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A Course in Spatial Visualisation

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Abstract. One of the higher level skills required of engineers is that of spatial visualisation. A common measure of spatial visualisation is the Mental Cutting Test (MCT), where subjects attempt to identify the correct cross section resulting from a cut through a solid object, presented pictorially. When students in Engineering at Monash University were tested by the MCT, it was found that there was no apparent development of the skill over the duration of their course. However, students who had undertaken a special 52 hour course in Spatial Visualisation during 1995, 1996, 1997 or 1998 improved their MCT scores significantly compared to a control group of students. In the latter years, modified forms of the MCT were used: these variants were found to be slightly more difficult for weak visualisers, so their improvement in skill was reflected in a larger increase in MCT score. It was concluded that it was possible to increase the visualisation skills of students, where the MCT is used as the measure of the skill.

Key Words: Visualisation, Mental Cutting Test, graphics education.

MSC 1994: 51N05.

1. Introduction

Several eminent engineers [1] and engineering groups [2] acknowledge the importance of visualisation skill for their profession, and, following suggestions that Australian post-1980 engineering courses are less effective in this area of skill development, there are now deliberate attempts to ensure that graduates in engineering have enhanced visualisation abilities [3]. For example, programmes at the University of Melbourne [4], RMIT [5] and Monash University [6] have all begun in the last decade, although it is difficult to assess the effectiveness of these programmes without the use of standardised testing methods. The perceived problem is not confined to Australia, with remedial courses in visualisation appearing at universities in the USA [7, 8].

This paper describes work conducted at Monash University over the years 1994–98 aimed at measuring spatial skills, improving the sensitivity of visualisation tests, and developing the skill for some engineering undergraduates.

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2. An Attempt to Improve Visualisation Skill

A course with the specific objective of developing visualisation skill was begun by the author for the Department of Mechanical Engineering at Monash University in the second half of 1994 [6]. It is an elective subject of 52 contact hours, available to all first level students in the common year, but, understandably, the majority of those enrolled have an expectation of progressing to mechanical engineering at the second level. Apart from the prime objective derived from its title, there is a major aim to develop skills in representing spatially visualised objects through projections (orthogonal, isometric and perspective), physical modelling and wireframe modelling in the PC. Secondary objectives include an introduction to CAD, principles of descriptive geometry, engineering terminology and machine functional/manufacturing analyses.

Make an isometric sketch of this group of artifacts, and their shadows, viewed from the right along 'A' and lit from behind the viewpoint of the drawing above.

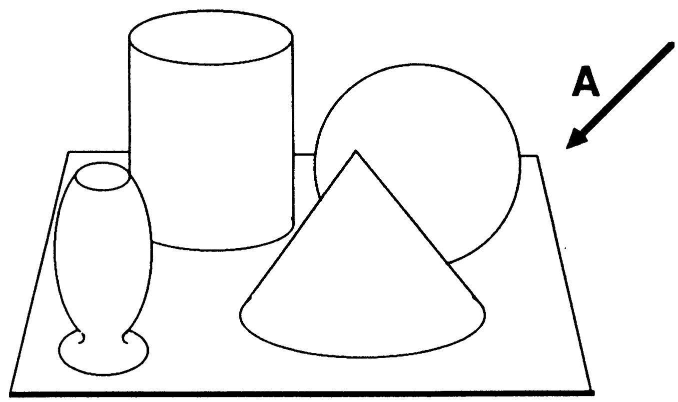

Figure 1: Freehand drawing tasks in spatial visualisation course

The course presents material in four topic areas, more or less in parallel. These are:

