Design fixation

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This paper reports on a series of experiments which were conducted to test the hypothesis that design fixation, defined as a blind adherence to a set of ideas or concepts limiting the output of conceptual design, is a measurable barrier in the conceptual design process. The results of the experiments clearly demonstrate the existence of design fixation. The paper discusses related issues such as the nature of the phenomenon, some experimental issues which arise in such investigations, and directions for future research.

Keywords: conceptual design, engineering design, creativity

Conceptual design in the context of engineering design is the process by which ideas are generated or configurations are created or selected to meet the specifications and constraints of an identified technological need. It is a front-end process, occurring very early in the engineering design process, ideally following a clear definition of need. The goal of conceptual design is to establish a core technical concept around which the entire design will be built. It may actually consume a relatively small part of the total design time or effort, but the leverage which early decisions have on the entire process is very large. Thus, the generation of the core technical concept is a crucial step in engineering design.

The research which is presented in this paper is based on a theoretical model of the conceptual design process which is comprised of a description of the thought processes involved. Briefly, the model represented in Figure 1 describes movement between two spaces, configuration space and concept space. Configuration space is an imaginary space which contains physically-realizable configurations, or more specifically, the mental representations of configurations such as diagrams and sketches and combinations of physical elements which comprise these physical objects. Concept space differs from configuration space in that the elements it contains are ideas, relationships, or other abstractions which may later become the basis for elements in configuration space. The main thrust in the model is that during the design process, movements from one configuration to another, that is, from one point in configuration space to another point in configuration space, rarely if ever take place without a movement to concept space and then back to another point in configuration space. In other words, changes to conceptual designs or configurations are motivated by these abstractions or concepts. Thus, movement within configuration space must be obtained by movement to concept space, possibly movement with concept space, and then movement back to configuration space. A more complete presentation of this theoretical model of the conceptual design process, is given elsewhere.[1]

Within the framework of this model, one is led to consider what drives these motions and what barriers may impede or prevent movement. In the conceptual design process, movement is essential. The character of conceptual design as a discovery process means that the designer should 'visit' many points in both concept space and configuration space in order to reveal more about the problem and potential solutions, thus discovering new aspects of the problem. Questions concerning driving forces and barriers are therefore important research issues.

The question of methodology with respect to driving forces arises. How should the designer best proceed in the process of conceptual design? This is a continuing research area for one of the present authors, and

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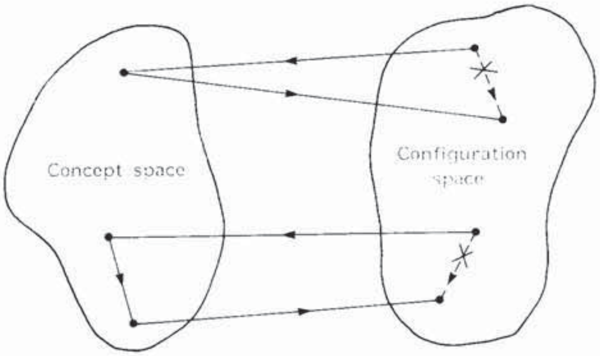


Figure 1 Model for conceptual design

References 1–4 present a methodology called parameter analysis which directly addresses the question of how to encourage movement.

The second question, that of the barriers which block the unfolding of good conceptual design thinking, is the focus of the present investigation and analysis. Design fixation refers to a blind, and sometimes counterproductive, adherence to a limited set of ideas in the design process. The common experience of being 'stuck-in-a-rut,' and years of observation of barriers in the conceptual design process in both students and professional engineers, strongly suggest its existence. Furthermore, experimental cognitive psychologists have studied similar mental blocks to problem solving and memory, lending further credence to the existence of the phenomenon.

