FLUENCY AND FLEXIBILITY OF CONCEPTS ARISING FROM PERSONALISED IDEATION TECHNIQUES

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ABSTRACT
When presented with a novel problem, a novice designer faces the daunting task of formulating suitable concepts to develop into a solution. Some novices, with a creative flair, can easily conceive several potential solutions. Various design methods have been published to help engineers generate ideas. Studies show that designers who generate many possible solutions to a problem are more likely to identify one of high quality. At Monash University, 244 undergraduate engineering design students were individually presented with a real design problem in which a split pin fastener was deemed unreliable, and were asked to propose plausible options. Only 44 students chose to apply a systematic ideation technique. Those who used *Morphology* generated a slightly below-average number of options, of limited variety. Other students who applied a C*lassification* technique generated a greater number of options, with more variety. In a parallel investigation, it was confirmed that those students with better spatial skills tended to generate options with more variety and perform better in the design course in which they were enrolled, whether or not they used systematic design methods.

Keywords: Ideation techniques, morphology, fluency, flexibility, spatial visualization, classification

1 INTRODUCTION
At an early stage of the design process, an individual designer will begin to explore a range of alternative concepts that might solve, or partially solve the perceived problem. There is evidence that designers who can generate a larger number of potential solutions (that is, those who are *fluent* in ideation) are more likely to arrive at a superior solution concept [1], as are those who can conceive design concepts that are in some way very different from each other (that is, those who are *flexible* in ideation) [2]. A difficulty faced by novice designers is that the creation of even one plausible solution to a novel problem can be challenging, and once created, it can be difficult to identify alternative possibilities (especially any options that are significantly different from the initial idea).
A number of authors have explored the ways in which successful designers appear to work, and have published various tools and other aids to facilitate the creative process (for example, *TRIZ* [3], *Brainstorming* [4] and *Synectics* [5]). It has been traditional to teach novice designers some of these techniques, and to encourage the use of those techniques during the formative stages of a designer's skill. These techniques generally encourage the generation of more concepts or broaden existing concepts, but the author has observed that novice designers tend to adopt a favorite technique and become comfortable with that technique, sometimes to their disadvantage.
At the author's University an opportunity arose to explore individuals' preferences of ideation techniques and to relate those preferences to success in a controlled design problem and to general design skills and achievements. Consequently, the principal objective of the present research was to determine whether novice engineers who had been instructed on several ideation techniques chose to use a technique when given the opportunity, and whether the more successful designers showed any preferences for particular techniques.

2 DEFINITIONS
This paper uses several special terms to describe various aspects of a designer's behavior. The more important terms are listed below.

2.1 Fluency

Fluency is defined as the number of plausible complete concepts generated by a designer in response to a design problem [6]. For the purposes of this paper, no distinction is made between workable and impossible solutions, on the basis that impossible solutions may provide a path to a different, but workable solution during further stages of ideation. However, minor variations of the same concept (for example, a sketch of a similar concept viewed from a different direction) are not counted as a separate concept.

2.2 Flexibility

Flexibility is understood to mean the 'breadth' of solution concepts generated by a designer as solutions to a design problem [6]. The measurement of flexibility is more difficult than the measurement of fluency, since there is no simple way to determine the 'breadth' of plausible solutions. However, since the case problem used in the present study had previously been used in a study at another University [7], during which a systematic Master Design Tree (MDT), that categorized solutions, was constructed for the 85 different solutions offered by novice designers, some idea of the breadth of possibilities was available to guide the present research. Consequently, a Flexibility score in the range 1 to 5 can be allocated to a designer whose design concepts (at least two concepts are needed) are located 'near' each other, or distant, respectively, in the MDT.

2.3 Morphology technique

The *Morphology Technique* is a well known method of generating a large number of concepts by firstly identifying the key aspects or functions of the solutions, then separately listing methods of fulfilling each of those functions [8, 9, 10]. A solution concept is defined by selecting one method of fulfilling each function and then integrating those separate methods. The set of functions and their separate methods is typically displayed in a matrix to facilitate a systematic search through the plausible solutions. The possible number of combinations of the methods (plausible concepts) is the multiple of the number of methods for each function: this quantity can easily reach into the thousands, even when there are fewer than five separate functions to be satisfied. When using the Morphology technique, a novice designer is faced with the task of (somehow) identifying a few of the more promising options, that may represent only 1% of the possible concepts contained within the matrix.

2.4 Classification technique

The *Classification technique* is an approach to ideation that was devised by the author during the early 1990's and taught to the subjects recruited into the present investigation during formal classes prior to the administration of the case problem. The technique has only been published in course notes, restricted to use at several Australian Universities [11], so it is appropriate to provide a summary of the technique to facilitate an understanding of this paper.