- Sketching — orthogonal, isometric, one, two and three point perspective, and the formation of shadows and highlights. This section is characterised by the presence of physical objects which students can use to check their visualisation. Exercises are graded in complexity, beginning with the conversion of isometric drawings into orthogonal projections, and progressing through the construction of perspectives created from an unusual station point, to the representation of dies used for casting a particular artifact. Fig. 1 illustrates one of these exercises.
- Physical modelling — the use of foamcore (an easily worked, rigid, flat modelling material), and the associated descriptive geometry theory of interpenetrating solids and surface development with single curvature. Students design an artifact, present their design in orthogonal projections and an isometric sketch, and then construct their model in foamcore (and usually in wireframe format). Examples of foamcore artifacts designed and made by students are shown in Fig. 2.
- Mental animation — the mental and graphical solution of kinematic problems from static (usually 2-D) representations, such as 2-D and 3-D paths of points in mechanisms. This portion of the course has been reduced in recent years to allow students to develop greater skills in the other aspects of the course, especially sketching. A typical problem, involving the analysis of motion in a helicopter control linkage, is shown in Fig. 3.
- Computer graphics — including the solutions of line and angle problems in descriptive geometry (such as true length, true shape, skew lines and shadow construction), and

an introduction to wireframe modelling. The technique is an extension of the purpose-written BEAGLE software developed at the University of Melbourne [4]. At Monash University, unmodified commercial CAD software 'CADKEY' is used as it conveniently provides a simple 4-view layout of viewports, allowing manipulation of any view and automatic updating of the others in an equivalent way to the BEAGLE programme. CADKEY wireframe manipulation is, however, somewhat slower, but more precise, than BEAGLE. A typical problem is shown in Fig. 4.

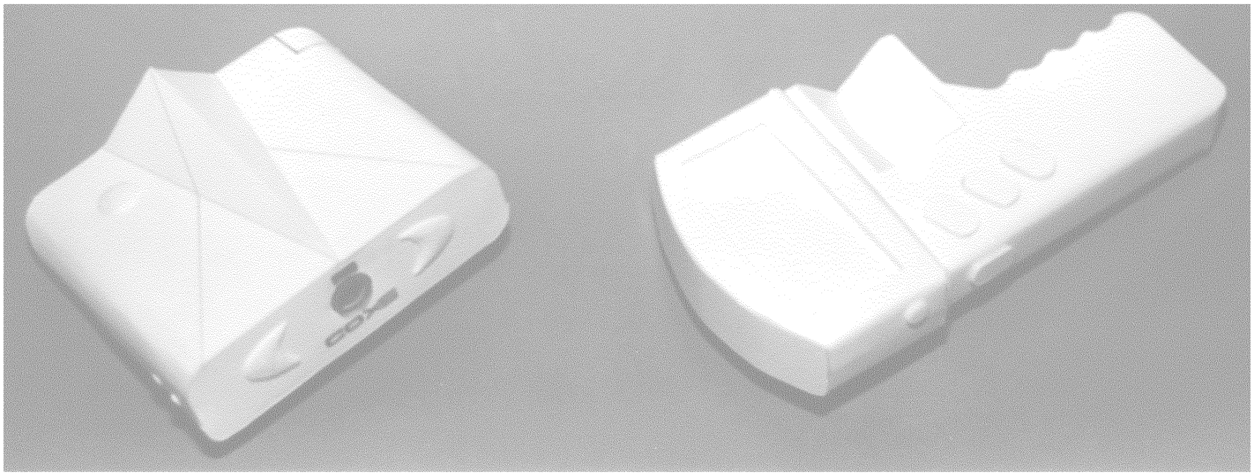

Figure 2: Foamcore models made in the spatial visualisation course

Determine whether the thread on the helicopter tail rotor pitch control is left or right handed.

