INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 05 MELBOURNE, AUGUST 15 – 18, 2005

THE IMPACT OF SPATIAL ABILITIES ON THE COMPREHENSION OF DESIGN DRAWINGS

Bruce Field, Colin Burvill and John Weir

Abstract

The paper reports the relationship between the visualisation capabilities of novice engineering designers, and their ability to read and analyse orthographic projections of machinery. Using a reduced version of a standard test for visualisation skill, and four specially-developed drawing tests within a second year course in engineering design, it was found that (a) students with strong visual capability performed better in the main examination, (b) those with strong visual skills were more adept at identifying kinematic flaws in a conceptual design, and (c) the better design students were also better at comprehending engineering drawings. Following the analysis of questionnaires, it was found that male students, having more experience with mechanical artifacts, performed better than females in the drawing tests (even though their visual skills were similar), and those students who had a pre-university graphics education were better visualisers, and performed better on the drawing tests. The results have implications for pre-university and early university programmes in graphics-education.

Keywords: Spatial skill, mental cutting test, engineering drawing, visualisation

1. Introduction

There is concern among engineering design educators that while there is an increasing need for visualization skill to complement the increasing use of visual tools in engineering design, we may be seeing a reduction in the spatial abilities of undergraduates [1].

If a novice engineer has weak visualization skill, then perhaps they will be unable to comprehend an engineering drawing, may misread drawings or be incapable of recognising the unworkability of their own design concepts [2] or those of others. This would have severe financial consequences in a world culture of accelerated design where being first to market, and with a flawless product, is imperative.

The authors are responsible for the engineering design education programmes at two of Australia's main engineering schools. Over the last ten years they have detected a decline in a number of graphical/visual skill objectives in their respective engineering curricula, and have also been concerned that their students have been performing less well in visual and graphical forms of problem-solving [3]. There appeared to be a relationship between the reduction in graphics and graphical problem solving, and the increase in spatial/pictorial errors in students' design work.

However, it was not clear that any decline, if real, was related to changes in the visual capabilities in the student cohort, or changes in the curriculum. Consequently, the authors sought to determine the relationship, if any, between fundamental visual skills and relevant engineering skills that appear to rely on visualisation. The two aspects of visualisation that were identified for the study were (a) the capability to 'read' a conventional orthographic engineering drawing and (b) the capability to identify spatial flaws (principally kinematic) in orthographic views of machinery.

The objective of the present research was to quantify the relationships (if any) between standardized measures of spatial skill and the level of comprehension in interpreting design graphics exhibited by undergraduate engineering students. If a sufficiently strong relationship could be found, this would justify a greater expenditure on resources to develop the capabilities of those undergraduates with inadequate spatial skills.

2. Measuring visual/spatial skill

While psychologists recognize that spatial skill is one human capability that varies widely between individuals, there is no universally recognized instrument for measuring that skill [4]. Part of the difficulty is the acknowledgement that spatial skill is categorized as a 'right brain' skill (along with intuition, creativity, and global problem solving)[5]. This contrasts with 'left brain' skills, such as language, mathematics and logic that are more easily measured by left-brain instruments that are structured, logical and numerical. There is general agreement that spatial skill is not a single capability, and the different capabilities are only loosely correlated. Those capabilities include ability to visualize 3-D objects after they have been hidden from view, an ability to visualize internally synthesized 3-D objects, an ability to manipulate 3-D images (rotate, cut and animate) and various 2-D and 3-D pattern recognition and manipulation abilities.

Fortunately, it is feasible to identify aspects of visual skill that are likely to be useful to engineers. These aspects include the ability to manipulate (rotate and animate) images of 3-D artifacts, and the ability to dissect (cut) images or 'see' into hollow artifacts. Consequently, researchers into the spatial skills of engineers have tended to use tests of visual skill that relate to these aspects. The most commonly reported tests used in studies of engineering spatial skill are called the 'Mental Cutting Test' and the 'Mental Rotation Test'[6,7].

2.1 The mental cutting test (MCT)

The MCT has been developing for more than 60 years. The test comprises 25 separate multiple-choice questions where the test subject chooses the correct answer from five alternatives. Each question includes a 3-D image of a one-piece geometric object being cut by a plane that is oblique to the viewing direction. The task is to identify the correct 2-D representation of the resulting cut surface. Instructions to the test (Figure 1) hint at the sequence of thought-steps needed to answer each question: these involve the removal of the foremost cut portion, the rotation of the remaining portion around two axes to present the cut surface orthogonally, then the removal of any visible portion(s) behind the cut surface.

The MCT takes 20 minutes to complete, and the result is a numerical score out of 25. A detailed analysis of the 25 questions in the MCT indicates that not all questions are of equal perceived difficulty [8]. There are some questions that almost every engineering student answers correctly, and some questions that only a few can answer correctly. Consequently, it has been possible to reduce the number of questions in the MCT to 10, or even to 5 of the most difficult for the chosen cohort, and still obtain a usefully wide spread of scores [9]. For the present research, the reduced set of 5 questions was used to obtain an indication of the subjects' spatial skills, because other tests (tests of graphics skill) were also to be administered within a limited time frame to restrict the influence of fatigue.