The Classification technique uses mutually exclusive Boolean logic to define successively restricted solution categories and sub-categories in a hierarchical structure. Once a sufficient number of sub-categories have been defined (typically eight sub-categories for straightforward machine design tasks), other techniques, such as personal *brainstorming* [4] are used to propose at least one solution in each of the final sub-categories. The outcome from the technique is a set of alternative concepts that are potentially the most *flexible* that can be devised. The next stage of the technique involves the systematic consideration of the solutions in each category, in order to identify common characteristics and thereby determine if promising solutions appear likely within the category. This then facilitates a new search (using any other technique, such as a *dissociative* technique [4] to work toward the best solution in the most promising category.

Figure 1 illustrates the Classification technique as applied to the problem: *How do we economically and safely get wheelchair-bound quadriplegics into cars?* The first stage is the Boolean division of all possible solutions into (a) *allow the occupant to remain in their wheelchair*, and (b) *don't allow the occupant to remain in their wheelchair* (as they transfer into the car). It should be apparent that these two categories of solutions contain all possible solutions to the problem, simply because they constitute an '*A + NOT A*' logical combination that together describe the whole design space. A designer could, at this stage, separately seek ideas that kept the occupant in their chair (an intellectually simpler task than the initial task), and later, seek ideas that used a separate seat in the car (again, an intellectually simpler task). However, as suggested in Figure 1, it is also possible to further 'divide' the solution space in each of the categories into mutually exclusive, but totally inclusive categories. The outcome is, in this case, eight mutually exclusive categories that 'sum' to the whole set of possible solutions that might satisfy the initial problem. For example, the first of eight categories of solutions will satisfy the restricted problem: '*Facilitate a wheelchair-bound person to become seated in a car by allowing them to drive into the car with an adjustable-height wheelchair'*. A number of ways of achieving this might then be proposed (two options are listed in Figure 1). Then attention can be turned to other categories.

The useful feature of this technique is that it forces the designer to be flexible, in that the ideas proposed across the categories are necessarily distinctly different. With novice designers working on a novel problem without attempting to use a systematic ideation technique, the author has noticed a tendency for most to use personal brainstorming and *narrow* their range of options by beginning with a plausible option (or working principle), then adding details to successively clarify their concept. The Classification technique helps them to 'begin afresh' and look for fundamentally different alternatives to what becomes a completely new and different problem.

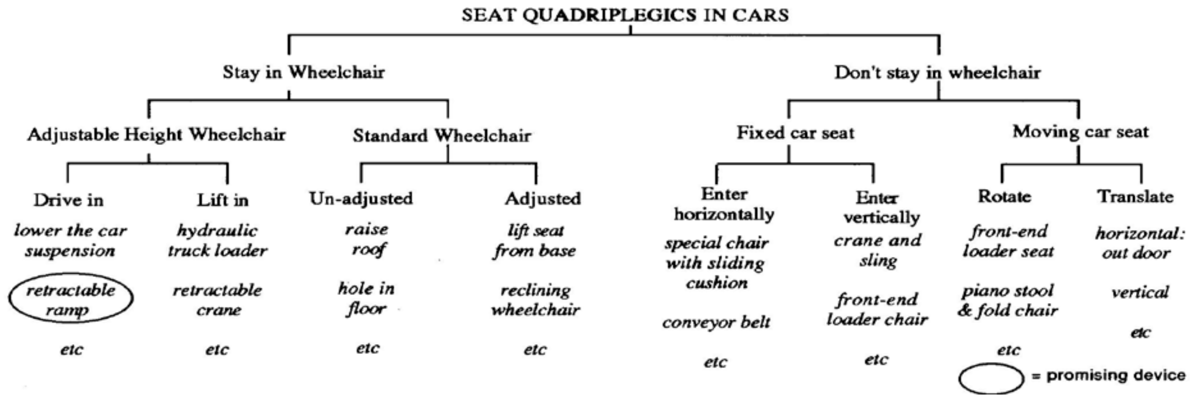

Figure 1 Example of Classification technique as taught to the study subjects

2.5 Spatial Skill

Spatial skill is a psychological term used to describe the ability of a person to use mental images. There are several aspects to spatial skill, including the ability to manipulate 3-D mental images based on their 2-D representations, the ability to orient oneself in space, and the ability to recognize objects in motion [12]. Educational researchers have utilized a small number of paper-based tests of a person's spatial skill during their investigations of the importance of those skills, and methods of improving that skill [13, 14, 15]. Common tests are the Mental Rotation test (MRT)[16], the Purdue Spatial Visualization Test (PSVT)[17], the Differential Aptitude Test: Space Relations (DAT-SR)[18] and the Mental Cutting Test (MCT)[19]. A version of the MCT was used during the present study because it was found to be more reliable than the MRT when administered to large groups simultaneously, and was quicker to administer than the PSVT and DAT-SR tests.

