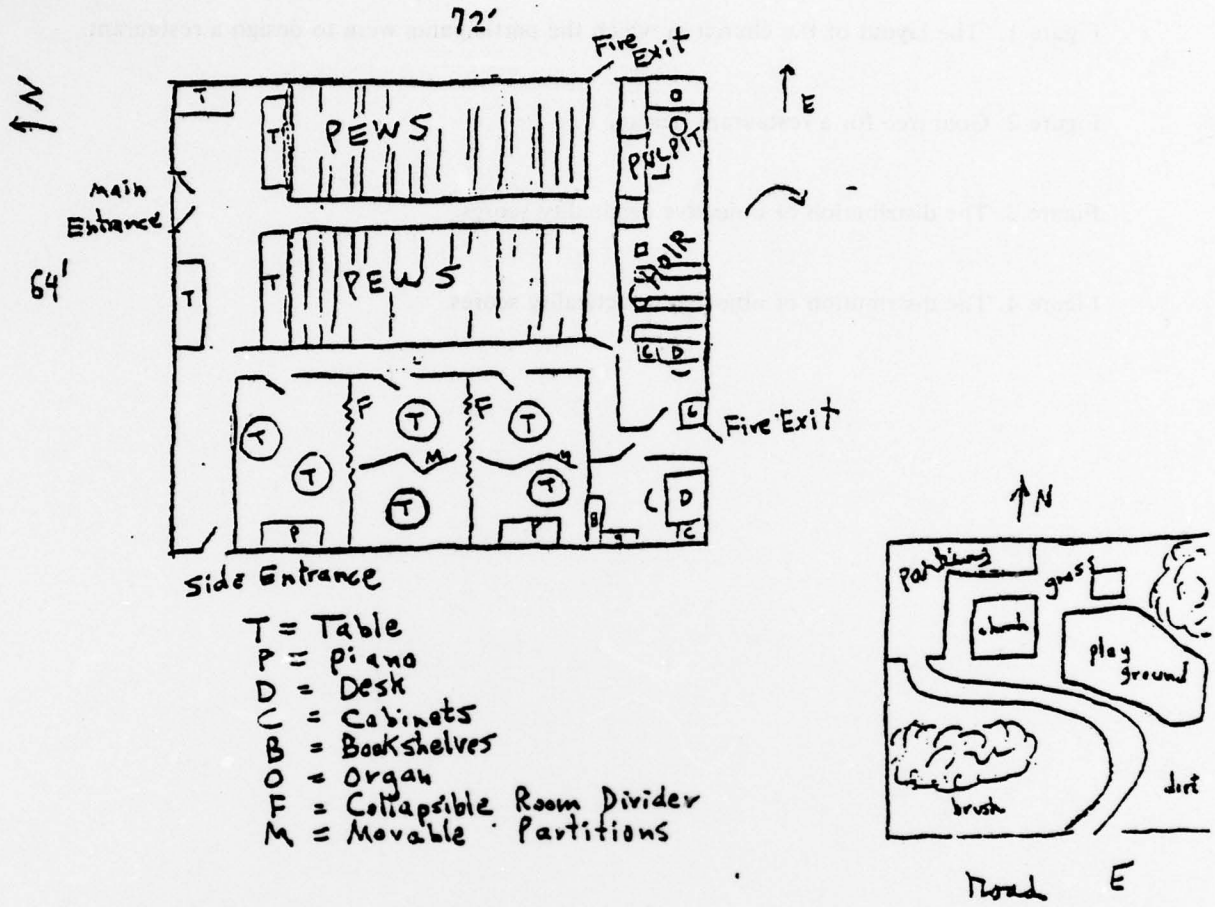

Figure 1. The layout of the church in which the subjects were to design a restaurant.