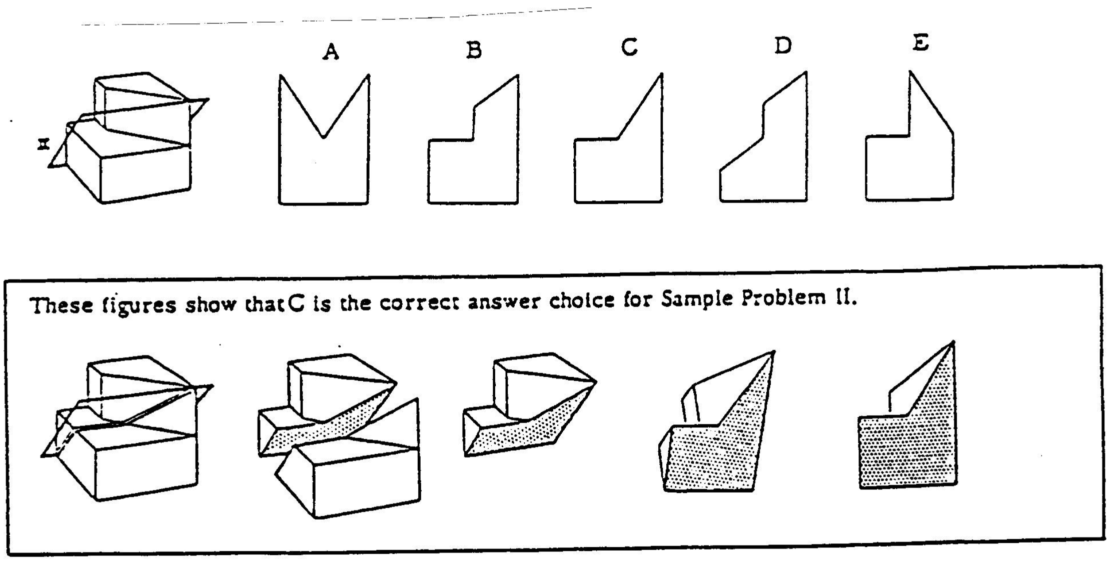


Figure 1. Sample problem from the MCT

2.2The mental rotation test (MRT)

The MRT is a well-established test of spatial skill [4]. The test comprises 20 multiple-choice questions, divided into two equal sets, with a three (3) minute limit for the completion of each set. In each question of the test there are four alternatives, and the subject is instructed that there are two correct answers to each question with the requirement that both answers be found for full credit. The test question is a 3-D line representation of an abstract geometric object comprising a number of cubes joined orthogonally. The possible answers include the same object viewed from a different angle, and views of different objects (either mirror images of the given object, or a differently structured object). Separate research [10] has indicated that the population average score on the MRT varies with age, but for the cohort under consideration (engineering students and professionals) the mean score is about 26 for males and 16 for females out of a possible 40. Magin and Churches [4] showed that the correlation between the MCT and MRT scores was high: above 0.6. A sample question from the MRT is shown in Figure 2.

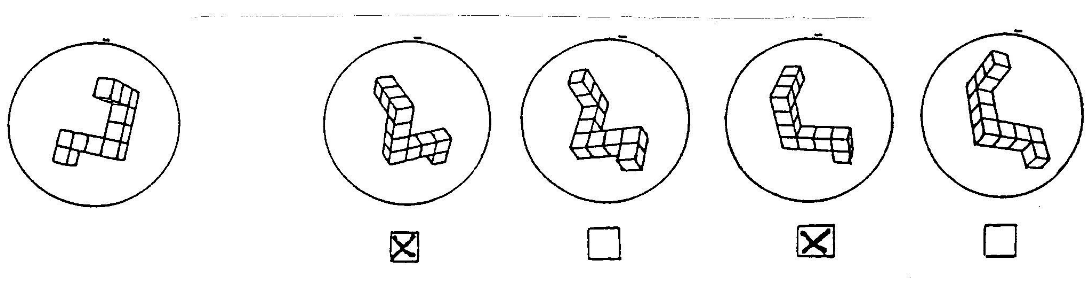


Figure 2. Sample question from the MRT

It is intended that the two identical objects in each question be identified by undertaking a mental rotation of either the sample or answer object around one or two axes so that the two images may be checked for similarity. Clearly it is also possible to form this similarity check by logical (non-visual) means, but the strict time limit on the test makes this approach ineffective.

The main difficulty in using the MRT is the lower reliability of the test compared to the MCT [4]. The short time period for undertaking the first part of the test means that many subjects misjudge the time and fail to complete the first part. They are more likely to complete the second part. The variable score resulting from the incomplete first part reduces the reliability, and makes the test less useful in test-retest experiments where the prior experience inflates the second score.

For this reason, and the difficulty of controlling the time periods for the two halves for more than 200 subjects, the MRT was not used in the current research.

3. Measuring skill in reading engineering drawings

In the present research, the authors were interested in two separate, but related aspects of novice designers' abilities to comprehend orthogonal engineering multi-view drawings. The first aspect was their ability to understand the three-dimensionality of the items represented in multi-view drawings and perhaps in understanding the 'shorthand' of conventions used in those drawings. The second aspect was their ability to conceptually animate multi-view representations of machinery and thereby identify shortcomings in the design of the machine. Each of these aspects was measured by two separate tests that were specially devised by the authors.

3.1Testing for comprehension of engineering drawings

The first test (Tc1), used to determine whether drawings are comprehended, followed a fairly conventional format (Appendix 1). Four views, including dimensions, sections and hidden line representations of an assembled gear pump were arranged in the third angle convention. The test comprised ten questions about the design. Most of those questions explored mechanical terminology, and required a mental translation of the views into 3-D objects, but other questions sought to explore whether the test subjects could move between views by recognising the same component in different orientations.