The MCT normally utilizes 25 multiple-choice questions of the type shown in Figure 2, where the path of a cutting plane is defined in a pictorial line drawing, and five alternative views of the resulting cut surface are presented. The subject nominates the correct cross section. Because the MCT was designed to provide a score across a wide range of subjects' ages, some of the questions are easily solved by those of normal university-age and entrance eligibility. To facilitate testing, only the ten most difficult questions from the MCT were retained, and the test was administered in ten minutes [20]. The outcome of this reduced version of the MCT is a score out of 10, and with the University students involved in the study, the scores ranged from 1 to 10.

3 CASE PROBLEM

The case problem used in this study was the same as that used in a related study and reported in 2007 [7]. The problem was written in text and graphics on paper as follows:

> In a commercial jet engine there are 42 inlet guide vanes arranged radially as shown in Figure 3. At the outer end of each guide vane is a mechanism comprising a *Fork end* attached to the guide vane, a *Lever* and a *Hinge pin*. The ends of the 42 levers protrude into ball joints in an external ring called the *Unison ring*. Consequently, if one inlet guide vane (the *'master' guide vane*) is

rotated about its radial axis, its lever causes the unison ring to rotate slightly, and the unison ring causes the other 41 inlet guide vanes to rotate through the same angle as the master guide vane.

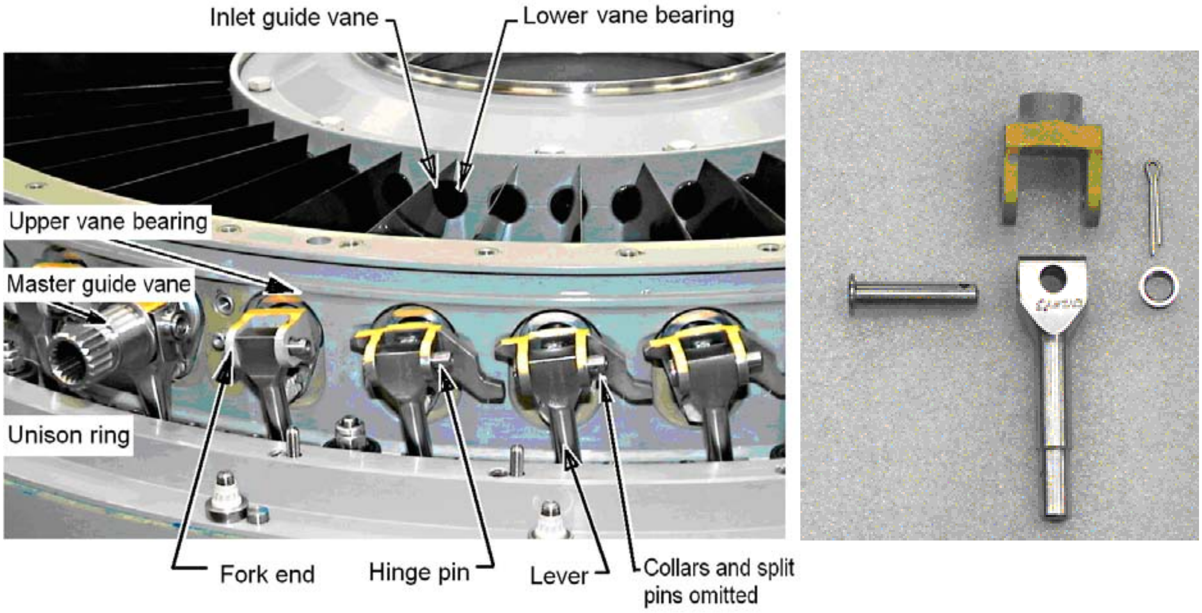

Figure 3. Photographs of variable inlet guide vanes (VIGVs), their unison ring and parts

Following an incident where a split pin was not properly inserted during scheduled maintenance, and fell out during service, the manufacturer wishes to modify the design of the actuating mechanism (preferably by eliminating the use of split pins) to make it relatively 'foolproof'. **With the use of sketches, suggest a range of feasible alternative solutions to this problem**. *Note that the marks allocated to this question represent approx. 30 minutes of work, but you only need to sketch a few alternatives before you answer the [next] question.*

Dimensioned isometric drawings of the critical components and the guide vane were also supplied. Prior to the examination, students were provided with a single page describing the function of a variable inlet guide, including the left-hand photograph in Figure 3. They were not given the questions that were to be asked during the examination, but were aware that questions would include analytical tasks, manufacturing considerations and formal engineering drawings.