EXPERIMENTAL COGNITIVE PSYCHOLOGY BACKGROUND

Experimental cognitive psychologists interested in thought processes studied fixation in problem solving as early as the 1930s. Fixation refers to an obstacle, often self-imposed by the problem-solver, which blocks successful completion of a problem. Maier,[5] for example, gave volunteer subjects the problem of tying together two strings which were suspended some distance apart from each other from the laboratory ceiling. When a pair of pliers was used as a grasp extender, the typical function of pliers, it did not extend the subject's grasp enough to reach both strings at once. To solve the problem, it was necessary to use the pliers as a pendulum weight, an atypical use for pliers. Maier observed that many of the subjects were not able to use the pliers in any way other than to grasp objects in the normal functioning mode for which they were designed. Restricting one's use of an object to previously encountered functions, as with the pliers, is termed 'functional fixedness', which is an identifiable type of fixation in problem solving. Another type of fixation is called 'mental set,' and refers to a situationally-induced obstacle to problem solving. Luchins[6,7] has conducted many experimental studies of mental set. In the typical study, subjects were given ten mathematics/word problems, the first nine of which could be solved by the same complex algorithm. The tenth could not be solved by the same algorithm, but could be solved with a simple and obvious alternative approach. Most subjects were so fixated upon the first algorithm that they did not notice the simple solution and could not solve the tenth problem, or else they took a very long time to find the solution. This blind adherence to one solution or one approach to a problem has been termed 'mechanized thought,' thinking which follows a previously laid-out pattern.

Whereas functional fixedness[5] is a long-term, enduring type of block to successful problem solving, the mental set or mechanized thought observed in Luchins' studies[7] is situationally-induced. The initial studies reported in the present paper are directed toward investigating the role of similar phenomena in the conceptual engineering design process. Fixation in the design process, if it exists, may be caused by either long-term or situationally-induced fixations, fixations which result from the examples which accompany design problems given to one group of subjects. These examples, designs which are usually intended to suggest other possible solutions to the designer, may have an inhibiting effect. As in the mental set problems used by Luchins, these examples may restrict thinking to concepts which have already been used in the examples. Design problems given without fixating examples might result in a wider range of design ideas not limited by the examples. We have termed this hypothetical type of block 'design fixation.'

In the present study, we have taken an experimental approach to understanding this aspect of creative design and invention. This approach goes beyond speculation, providing critical empirical tests of hypotheses related to the design process.

GENERAL METHOD

The general method used in the present study was fairly consistent throughout all four experiments. In all cases, a design problem was given to a group of subjects, usually engineering design students, and they were requested to generate as many designs as possible to meet the needs of the problem. Typically forty-five minutes was allotted to this task. Half the subjects (the control group) were given the problem without an accompanying example, and half (the fixation group) were given a sample design with the problem. It was hypothesized that the examples given to the fixation group would restrict the range of design ideas, causing them to conform to the given sample.

EXPERIMENT 1: THE BICYCLE RACK PROBLEM

The question tested by experiment 1 was simple and straightforward: would design fixation be observed in a controlled field experiment? It was hypothesized that the range of ideas generated for a design problem would be restricted by presenting the problem with a sample design, as compared with presenting the problem without an example.

Subjects

Twenty-five senior mechanical engineering students at Texas A&M University served as subjects in experiment 1. Twelve subjects were randomly assigned to the control group and 13 to the fixation group.

Materials

The design problem of a car-mounted bicycle rack was given to the students in the form of a class quiz. The instructions were printed on a single page. They stated that the problems to be addressed were: 1), easy mounting of the bicycle; 2), easy mounting of the rack; 3), cannot harm bike or car; and 4), must be versatile for all bikes and cars. The fixation group received a second page with the example diagram of the bike rack (Figure 2). The diagram showed two views of a partially-flawed bike rack design, and pointed out one of the flaws in the sketch (that the middle bicycles are difficult to mount). Importantly for this experiment, it was a top-mount design having suction cups holding it to the car roof and railings for the bicycle tyres.

A questionnaire given to all participants asked whether each had a bicycle and/or a bike rack for the car, and whether they had ever worked in a bike shop. This questionnaire was intended to assess subjects' prior experience with the experimental problem.