The second test (Tc2) had a more unusual format (Appendix 2). Three orthogonal views of a valve assembly with some hidden lines but no labels or dimensions were presented. Eight other images were also presented. These comprised both orthogonal and pictorial representations of objects. The task was to identify which of the eight images were representations of parts from the assembly. (The correct answers are A, B, F, G and H).

Both tests were scored with simple correct/incorrect (binary) counts for correct responses, with a possible 10 and 8 points respectively.

3.2Testing for kinematic visual skills

Both tests for kinematic visual skills followed the same format. In each case, two orthogonal sectioned views of a hypothetical machine were presented.

The first test (Tk1) represented a small reciprocating air compressor (Appendix 3) that might be used to inflate automotive tyres. It was expected that the items within this representation would be fairly familiar to the subjects, so there would be minimal demands placed on their static spatial visualisation skills. The item contained seven deliberate errors that made its assembly or functionality impossible (e.g. the impossibility of placing the connecting rod onto the crankshaft, and the impact of the connecting rod with the cylinder bore, respectively). The design also contained manufacturing shortcomings that are not relevant to the present analysis. The design errors were intended to range from 'obvious' to 'subtle', thereby facilitating a range of scores from subjects who possessed a range of spatial-kinematic skill.

The second test (Tk2) represented a drive system for the valve of a small steam engine (Appendix 4). It too was a mechanical slider-crank mechanism, but contained different shortcomings: nine kinematic flaws, limiting assembly or function, and a manufacturing flaw. For example, it is impossible to assemble the cover plate into the casing, or the slider into the casing, and if the device could be assembled, the connecting rod would impact the casing around the bushing, and the 'crank pin' bolt would impact the cover plate retaining screws.

The solutions for tests Tk1 and Tk2 are shown in Appendices 5 and 6 respectively.

4. Identifying individual differences

The experimental work was conducted at the University of Melbourne during 2004 [11]. Approximately 200 second year mechanical and mechatronics engineering students were enrolled in a course in engineering design. The first year of their course included work on the conventions of engineering drawing, including the principles of orthogonal projection, but with minimal practice in the production of orthogonal drawings. There was coursework in the use of solid modeling software.

The first stage of the testing was to administer tests Tc1 and Tk1 at different stages during the course. These tests were to occupy about ten minutes each during the scheduled lecture programme, and were part of the authors' teaching strategy where a series of up to ten 'spot tests' on relevant topics are presented during the semester. One of the other tests was a simplified version of the MCT. The testing environment did not ensure that each subject's work was independent, although collaboration was actively discouraged.

These tests were aimed at 'conditioning' the students to the type of testing to be used in the main study, so that there would be fewer misunderstandings when the main study began. Experience with unprecedented Tk1 in 2003 had shown that many students failed to focus their efforts on the type of fault (kinematic) that was present in the design. Solutions to Tc1 and Tk1 were discussed with the cohort at the completion of the respective tests.

The second stage of the test programme included the five-question MCT, and tests Tc2 and Tk2 in a controlled environment that prevented any collusion. However, while the total time allowed for these tests was controlled, the allocation of effort to each test was not.

The third stage of the test programme was a set of questions about the students' prior experiences (Appendix 7). This questionnaire was administered to volunteers from the main study. There were 66 valid responses. The purpose of the questionnaire was to identify any characteristics of strong and weak visualisers that might indicate ways in which visualisation skills can be improved. The authors had previously administered a similar questionnaire to undergraduates at Monash University, and had sought to find characteristics that differed between the better and weaker visualisers. It appeared that the better visualisers were more likely to have engaged in hands-on hobbies as children [9].

In addition, each student's overall percentage mark in the design examination was included in the study. There were other results that could have been incorporated, such as the overall mark for the design subject (including all assignment outcomes), however such results were rarely independent scores, since the mark a student receives in design includes a significant component of group work, which includes non-design achievements such as interpersonal communication. The semester's work in engineering design included analytical problem-solving issues in structural integrity such as structural distillation, estimation, axial loading, shafts, fatigue, pinned joints, contact stresses, and bolted joints.

5. Results and Discussion

The principal focus of the research was to seek any causal relationships between the visual skills of the cohort, and their capabilities on the two types of engineering graphics tasks. The secondary intent was to seek any aspects on the subjects' backgrounds that might indicate reasons why skills differed, and consequently to help formulate techniques to improve appropriate visual skills. To this end, the tool chosen to form relationships was the Pearson Correlation Coefficient. For the number of responses to each of the five components of the set of tests (varying between 150 and 180 responses), a correlation coefficient above 0.25 is significant at the 1% level, and was chosen for the analysis. Correlations above 0.2 are also notable, since these are significant at the 5% level of confidence.

5.1Test results

The correlations between the spatial skill score and each of the four visualisation test scores, along with the overall design score are shown in Table 1. The significant correlations are highlighted in bold.

Table 1. Correlations found during the experiment. The bold correlations are significant at the 1% level, and the superscripts refer to the discussion to follow.

Test	μ (%)	sd (%)	N	Spatial skill	Tc2 (Valve assy.)	Tk2 (Slider)	Tc1 (Gear pump)	Tk1 (Compressor)
Spatial skill	67	28	180					
Tc2 (Valve assy.)	39	19	179	0.12 [7]				
Tk2 (Slider)	34	22	180	**0.38** [2]	0.15			
Tc1 (Gear pump)	47	17	159	0.20	0.15	**0.43** [3]		
Tk1 (Compressor)	31	23	156	0.11	0.08	**0.31** [4]	0.21	
Design exam	60	20	180	**0.41** [1]	0.11 [8]	**0.39** [5]	**0.28** [6]	0.05

It is apparent from correlation (0.41 [1]) that students with higher visualisation skills performed better in the design examination. This was to be expected, since the process of creative design is believed to involve visualisation [5]. Nevertheless, it is reassuring to find such a strong statistical relationship in what has commonly been stated anecdotally.