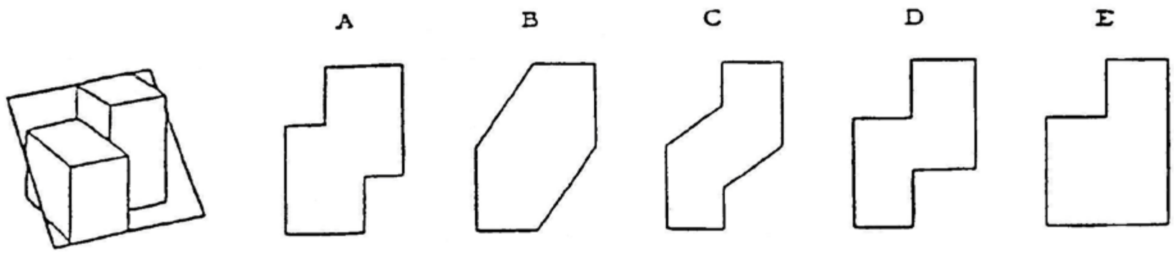

Figure 2 Sample problem from the Mental Cutting test (MCT). Respondents are required to select the cross section A-E that would result from the cutting plane shown in the pictorial representation (The correct selection is option D)

3.1 Subjects

The study involved 244 undergraduate engineering students enrolled in the second year courses MEC2406 Engineering Design 1 and TRC2100 Mechatronics Design [21] at Monash University, Australia in June 2009. These two introductory courses in engineering design were identical, and students all had similar preparations in mechanical and structural engineering sciences during the previous year. The course structure (one of four equally-sized courses taken by full time students) placed approximately equal emphases on design methods, manufacturing technology and hand-drawn engineering graphics. The lecture series on *ideation methods* covered six techniques in two hours, and was backed up with learning tasks (assessed and unassessed) for a further three classroom hours, during which students were encouraged to separately try several methods and determine which seemed more comfortable. During the 12-week semester, two major projects were undertaken: (a) the Australasian *Warman* competition [22] involving the design, construction and demonstration of a two-vehicle device to transport a relay baton and (b) a paper-based conventional open-ended machine design involving simple mechanics and formal documentation of the recommended design.

3.2 Administration of Task

The case problem was included as a small portion of the end-of-semester formal examination that in total contributed 40% of the final grade for both courses. Consequently, each student worked fully independently during the examination. The examination paper included space for writing answers, plus additional space for any separate calculations or preparatory work. Consequently, all of a student's written or sketched work during the examination was available for further analysis. Six weeks earlier, during a conventional lecture, the reduced version of the MCT had been administered to 138 students who were present at the lecture.

4 RESULTS AND ANALYSIS

The examination results yielded the following outcomes for each student:

(a) A count (their *Fluency*) of the separate concepts sketched or otherwise described (the Fluency varied between 1 and 8)
(b) A score for the spread of concept ideas (*Flexibility*) based on the relative locations of the extreme concepts on the MDT (scored at 1-5)
(c) A score for the quality of the ideation sketches (1-3 as assessed by the author)
(d) A final grade for the examination (and, subsequently, a final percentage score for the course).
(e) Evidence of the use of any formal ideation techniques

An MCT (visualization) score out of ten for 138 of those students was also available from earlier testing.

4.1 Correlations of performance parameters

Previous research has shown that both visualization skill and ideation fluency are correlated with design capability [20, 1]. Table 1 shows the correlations for these parameters in the current study and supports those previous findings. In addition, the score for the quality of a student's ideation sketches was, as expected, correlated with their visualization score (0.27 correlation coefficient, $p<0.05$). The correlations therefore suggest that the experimental procedures adopted for the study were valid.

Table 1 Correlation results for Flexibility, Fluency, Visualization and Design Course score

	Fluency/8	Flexibility/5	Visualization/10	Design Course 'D'/100
Mean score	3.9	2.88	4.96	63
S.D.	1.32	1.08	2.19	8.06
N	244	244	138	244
Correlation with 'D'	0.217	0.202	0.36	
Significance of correlation	$p< 0.05$	$p<0.05$	$p<0.01$	

In this study, the scores for Fluency and Flexibility were highly correlated (correlation coefficient of 0.64, significant at $p<0.01$), indicating that those students who generated multiple solutions generally achieved a greater variety at the extremes than those who generated only a few solutions.

Although those students who were fluent and had high visual skills were more likely to achieve good grades in the design course (a multiple regression showed a 0.4 correlation with the combined scores of fluency and visualization, $p<0.01$), the separately useful design skills of Fluency and Visualization were not correlated in this study, with a correlation coefficient of only 0.04, indicating a high level of independence.