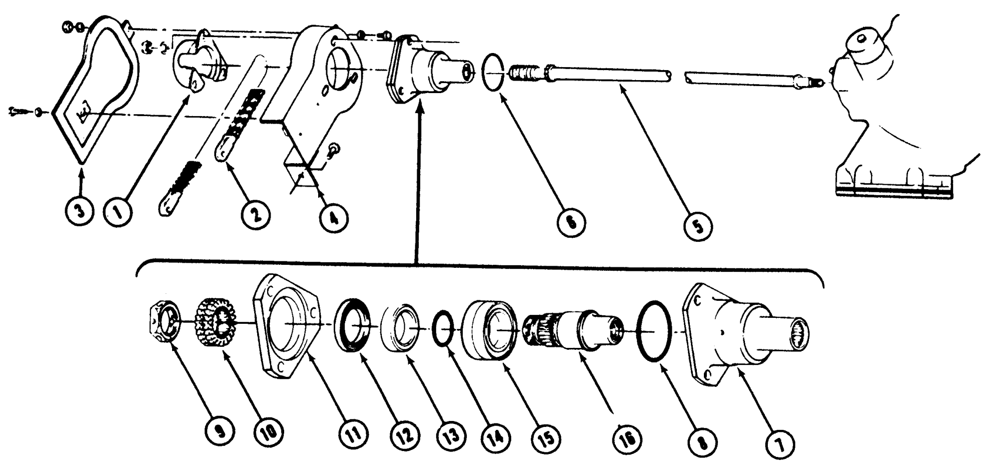

Figure 3: Spatial motion task used in spatial visualisation course

The earliest parts of the course in each of these topic areas focus on techniques and skills in representation, especially sketching from real artifacts (there is no drawing board work in this subject), manipulating foamcore, and creating lines in a wireframe model. In the middle of the course, increasing effort is spent on developing visualisation skill, using students' representational skills to communicate solutions of graded visualisation tasks. For example, students make sketches of real objects from a different viewpoint, predict the motion of a helicopter rotor pitch control rod, and develop the surface of an icosahedron for maximum economical use of material. The later tasks focus on more complex visualisation, including the prediction of shadows and highlights from single-point lighting of artifacts, the design, At what elevation is the sun when the shadow of the taller building does not fall onto the roof of the other?

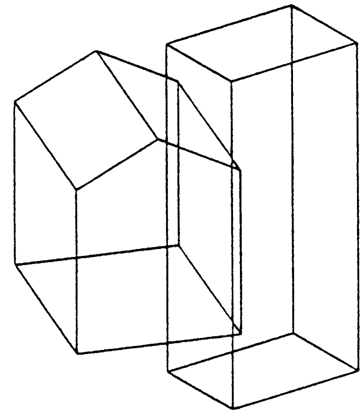

Figure 4: CADG problem used in spatial visualisation course

construction and simple analysis of a model bridge or a digital camera, an exploded view and functional analysis of a flow control valve, and the construction of a wireframe model of their bridge or camera design.

The most unusual aspect of the teaching programme is the extensive use of physical models, both in the abstract exercises (e.g. orthogonal sketching) and the engineering context tasks (e.g. exploded views). In most cases, the use of actual models makes the learning tasks self-assessing. For example, after students have attempted to draw the isometric view of a group of four blocks from its orthogonal projections, they are invited to build and look at the actual object, using DUPLO blocks. After they have attempted to sketch the form of the die set used for casting a zinc cam, they can form an impression of the cam in 'Playdoh' to check their prediction.

Students entering the 1994, 1995 and 1996 elective subject were surveyed on their motivation, and it was found that while the majority chose the subject because they perceived it to be more relevant to their chosen specialisation, or because they had a graphic background which they wanted to develop, some simply did not want to take the other options, namely second subjects of physics or chemistry. This made it important to check the incoming skills of the cohort, because a wide range of visualisation abilities was expected.

3. Measuring Visualisation Skill

There has been widespread research into visualisation skill, with the majority of this research focusing on the differences between individuals and the change (if any) in measures of the skill after subjects have undergone a set of conventional educational experiences. For example, Suzuki et al. [9] relate the improvement of visualisation skill as measured by a 20 minute "Mental Cutting Test" (MCT) (identifying the sectional view created by cutting a 3-D object with a plane) such as that described below, to educational programmes in descriptive geometry, but could find no significant improvement of the skill following a programme in mechanical drawing. These results may help explain the anecdotal deterioration in visualisation skill observed at Australian Universities (at least that skill associated with the representation of 3-D objects), where coursework in descriptive geometry has generally declined in the last decade, even though a training course of mechanical drawing remains in the degree programmes of most engineering courses.