Correlations with Tk2, the valve-gear slider mechanism, (correlations [2, 3, 4 and 5]) are strong with all other items except Tc2 (valve assembly). Tk2 had a very similar form to Tk1 so their strong correlation (0.31 [4]) was to be expected. Tk2 has a strong correlation with the test for spatial ability, suggesting that students with strong spatial skills are more successful in identifying the kinematic errors in designs. The weaker correlation between Tk1 and spatial skill (0.11) may indicate that students were unprepared for that type of test (as was the outcome in 2003), but were able to focus their effort in Tk2. The high correlation between Tk2 and Tc1 (0.43 [3]) is unexpected, except that it may well arise from the observation that those who are good designers, as shown by their examination mark, can also deduce facts from a drawing (0.28 [6]).

It was surprising that performance on Tc2 was not strongly correlated with any other scores. While the form of the test was completely unlike any other test in the experience of the students, this should only have lowered the average score. However, the low correlation with visualisation skill (0.12 [7]) and the examination (0.11 [8]) suggest that the skill in extracting and manipulating mental images from the drawing is relatively independent of the measured visualisation capabilities. In this instance the skill is more likely to be related to the subjects' untested familiarity with the conventions of engineering drawing.

5.2Questionnaire outcomes

There were two outcomes from the questionnaire that are worthy of comment.

Firstly, although there was little difference between visualisation scores of males and females in the sample (66% and 62.2% respectively), the males performed significantly better on the four drawing tests (40% and 26.5% averages, respectively). The sample included 54 males and 10 females, reflecting a similar ratio for the whole cohort. As well, 72% of the males, and only 44% of the females indicated that they had been involved in constructional hobbies such as Lego® and automotive repair. This data supports the belief that prior experience in mechanical equipment is advantageous in these tests, and that visualisation capability is only part of the skill needed to solve the tests successfully.

Secondly, the group of students with pre-university studies in graphics performed better in both the spatial test and the engineering drawing tests, although there was no significant difference between the groups in their examination score. Those with prior experience averaged 49% while those without averaged 42% on the tests. It was not possible to determine whether the prior experience in graphics caused the superior performance, or whether inherent visual skill led students into their earlier graphics experience, but it appears that non-engineering graphics exposure may help to support engineering visualization tasks.

6. Conclusion

The main outcomes of the research were as follows:

- Engineering students with strong visual skills performed better in the design examination.
- Engineering students with strong visual skills were better at identifying kinematic errors in design concepts presented as orthogonal sections.

- The stronger engineering design students could more successfully read engineering drawings, but their visual capabilities were not a dominant factor.
- Male engineering design students performed better on the comprehension and kinematic tests than female, even though the visual skills of the two groups were similar.
- Engineering design students with pre-university graphics training had better visual skills, and were more adept at reading engineering drawings.

References

[1] Martinez, D. (1999) "The importance of engineering graphics to our future engineers and the state of the art methods used to teach those concepts". *Proc 29th ASEE/IEEE Frontiers in Education Conference*, Puerto Rico, p13

[2] Kavakli, M. and Gero, J.S. (1998) "Drawings and the design process"' *Design Studies*, **22**, No. 4, pp 347-364

[3] Field. B.W., Burvill C.A. and Weir J.A. (2001) "Conceptual errors in machine design" *Proc 13th ICED,* Glasgow, pp253-260

[4] Magin, D.J. and Churches, A.E. (1994) "Reliability and stability of two tests of spatial abilities*." Proc 6th International Conference on Engineering Computer Graphics and Descriptive Geometry,* Tokyo, pp801-805.

[5] Field, B.W. (1995) "Why do we only educate half the engineer?" *Proc 7th Annual Convention and Conference of the Australasian Association for Engineering Education*, Melbourne, pp350-354

[6] College Entrance Examination Board (1939). *"CEEB special aptitude test in spatial relations"*. USA

[7] Vandenberg, S.G. and Kuse, A.R. (1978) "Mental rotations, a group test of three dimensional spatial visualisation". *Perceptual and Motor Skills*, **47**, pp599-604

[8] Ohtsuki, N., Nagae, S, Irie, K., Short, D. and Ezaki, T. (1994). "Using the mental cutting test (MCT) to evaluate the effectiveness of descriptive geometry course*." Proc 6th International Conference on Engineering Computer Graphics and Descriptive Geometry*. Tokyo, pp806-809.

[9] Sok, V. (2001). "*Visualisation in engineering design"*. Unpublished Final Year Thesis, Department of Mechanical Engineering, Monash University.

[10] Field, B.W., Manuelli, S. and Chao, M. (1996) "Spatial visualisation skills of engineering undergraduates." *Proc 8th Annual Convention and Conference of the Australasian Association for Engineering Education*, Sydney, pp396-400

[11] Liu, S.S. and McNair, H.S. (2004) *"Visualisation skills of undergraduate mechanical engineering students"* Unpublished Final Year Thesis, Department of Mechanical and Manufacturing Engineering, University of Melbourne.