EXPERIMENTAL DESIGN AND PROCEDURE

After the class was randomly split at the beginning of the class period, the experimental procedure was given separately to the fixation and control groups. Each subject was given the instruction sheet and the questionnaire, and the fixation group was also given the example page. Oral instructions from the experimenter requested that they construct as many designs as possible, write comments with each design, and number each individual design. One hour was given for this task.

EXAMPLE DESIGN

Example of a present day bike rack. The bicycle is set in the rails and the vinyl coated hook is attached to the seat tube of the bike, and then the hook is tightened down by hand with a wing nut. One should note the difficulty of mounting the middle bikes on the rack.

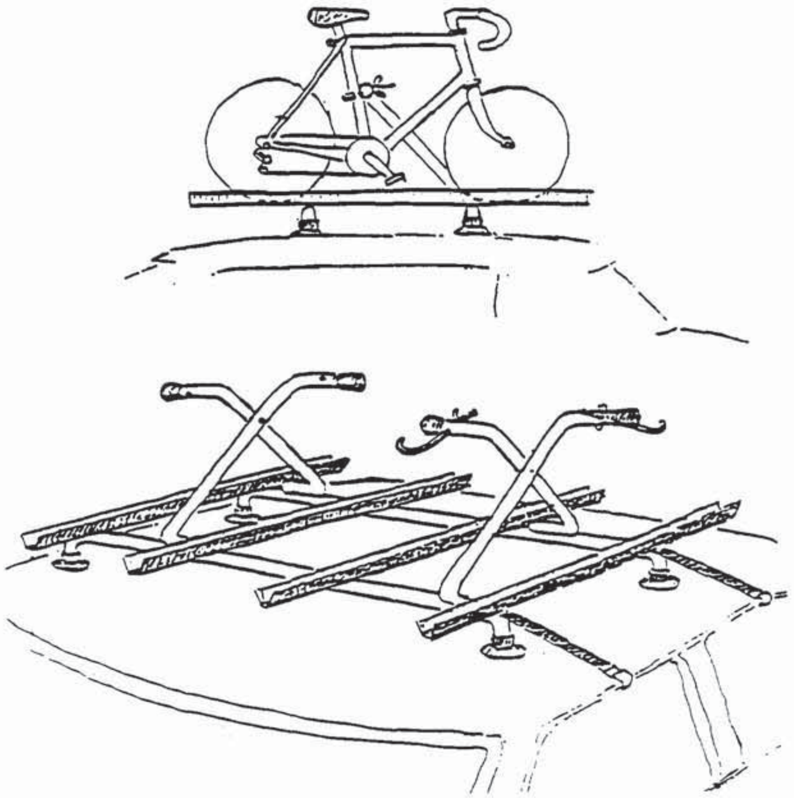


Figure 2 Bike rack problem example design

RESULTS AND DISCUSSION

The subjects' responses were scored for: 1), number of designs; 2), number of top mount designs; 3), number of designs with suction cups; and 4) number of designs with tyre railings. Measures 2, 3, and 4 are indications of how similar the designs were to the fixating example given to the fixation group. The mean scores for the control and fixation groups are shown in Table 1.

While the mean overall number of designs per subject did not differ for the control (4.5) and fixation (4.3) groups, there were clear effects from the fixating example on each of the other measures. The fixation group had more top-mount designs, more designs with suction cups, and more designs with railings than the control group. Each of these results supports the conclusion that subjects showed substantial design fixation caused by the fixating example given to the fixation group.

Having demonstrated a clear occurence of design fixation, we went on to test the replicability and generality of the phenomenon with several variations in the original procedure, and with very different design problems.

EXPERIMENT 2: THE MEASURING CUP FOR THE BLIND PROBLEM

The fixating features of the fixation group example given in Experiment 1 (top mount, suction cups, tyre railings) were not exceptionally negative aspects of the designs. Thus, it might be hypothesized that fixation group subjects would be less fixated by more obviously negative features of an example design, since they would not wish to produce designs with such obvious flaws. This hypothesis was tested in Experiment 2, in which an example design with more obvious flaws was given to the fixation group. Furthermore, a design problem which was less familiar to the students was used to better avoid long-term fixation.