The MCT was shown to be reliable by the Kuder-Richardson KR20 formula, scoring above 0.86 in experiments by Magin and Churches [10] at the UNSW. This means that the difficulties of each of the items in the test bank are similar. The stability of the test was also found to be acceptable, with a test/re-test correlation of more than 0.8. Typically, subjects improved their performance by about 10% on the test/re-test, in a consistent way. These characteristics of the MCT make the test suitable for use in medium-size groups, although the relevance of the test to 'real' spatial ability may be subject to philosophical debate.

3.1. Forms of mental cutting test

Many of the researchers in the field of the development of spatial skills in engineers are using the Mental Cutting Test (MCT) as the 'standard' for evaluating and comparing individuals, or changes in individual skill. Unfortunately, evidence on spatial skills shows that there may be a gradual increase and decrease in the skill level over the lifetime of an individual reaching a peak in their 20's, and a significant spread of skill across the population, so that successive tests over a modest period of time, associated with subjects' experiences, may yield apparent changes which could well be associated with any of several phenomena. These phenomena include age, test-retest (practice) effects, and test environment in addition to true changes in ability associated with a specific experience. It therefore requires a large number of subjects, and a carefully designed experiment to determine significant effects of identified experiences.

Even so, only the most optimistic researcher would expect more than a small change in the MCT scores of individuals resulting from a specific experience occupying perhaps four months in a subject's 18th year of life, further demanding large numbers of otherwise similar subjects. With this experimental difficulty in mind, it would be desirable to find a spatial test which would be more sensitive, especially in the middle range of skills of the test cohort.

A decade ago, some attention was paid to 'hemispheric specialisation', and it was shown that most individuals processed similar types of information in similar regions of the brain. Furthermore it was found that spatial problems invoked activity in the right hemisphere, while the left hemisphere processed verbal, logic and mathematical information. With a major focus on left brain skills, it seemed that most children were schooled in a strongly biassed way, and many of the right brain activities (including intuition, creativity and visualisation) were only developed in children with such a preference (and normally a disinclination for left brain work). More recently, these hemispheric preferences have been recognised as influencing an individual's learning style, and consequently success or difficulty in undertaking standardised educational programmes, which tend to utilise one or the other hemisphere. Importantly, skills in the less utilised hemisphere are likely to deteriorate. However, some writers have argued that it is not difficult to re-establish right brain skills with the correct programme (Betty Edwards [11] is a notable proponent of this claim).

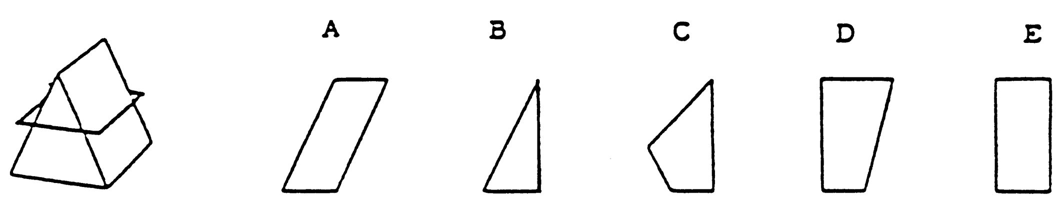

Figure 5: The standard form of MCT questions

If it is possible to increase visual skills in a modest time period by unlocking latent skills, then it should be possible to develop a test to measure this change. The conventional Mental

Cutting Test (MCT) places a pictorial view of a three dimensional object at the left hand edge of the page, and offers five alternative views of the resulting section resulting from the cut, as shown in Fig. 5. The subject is required to choose the single view that represents the correct section. The mental processes involve appreciations of the number of sides on the resulting shape, their shapes and inclinations, and their relative lengths. Some aspect of image rotation is also required.

The author and his co-workers reasoned that the MCT is structured like a western book, where the comprehension begins at the upper left hand corner and progresses across the page before moving downwards. On the other hand, genuine visual skill should not be directional. It was further reasoned that if the 3-D cut image of the object in the MCT was placed on the right hand of the alternative solutions, the left-brain dominant person would be forced to 'read' the problem from right to left, and may find the task more difficult then a stronger visualiser. The questions would now have the appearance of Fig. 6.