Acknowledgements

This paper incorporates the experimental and analytical work conducted in 2004 by S.S. Liu and H.S. McNair, final year engineering students at the University of Melbourne.

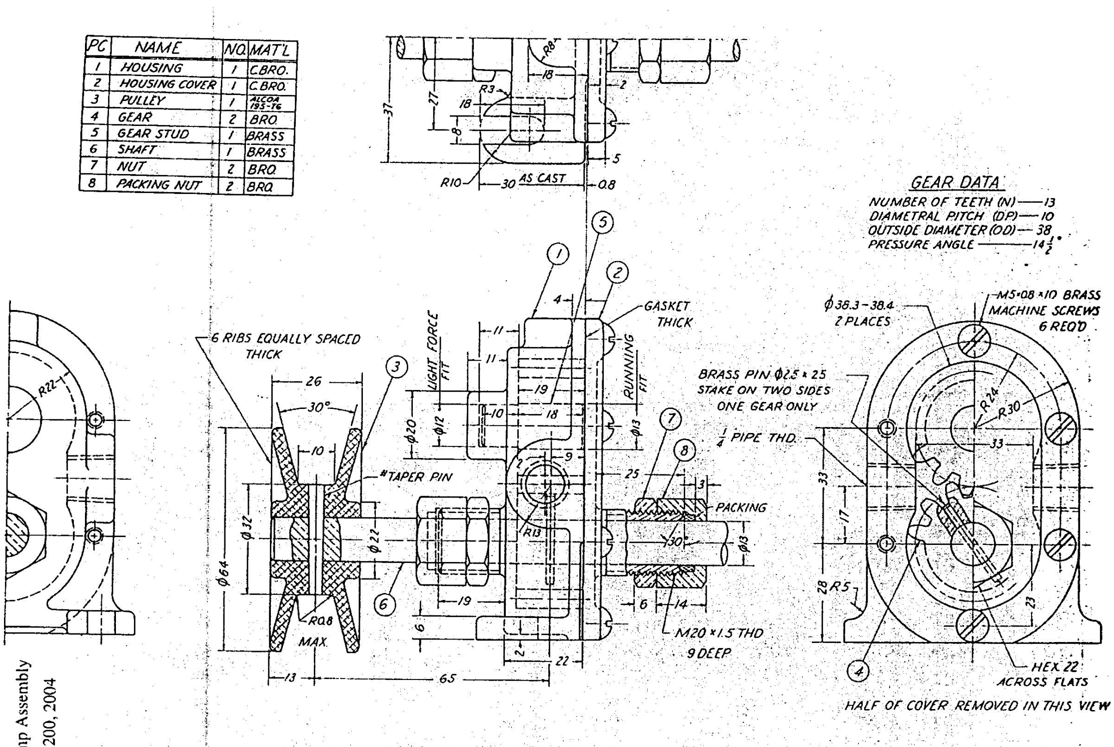
Authors

Bruce Field. Associate Professor, Department of Mechanical Engineering. Monash University, Clayton, Vic, Australia bruce.field@eng.monash.edu.au

Colin Burvill. Senior Lecturer, Department of Mechanical and Manufacturing Engineering, The University of Melbourne, Parkville, Vic. Australia.

John Weir. Lecturer, Department of Mechanical and Manufacturing Engineering, The University of Melbourne, Parkville, Vic Australia.

Appendix 1: Portion of first test of drawing comprehension: Tc1



Extension problem: Gear pump assembly
Source: *Introduction to Engineering Drawing*, by W J Luzadder & J M Duff, Prentice-Hall 1993.

(Continued next page)

Answer the following ten questions:

Qn.	Description	Answer:
1.	How is the **pulley** (part 3) secured to the **shaft** (part 6)?	
2.	What is the diameter of the **shaft** (part 6)?	
3.	How is the **cover** (part 2) secured to the **housing** (part 1)?	
4a.	What dimension is the most critical in the pump assembly?	
4b.	Is there any provision to adjust this dimension?	YES / NO
5.	What is the length of the **shaft** (part 6)?	
6a.	What is the vertical distance between the bottom of the **pulley** and the bottom of the **housing**?	
6b	What implication does this have for mounting the pump?	
7.	What is the diametral clearance between each **gear** and the inside of the **housing**?	
8.	If you were to drill two holes in a mounting surface to firmly mount the pump, what would be the spacing of the holes?	
9.	What is the function of part 7, the **nut**?	
10.	What is the overall height of the **housing**?	

Appendix 2: Second test of drawing comprehension: Tc2

Figure 4b-1 shows an engineering drawing of a valve assembly (third angle projection). Figure 4b-2 shows eight sketches of a range of components, labelled A to H. Use table 4b to indicate whether each of the sketches represents a view or section of a component in the valve assembly (figure 4b.1). Accepted responses: **Y** = "Is a view or part in assembly", **N** = "Is not a view or part in assembly", "blank" = no answer.