4.2 Ideation Techniques

During the examination, several students sketched or wrote elements of some of the ideation techniques that had been formally presented and practiced during earlier stages of the course (beginning some six weeks earlier). Although four different individualized, systematic ideation techniques had been demonstrated during formal lectures and students had been free to explore the ways in which those techniques might work in a series of learning tasks, aimed at identifying matching characteristics of problems, only two of those techniques were consistently articulated in the examination papers, by a total of 44 students from the cohort of 244 (only 18%). Most of the remaining students simply listed or sketched alternatives in an apparently random way. The nature of the examination was that all work was to be recorded on the examination paper, and papers were inspected to seek evidence of systematic formal methods.

4.2.1 Morphology

Twenty three students drew or described a Morphology table. Figure 4 is the table that was constructed by one of the more successful students, and two of the six alternatives that were sketched. The table has a potential for 7 x 7 x 5 = 245 alternatives. The six alternatives were given a Flexibility score of 4/5. This student adopted a useful set of 'aspects' to begin ideation, and appears to have selected six reasonably promising options for detailing.

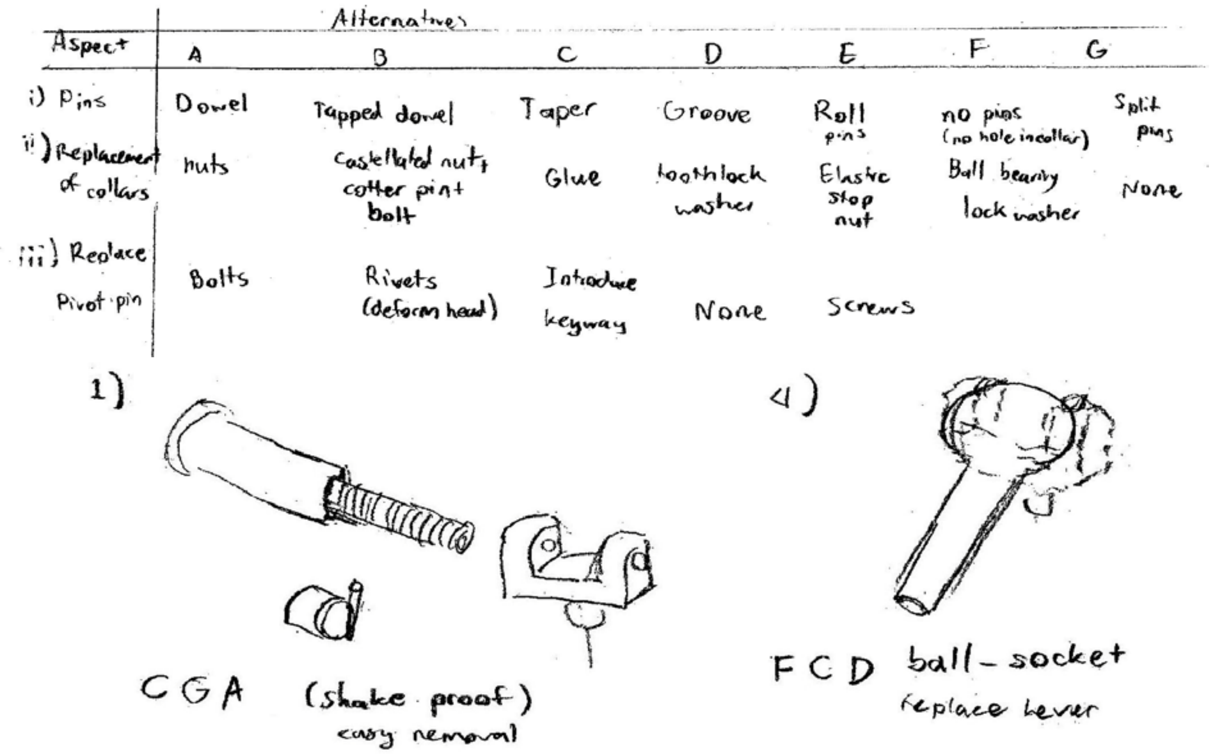

Figure 4. Morphology table and sample sketches showing high Flexibility.

Figure 5 shows the Morphology table and the two most different alternatives from the 4 alternatives sketched by a second student. This table has a potential for 3 x 3 = 9 alternatives. The Flexibility score for this student was 3/5. Although this student has a good sketching ability, he did not select useful 'aspects' to begin ideation, so the options became more restricted. For example, the first aspect restricted the solutions to replacements for the existing pin, as a separate piece.