The design problem used in Experiment 2 requested designs for a measuring cup to be used by visually handicapped individuals. None of the participants reported any prior experience of, or contact with, such devices.

Subjects

The 31 subjects in Experiment 2 were students enrolled in a senior level mechanical engineering design course. There were 15 students randomly assigned to the control group and 16 to the fixation group.

Table 1. Bicycle rack designs generated as a function of treatment group in experiment 1

	Control group	Fixation group
Number of designs per subject	4.5	4.3
Percentage top mount designs	59	71
Percentage with suction cups	6	54
Percentage with tyre railways	15	48

Materials

The experimental test was named an 'Idea generation exercise,' and the instructions were printed on a single page. Subjects were asked to design a volume-measuring apparatus for use in cooking by the blind. They were asked specifically to address the following problems: 1), easy operation by the blind; 2), use for powders and liquids; 3), prevent waste of food products; 4), graduate from 1/4 to 2 cups; 5), no splatter during operation; 6), easy to clean; and 7) inexpensive.

The example design, given only to the fixation group, is shown in Figure 3. The two intended, but unstated, flaws were that the example was not infinitely variable (but should have been), and it had no overflow device (but needed one).

Experimental design and procedure

The experimental design and procedure were identical to that used in Experiment 1, except that only forty-five minutes were given for the task.