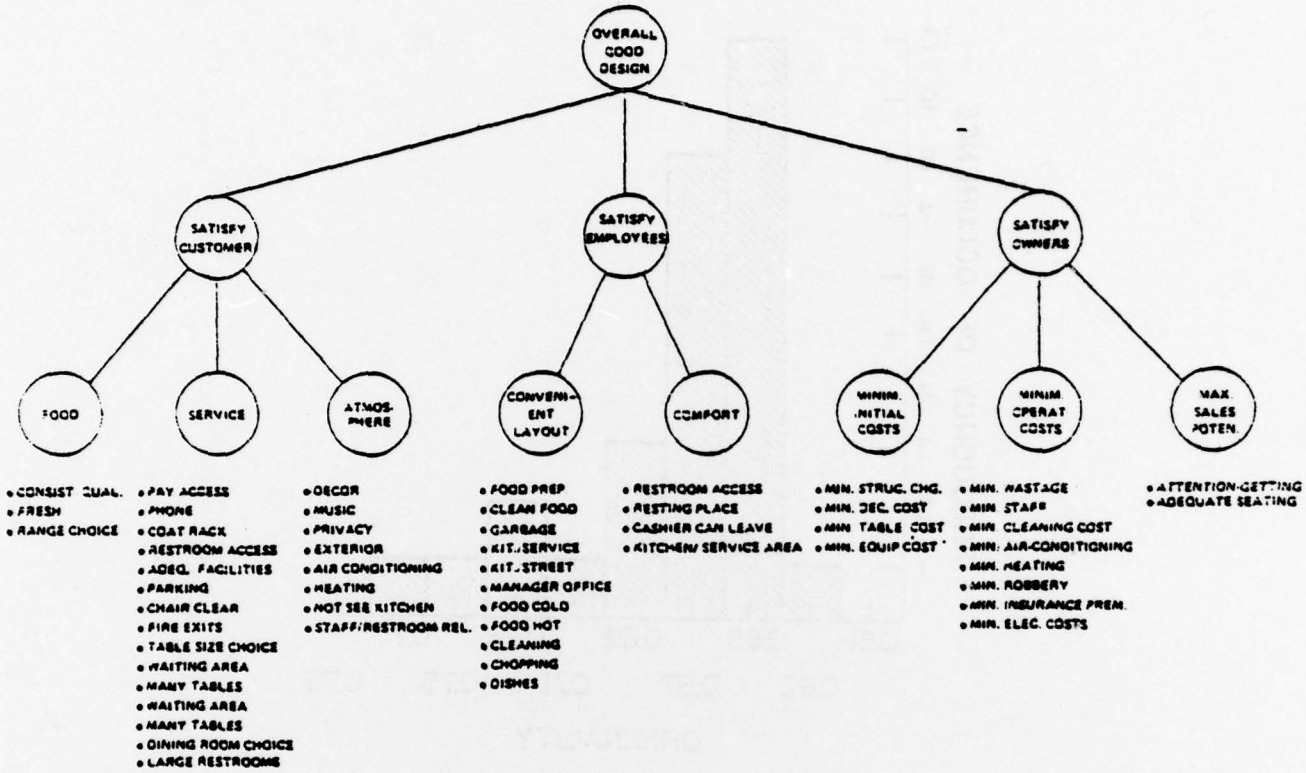

Figure 2. Goal tree for a restaurant design.

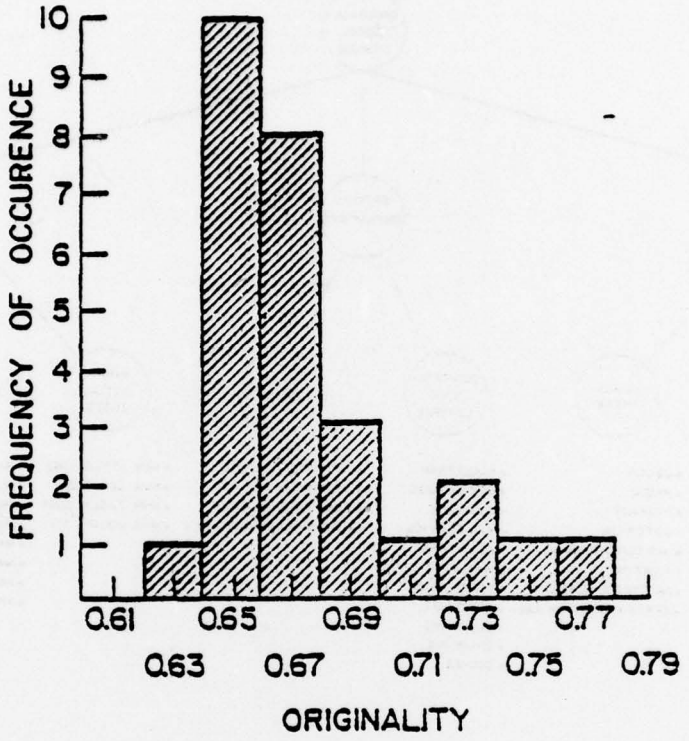

Figure 3. The distribution of objective originality scores.

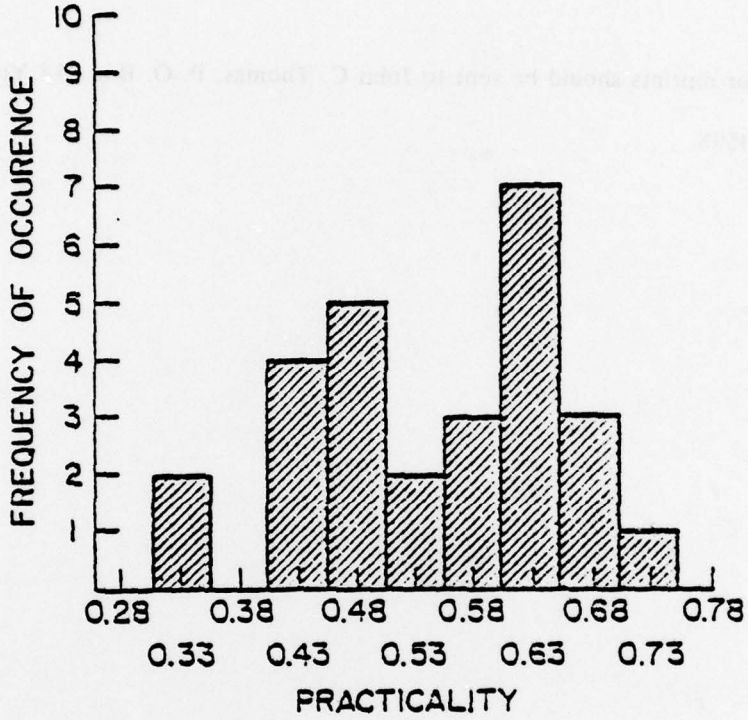

Figure 4. The distribution of objective practicality scores.

Footnotes.

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