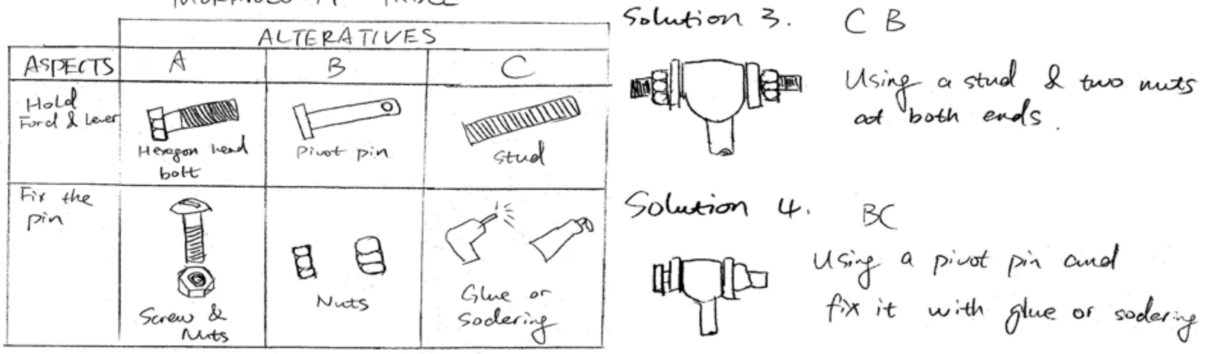

Figure 5. Morphology table and sample sketches showing low Flexibility

4.2.2 Classification technique

Twenty one students drew a Classification chart. Figure 6 is the chart that was drawn by one of the more successful students along with the two most different examples of this student's five ideation sketches. The Flexibility score for this student was 5/5. The Classification began with a sensible division of options that sought to solve the split pin problem but still retain the pin, with a novel approach to spreading the pin. The other options then divided into a special pivot pin and a threaded pin, and those categories divided into two options each. One solution was sketched for each of the five terminating categories.