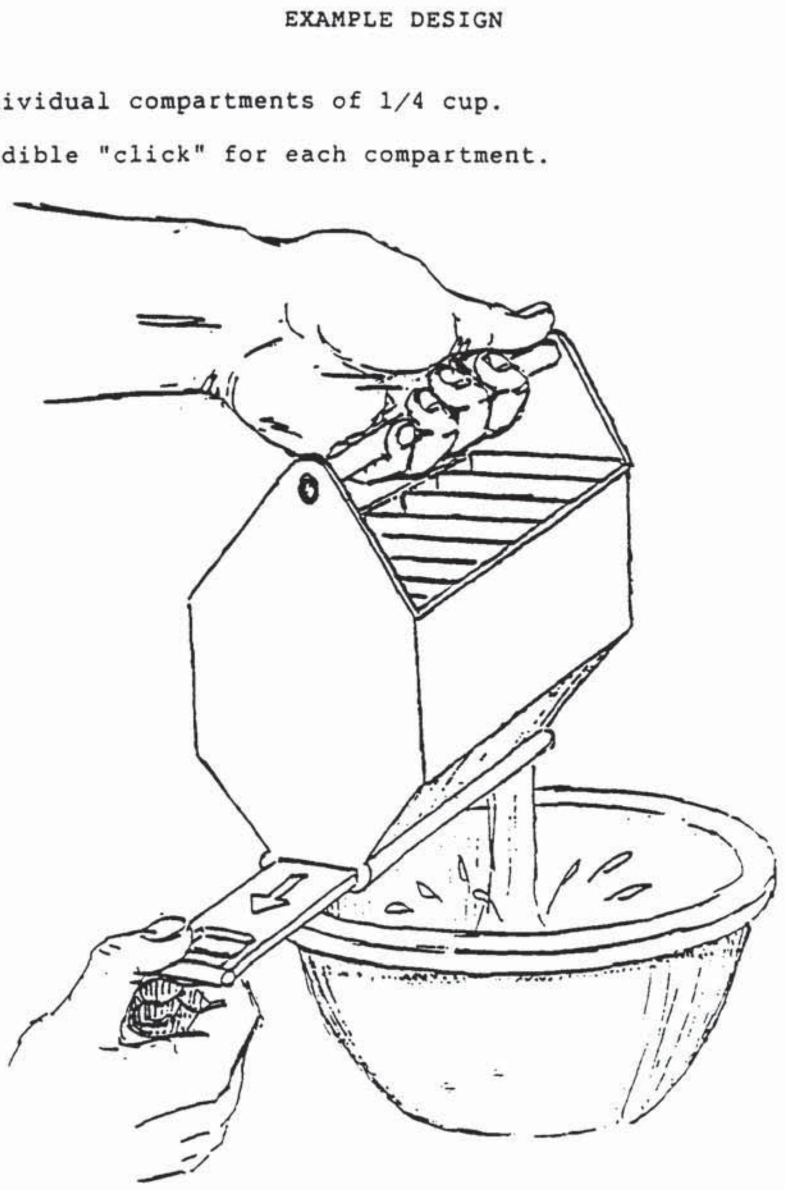
RESULTS AND DISCUSSION

The subjects' responses were scored for: 1), number of designs; 2), number of non-infinitely variable designs; 3), number of designs without overflow devices; and 4) number of designs which were highly similar to the example design. Measures 2, 3, and 4 are indications of design fixation. Mean scores for the control and fixation groups are shown in Table 2.

The overall results are similar to the results of Experiment 1. As in Experiment 1, the mean number of designs generated by each subject in the control group did not differ from that of the fixation group. The fixation group, however, showed evidence of design fixation. Those subjects generated more non-infinitely variable designs than the Control group, more designs without overflow devices, and more overall designs similar to the example. As in Experiment 1, each of these results supports the idea that subjects in the fixation group suffered design fixation, relative to the control group. These results are compelling evidence of the potentially detrimental effects of design fixation because the fixated features were negative characteristics of the design.

EXPERIMENT 3: THE SPILLPROOF COFFEE CUP PROBLEM

Further evidence of design fixation was sought in


EXAMPLE DESIGN

- 8 individual compartments of 1/4 cup.
- An audible "click" for each compartment.

Figure 3 Measuring cup for the blind problem, example design

Experiment 3, in which subjects were asked to design an inexpensive, disposable, spill-proof coffee cup. In this experiment, as in Experiment 2, negative aspects of the sample design were given to the fixation group. The straw (Figure 4) employed in this design will leak when the cup is rotated 90 degrees from the angle shown in the diagram. The cup will also leak if the cup is squeezed, another negative characteristic. Finally, the hot liquid emerging uncooled from the straw shown in the example would burn one's mouth. Not only should these problems have been evident to the design students, but they were also explicitly instructed that no straws were to be used in their designs.

In an effort to relate the present studies on design fixation to creativity, the designs generated by the students were scored according to some measures of creativity[8]. These indices included the number of categories of ideas (flexibility), and statistical infrequency of the design (originality). Although these indices are usually used to assess individual differences in creative thinking, they provided a measure of the degree to which the induced fixation inhibited creativity in the design process.

Table 2. Measuring cup for the blind, designs generated as a function of treatment group in experiment 2

	Control group	Fixation group
Number of designs	2.8	2.9
Percentage non-infinitely variable designs	57	78
Percentage without overflow device	17	54
Percentage highly similar to example	7	50

EXAMPLE DESIGN

Below is an example solution to show how each design should be presented.