Table 4b: Responses for question 4b (i.e. **Y, N** "blank")

Label	A	B	C	D	E	F	G	H
Response								

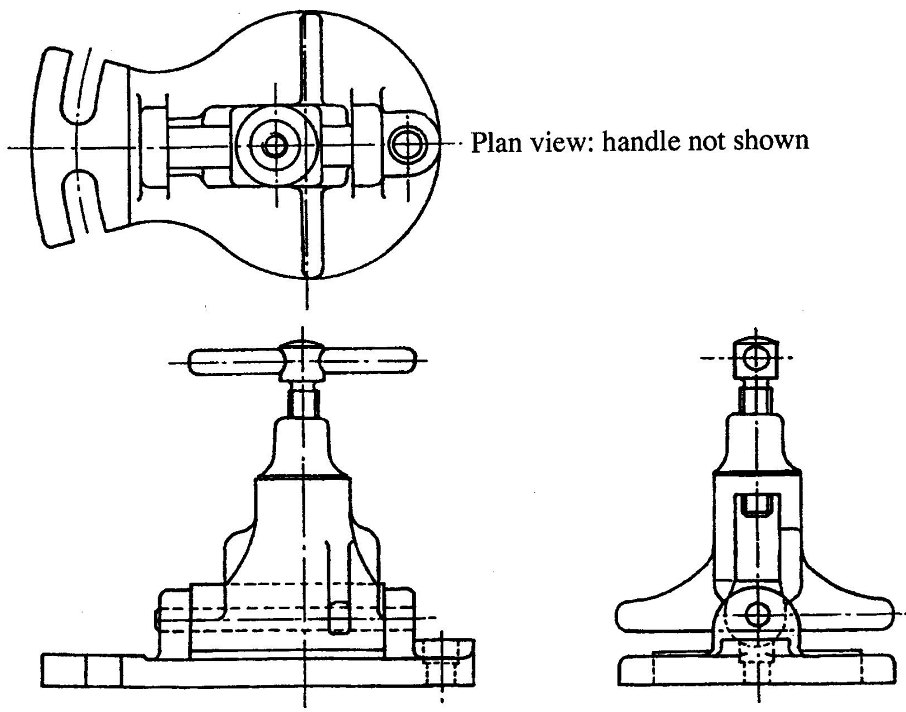


Figure 4b-1: Valve assembly engineering drawing

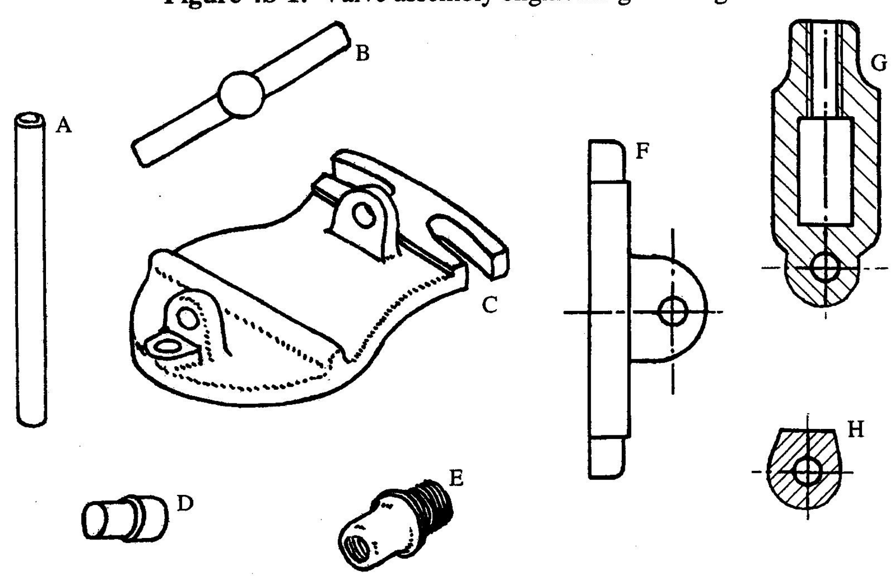
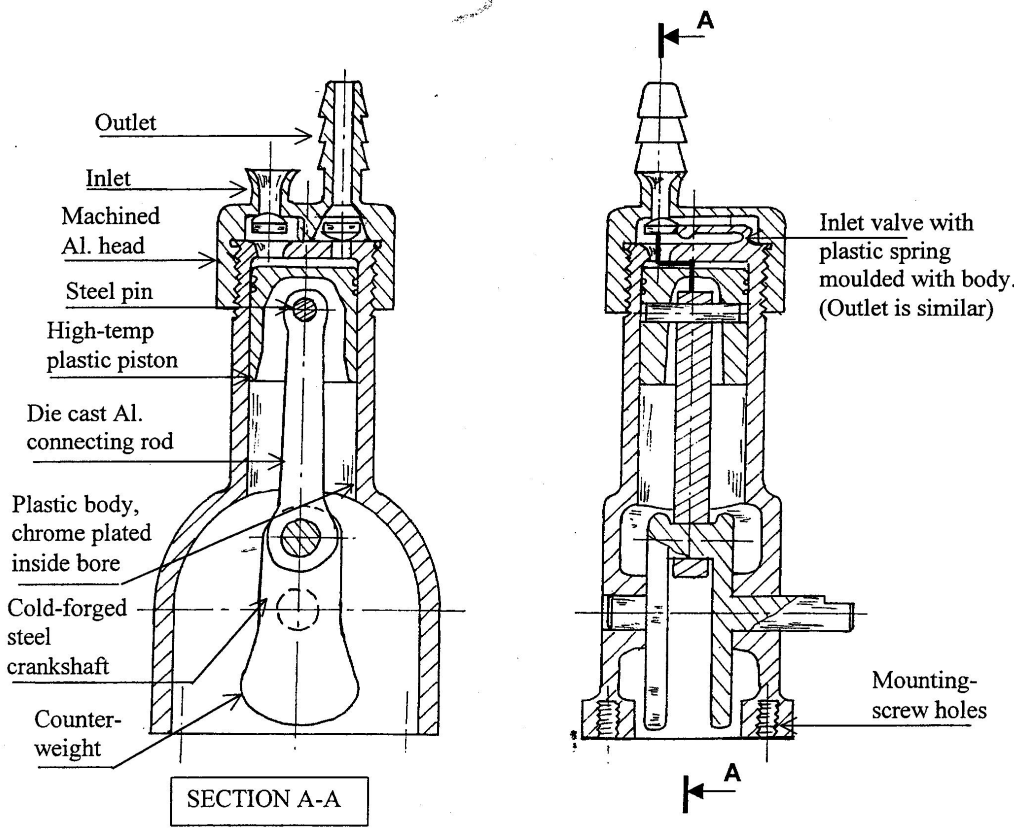