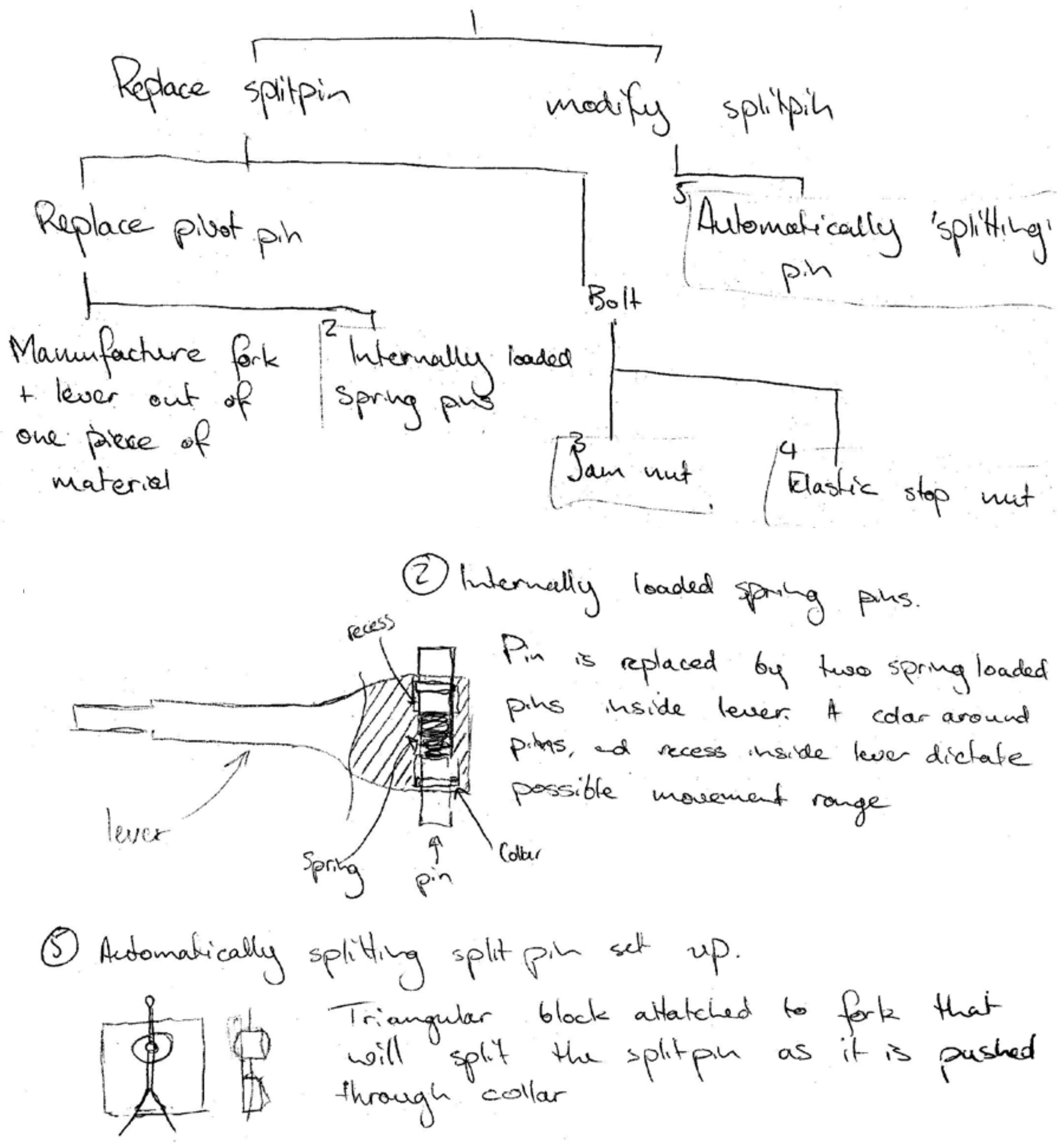

Figure 6. Classification chart and sample sketches showing high Flexibility

Figure 7 shows the corresponding Classification chart and extreme alternatives from a student who demonstrated low flexibility while using this technique. The Classification chart appears to be thorough, but it begins from the narrow problem of attempting to retain a collar onto a pin used in the existing fork and lever. The first three levels (yielding four categories) and most of the options in each category are in fact duplications of the author's classification of 'joining techniques' presented to these students during a separate part of the course on manufacturing technologies. During the lecture program it had been suggested that the classification be kept at hand during design problem solving when there was a need to join parts together: this student has attempted to use the advice during this examination problem, but has missed the more promising options that bypassed the need for a joint.

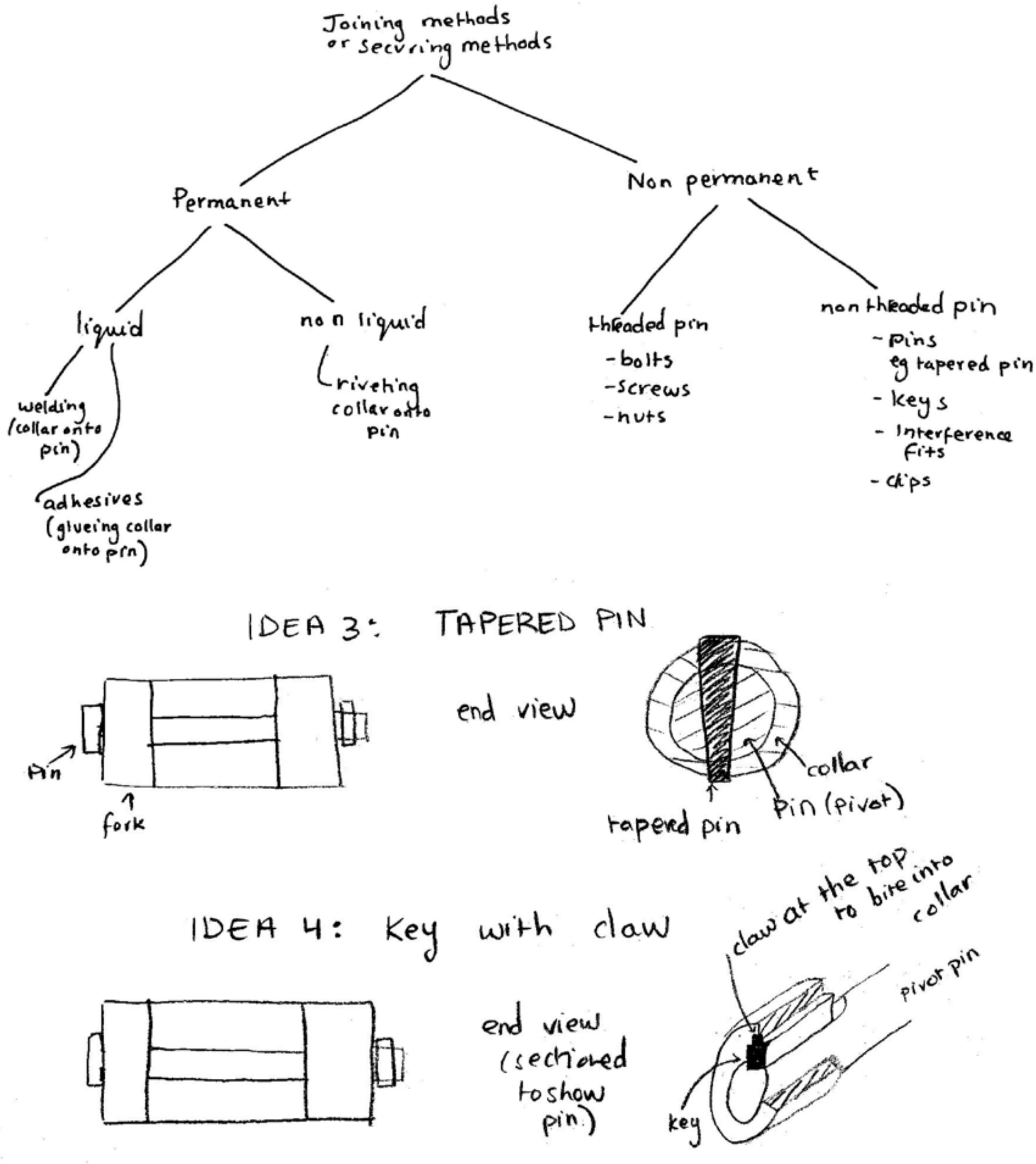

Figure 7. Classification chart and sample sketches showing low Flexibility.