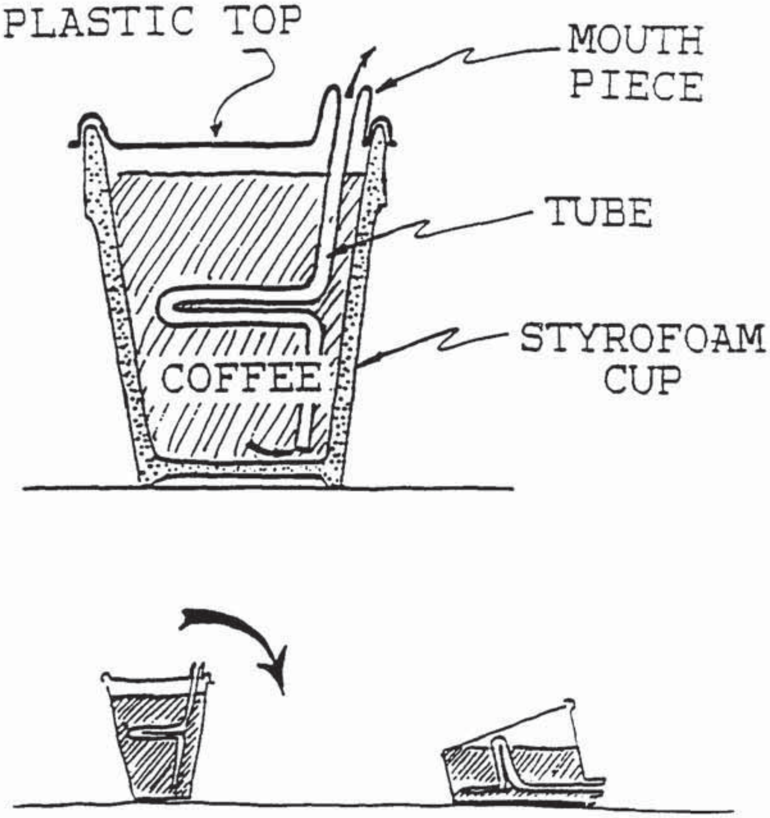


Figure 4 Disposable spill-proof coffee cup problem's example design for the third experiment

Subjects

Thirty-five seniors in a mechanical engineering design course at Texas A&M University served as subjects in Experiment 3. Of these, 17 were randomly assigned to the control group and 18 to the fixation group.

Materials

The 'Idea generation exercise' used in Experiment 3 was printed on a single page. The instructions directed subjects to create as many designs as possible for a disposable, spill-proof coffee cup. Besides being disposable and spill-proof, the designs were to be operable with one hand, durable, and they were to have no straws or mouthpieces as part of the design.

The example design given to the fixation group (Figure 4) used a straw and a mouthpiece, and would leak.

Experimental design and procedure

The experimental design and procedure were the same as those used in Experiment 2.

RESULTS AND DISCUSSION

Subjects' responses were scored for: 1), number of designs; 2), number of designs which would leak; 3), number of designs with straws; and 4), number of designs with mouthpieces. Each subject was also scored for flexibility and originality. Flexibility was calculated as the number of different approaches to the design problem divided by the total number of designs for that subject. The lower this measure is, the more restricted is the range of ideas generated by a subject. Originality was computed as the sum of the 'o' scores for an individual's ideas divided by the number of ideas for that subject. The 'o' score for each item was calculated as $o = 1 -$ ((number of similar designs generated by other subjects)/ (total number of designs for all subjects)).

As in the previous two experiments, the control and fixation groups generated the same total number of designs (Table 3). On the three measures which indicated evidence of design fixation, subjects in the fixation group scored higher. Fixation subjects generated more designs which would leak, more designs with straws, and more designs with mouthpieces than did the control subjects (Table 3). These results again show very clearly that design fixation was induced by the example design given

Table 3. Spill-proof cup designs generated as a function of treatment group in experiment 3

	Control group	Fixation group
Number of designs per subject	4.1	3.4
Percentage designs that leak	30	39
Percentage designs with straws	1	17
Percentage designs with mouthpieces	10	39
Flexibility	0.95	0.85
Originality	0.64	0.53

to the fixation group even though the fixated characteristics were negative aspects of the design.

The creativity measures, flexibility and originality, were also smaller for the fixation group than the control group (Table 3). This indicates that creative performance may be inhibited when an example induces design fixation.

EXPERIMENT 4: PROFESSIONAL ENGINEERS

Experiments 1 – 3 are compelling demonstrations that design fixation can occur with advanced undergraduate engineering students in a design course. The importance of this phenomenon for professional engineers, remained to be demonstrated. Therefore, in Experiment 4 a group of professional design engineers from the structural design department of a major corporation were given tests similar to those described in Experiments 1, 2, and 3. One hypothesis was that professional engineers, who have considerably more experience and expertise than students in an undergraduate course, would be less susceptible to design fixation, having learned to cope with the problem during their careers. Another hypothesis, however, states that the effects seen in students will again be observed in professionals.