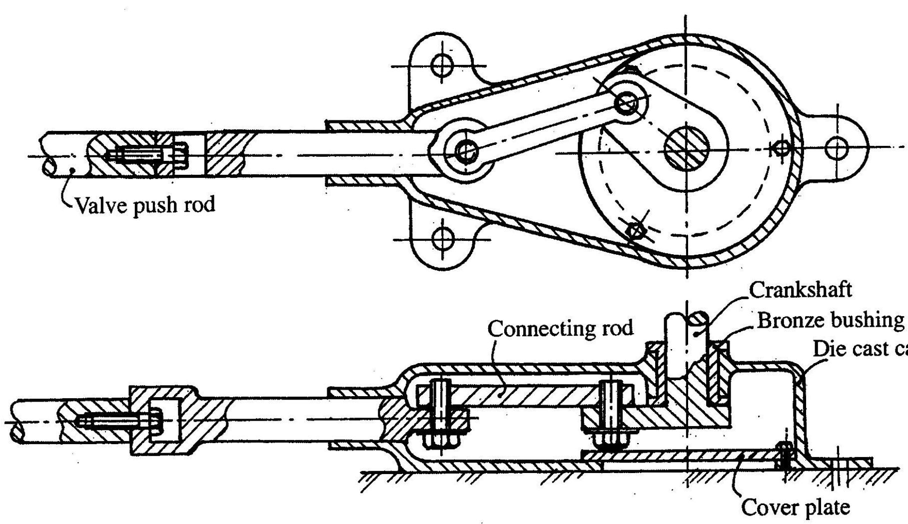
Figure 4b-2: Eight views or sections that may be parts of the valve assembly in figure 4b-1