4.2.2 Comparison of techniques

Table 1 summarises the differences in Fluency and Flexibility exhibited by students who drew a Morphology table, a Classification chart, or neither during their solution of the examination question.

Table 1. Significance of differences between means of Ideation Techniques

Ideation Method	N	Flexibility score / 5 & comparisons				Fluency score / 8 & comparisons			
		Mean	S.D.	**c/f None**	**c/f Classific'n**	Mean	S.D.	**c/f None**	**c/f Classific'n**
Morphology	23	2.54	0.98	**p<0.15**	**p<0.08***	3.58	1.5	**p<0.29**	**p<0.04***
Classification	21	3.09	1.09	**p<0.39**		4.48	1.29	**p<0.06***	
None shown	200	2.88	1.08			3.9	1.32		

* Significant difference

Neither of the groups that formally applied an ideation technique achieved a significantly different Flexibility from those who did not describe a systematic technique, although those using Morphology tended to slow less Flexibility. However, those who drew a Morphology table achieved, on average, significantly less Flexibility (in the order of 10%) than those who drew a Classification chart.

Although those who constructed a Morphology table presented, on average, fewer solution concepts than those who did not illustrate a systematic approach to ideation (3.58 concepts compared with 3.9), this difference in Fluency was not significant. Since the task was part of a longer examination, for which the available marks were limited (and therefore related to the expected amount of time to be spent on the task), it seemed plausible that once students invested some time into constructing the Morphology table, they had less time to spend on detailing a number of options, so articulated slightly fewer than those who only presented options, without explaining where those options came from.

On the other hand, those students who drew a Classification chart presented significantly more options (4.5 compared to 3.9) than those who did not demonstrate any systematic technique, even though those students would also have spent some time in constructing the chart. It appears that once the Classification chart had been taken to three levels, with four categories, there was an incentive to seek at least one solution in each category. By its method of construction, the Classification chart forces distinctly different, or 'opposite' options for each category, and a comfortable number of categories. Consequently, the Classification technique appears to encourage both Flexibility and Fluency, although in this case, those who used the Classification technique did not show advanced Flexibility: perhaps for a similar reason (time restrictions) to those who constructed a Morphology table.

Those students who used a Classification chart in the examination performed slightly better than the average student in their overall score for the design course (3% higher in 63%) ($p<0.1$), and, although those students who used Morphology during the exam scored below the average (2% lower), the difference was not significant. Nevertheless, the students who used the Classification technique scored, on average, 5% more than those who used the Morphology technique ($p<0.02$).

The preferred use of the Classification technique by the better performing design students was reflected in their higher spatial skill level (an average of 5.9 / 10 for the MCT whereas those choosing to use Morphology averaged 4.3 / 10 for the MCT).

5 CONCLUSIONS

In a study of 244 undergraduate engineering designers, it was shown that:

5.1 The novice designers with significantly better spatial visualization capabilities (as shown by a 10-question MCT) obtained higher grades in their introductory design course,

5.2 When asked to generate concepts to a mechanically simple design problem, only 18% of the cohort chose to construct a formal ideation aid,

5.3 Of the 44 novice designers who used a formal ideation aid, those who used a Classification chart approach generated more concepts (that is, were more *Fluent*) than those who did not use a formal ideation tool, and were also more *Fluent* than those who chose to construct a Morphology table.

5.4 Although the Classification chart technique focuses on generating a broad range of concepts, the novice designers who used the technique did not, on average, submit concepts with a more substantial spread of alternative working principles (that is, concepts with greater *Flexibility)* than those who did not use an ideation tool, but they did display significantly more *Flexibility* with their concepts than those who used a Morphology table.

5.5 The novice designers who used the Classification technique performed significantly better overall in their introductory design course than those who used a Morphology chart.

It is not possible to ascertain if those novice designers who chose to use a Classification technique for ideation (learned some six weeks before the examination) became better designers as a result of their choice, or if some of those novice designers who already possessed superior design skills chose to use a Classification approach. However, since spatial skill is regarded as a slowly-developing capability, and since the Classification technique was preferred over Morphology by those with higher spatial skill, it would seem that the Classification approach was preferred by those novice designers who were already better equipped to become engineering designers.

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