Subjects

Thirteen professional engineers from the structural design department of a major corporation in Fort Worth, Texas volunteered to participate in the experiment. Seven were randomly assigned to the control group, and six to the fixation group.

Materials

The materials for Experiment 4 consisted of an 'Idea generation exercise' similar to that used in the previous experiments, and a questionnaire concerned with aspects of the design engineer's work which are related to design fixation. The 'Idea generation exercise' outlined the design problem, asking participants to design an apparatus to take samples and measure speed and pressure at different points along the intestinal track. The following requirements were listed: 1), maximum diameter ⅜in, 2) able to measure speed and pressure and sample contents at 20 or more points along the entire intestinal tract; 3), able to ascertain locations of measurements and samples, and 4) minimum discomfort to patient. The example given to the fixation group is shown in Figure 5. It has an opening in front of the 'pill', a control box, and a cord. The inconvenience and disconfort involved in the use of a device with a cord was a particularly problematic aspect of the example.

The questionnaire explained what was meant by the phenomenon of design fixation as induced by examples, and asked whether engineers were aware of it in their work and in the work of their colleagues. It also asked for the estimated percentage of time on the job spent engaged in creative and conceptual problem solving, and requested a self rating of creativity on a scale of 1–10.

Experimental design and procedure

Cover sheets explaining the needs of the study were attached to the materials and sent to the head of the company's design department. The exercises and questionnaires were distributed to the engineers in the department, half with the example design and half without. The engineers were asked to administer the exercises and questionnaires to themselves. They were to work independently for one hour on the problem stated in the instructions, and they were to look at the questionnaire only after the exercise had been completed.

RESULTS AND DISCUSSION

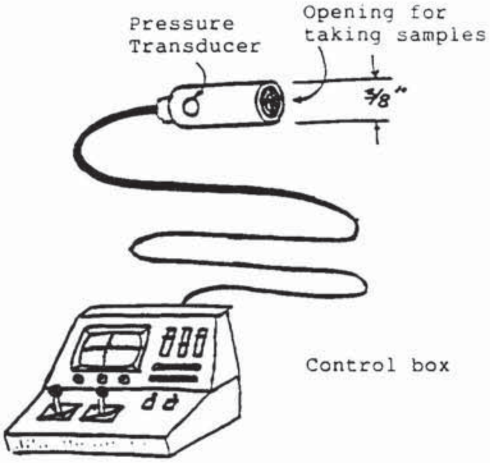
Table 4 shows the mean number of designs generated by each engineer in the control and fixation groups. Each of these measures showed the same result as in the previous studies on design students, that the fixation group conformed even to the negative aspects of the example design more than the control group. Those engineers in the fixation condition generated more designs with cords, more designs with control boxes, and more designs with an opening in front of the pill. The conclusion is that design fixation was empirically verified in professional design engineers.

DISCUSSION

The primary objective of studying the role of fixation in the design process is to increase understanding of the nature of the conceptual design process and to be able to improve the methodologies for conceptual design which may be used to increase the effectiveness of design practice. The long-term goal is to create modifications to methodology which will reduce the detrimental effects of design fixation. However, this work has just begun and many questions remain before the long-term objective can be reached.

EXAMPLE DESIGN

Below is a general example design to show how each design should be presented.



The patient swallows the end of the cable. The speed is measured by the speed of the cable, and the other measures are taken as shown above.

Figure 5 Pill problem, example design

The results described above suggest a number of important issues. One very important question deals with the temporal effects of design fixation. Is fixation primarily a short-term effect, or are longer term effects also important? The understanding of the nature of conceptual design certainly suggests that short-term effects can be very strong influences on the way in which the process unfolds. However, it is also possible that design experiences from years of educational and professional experience also contribute fixations which have detrimental results on the effectiveness of conceptual design.