Appendix 3: Image from first test of kinetic visualisation: Tk1

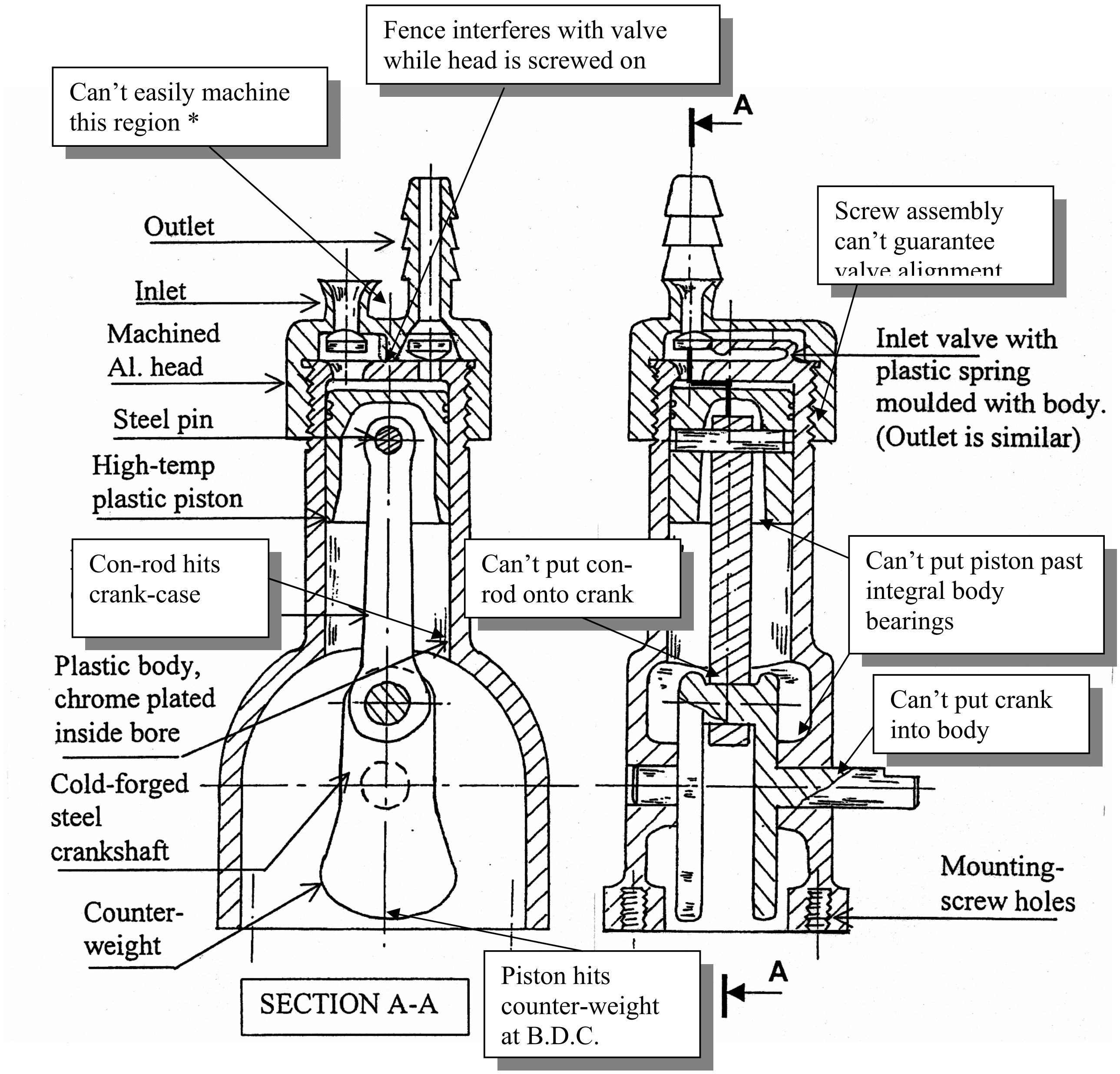


Appendix 4: Portion of second test of kinetic visualisation: Tk2

The conceptual aspects of the device in figure 4c are acceptable, but there are several constructional (detailed design) aspects that are unsatisfactory. The material choices are acceptable. Identify and numerically label key faults that are impractical/impossible using figure 4c and briefly describe the fault in table 4c.



Appendix 5: Solutions to Visualisation Test Tk1

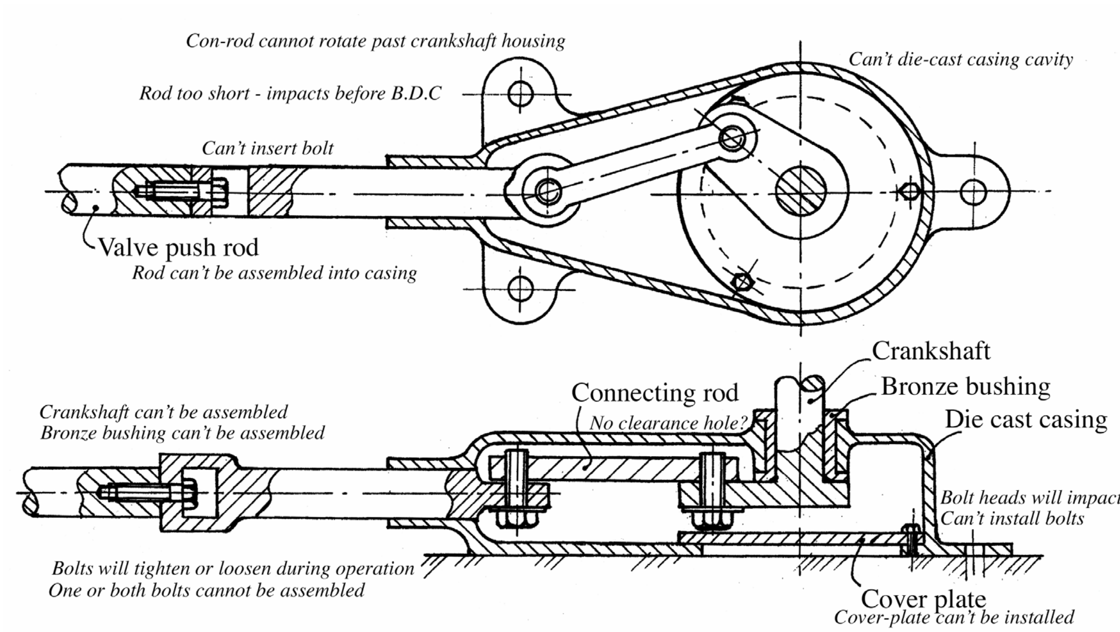


Major shortcomings labeled

* Other considerations:

- Crank-shaft cannot be cold-forged. Correct assertion (demonstrates understanding of manufacturing limitations). Crankshaft could be fabricated using friction welding.
- Chromed plastic. A common practice.
- Injection moulding of body. Is possible using a multi-insert injection mould die but would be inappropriate if low-cost is an objective.
- The awkwardness of the machining on the head was not scored in this visualization test.

Appendix 5: Solutions to Visualisation Test Tk2



Appendix 7: Questionnaire

Design 200 – 2004 : Survey of Graphic Skills

Please include your student ID on this survey so academic staff can correlate your responses with other work completed in your design 200 subjects (mid-year exam and class-tests).
At no stage will your performance be identified, even if you agree to participate in the follow-up quiz.
CRB, JGW.

Student ID Number: ____________________________

Gender (circle one): Male / Female

Your current enrolment status: (you may tick more than one box)

- ☐ Mechanical / Manufacturing
- ☐ Mechatronics
- ☐ Science
- ☐ Commerce
- ☐ Arts
- ☐ Other: ____

Are you an:

- ☐ International student Country of Origin: ____________________________
- ☐ Australian Resident
- ☐ Exchange student Country of Origin: ____________________________

Have you completed any graphic related courses or subjects **before** university?
If so, please specify the course or subject name and where you did it.

Course / Subject name ____

Institution ____ Year __________

Have you had a part-time job or hobby that involves visual thinking or drawing?
E.g. Drawing / Painting / CAD. If so, please specify.

____
____

Have you had a part-time job or hobby that involves construction-type activates?
E.g. Meccano / Lego / Automotive / Origami. If so, please specify.

____
____

When attempting to interpret an engineering drawing, does it help if you:

- ☐ Visualise the object in 3D.
- ☐ Sketch the object in 3D.
- ☐ Have seen the physical object (or a similar object) previously.
- ☐ Other ___________________________________

Thank you for taking the time to participate in this survey.