A question is also raised concerning whether fixated behaviour is only detrimental or whether there are some beneficial effects to such a phenomenon. One might become fixated on a feature of a past design which is extraordinarily beneficial to resulting design solutions, or features which are detrimental to the performance of such solutions. The question then arises whether or not fixation on these so-called good features is as detrimental as fixation on bad features, or whether the primary effect is simply the fact that any fixation is a barrier to movement in the conceptual design process, and thus arguably a detrimental effect.

Table 4. Pill problem designs generated by professional design engineers as a function of treatment group in experiment 4

	Control group	Fixation group
Number of designs per subject	1.6	1.5
Percentage designs with cords	36	78
Percentage designs with control box	73	100
Percentage designs with front opening	9	56

The nature of conceptual design is such that 'prior information' is an essential element of the process. Designers can see new configurations based on what they know, not on things which they do not know. Thus, we must be careful to differentiate between design fixation and the possibly limited scope of knowledge and experience with which the designer must work. Design fixation, as a barrier to progress in conceptual design, if it is to be a useful concept, should probably be seen only as that which prevents the consideration of all of the relevant knowledge and experience which should be brought to bear on any given problem.

The ability to generalize the results of the present experiments is enhanced by the fact that both students and professional engineers showed the same effects, and that the phenomenon was robust across a number of different design problems. One important factor which we do not understand, however, is the effect of design fixation when much more complex designs are called for. The experiments, for obvious reasons, used problems of low-order complexity to discover whether or not design fixation actually exists as a phenomenon. However, problems of high-order complexity are typical of almost every useful design problem, whether the system being considered is simple or complex. Does design fixation have an increased role in the prevention of movement within conceptual design or is its role diminished because the domain under consideration contains so many more possible parameters?

Another issue which was raised in our investigation concerns factors which may independently or interactively affect design fixation. Is the fixated information primarily conceptual, or is it also possible to become fixated on visual information? There are possibilities here which open up additional avenues for investigation in the future.

In addition, the nature of the conceptual design process suggests that the starting point or the initial condition for the conceptual design process is a very important variable affecting the outcome of conceptual design. Thus, the question is raised as to whether the process is more dependent on where the design activity starts, or on the events which take place along its course? It is also possible that these two effects, because of the nature of the process, are in essence the same.

EXPERIMENTAL ISSUES

Many of the issues discussed above can also be translated into experimental questions. However, in addition to these obvious experimental issues, there are others which are also important. As research continues, it will be important to learn how to design experiments which at least partially decouple the effects which are being studied so that they can be observed somewhat independently. This raises the additional question of whether or not the experiments bias our results toward spurious findings. Thus, experimental bias is another potentially important experimental issue.

The question raised above concerning the role of the starting point in the design process suggests some very difficult experimental questions regarding being able to truly characterize the prior knowledge and experience of experimental subjects and to work with a group of subjects for which this body of knowledge is somewhat common. The selection of suitable design problems becomes even more difficult if it turns out that the starting point considerations are very important.

CONCLUSIONS

Out research has clearly and repeatedly demonstrated the existence of design fixation. The interest in this area stems from a desire to understand more deeply both the nature of conceptual engineering design as well as to make significant improvements to methodologies by which conceptual design can be enhanced. The research has raised far more questions than it has answered but has clearly opened up a very interesting avenue of investigation. One very important aspect of this research is its clear boundary-spanning character, combining the highly technological discipline of engineering design and the very different character of the cognitive sciences. This combination is a clear demonstration of the multi-disciplinary character of engineering design and of the need for investigators in many disciplines to learn how to effectively carry out cross-disciplinary research. The fundamental differences between engineering design and cognitive psychology are great, much greater than the differences between two disciplines which are both within the engineering area. The authors believe that engineering design researchers should be more willing to recognize the broad multi-disciplinary character of the subject matter and to meet this difficulty head-on.

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