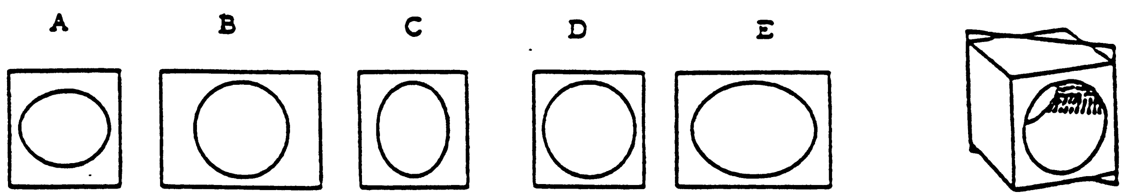

Figure 6: Reversed form of MCT questions

In 1996 his hypothesis was tested with a modified form of the MCT (the 'Oscillating' MCT) where every second problem was reversed in this way, and administered to a group of engineering students. The findings were very enlightening, with the average score for the modified test being significantly lower (by some three points) than for a similar group of students who took the conventional MCT ('Standard' MCT). The details of this investigation are tabulated below. Furthermore, an analysis of the individual problems found that the lower score was associated with a greater relative error rate for the questions with the pictorial image on the right hand side.

These groups of students were retested after some had undertaken a course in spatial skill development, and their increase in score was very much larger than had been measured with the standard MCT in previous years. It was provisionally concluded that the modified MCT was harder to complete correctly when the problems were reversed, but that after spatial skill training, the tasks were less onerous. This change in ease was in addition to the increase in spatial skill which allowed students to solve the more difficult problems.

For 1997, all of the questions in the MCT were presented in this reversed format ('Right hand' MCT), but it was noted that the performance of the test cohort on this modified test fell between the scores obtained on the 'Standard' MCT, and the 'Oscillating' MCT used in 1996. In 1998 the version of the test first presented in 1996 was again used.

4. Research at Monash University

Visualisation research at Monash has had two separate foci:

- improvement in visualisation skill following a special course, and
- levels of visualisation skill in engineering students.

Table 1: MCT Results for Monash Students

	Year				
	1994	1995	1996	1997	1998
Version of MCT	Standard	Standard	Oscillating	Right Hand	Oscillating
Experimental Group:					
Group size	25	39	41	29	21
Pre-test Mean	17.7	15.7	12.3	17.0	13.5
Pre-test SD	5.2	5.0	5.4	5.7	5.3
Post-Test Mean	18.3	18.4	17.2	19.6	18.1
Post-test SD	5.1	3.9	4.5	4.7	4.4
Mean Improvement	*0.6*	*2.7*	*4.9*	*2.6*	*4.6*
SD Improvement	2.1	2.9	3.1	3.4	3.6
Control Group:					
Group size	11	16	18	13	20
Pre-Test Mean	15.9	14.9	12.1	13.2	12.9
Pre-Test SD	4.5	5.5	5.6	5.9	5.5
Post-Test Mean	16.5	16.6	14.0	13.7	14.8
Post-Test SD	4.0	5.3	5.1	6.7	6.2
Mean Improvement	*0.6*	*1.7*	*1.9*	*0.5*	*1.9*
SD Improvement	2.3	2.9	3.0	4.7	4.0
significant	No	Yes	Yes	Yes	Yes

4.1. The Effect of the Course in Spatial Visualisation

The first level elective course in spatial visualisation was described earlier. Students were tested with various forms of the MCT in the first week of their study, and again at a later stage in the subject. Control groups of students who were also undertaking engineering studies at the first level, but who had not enroled in Spatial Visualisation were also tested in the same weeks as the experimental group. Table 1 summarises the results from the groups.

The MCT results for 1994 showed that the students undergoing the course in spatial visualisation did not significantly increase their score compared to the control group.

However, the larger class size in 1995, together with a slightly different teaching method which gave rewards (marks counting towards final grading) for completing the freehand drawing learning tasks, showed a significant improvement in MCT scores compared to the control group.

It was concluded that a dedicated course in spatial visualisation could be effective in improving the skill as measured by the MCT. No significant changes to the teaching programme were introduced for the 1996 course: by now students were well aware that for reasons of equity, it was expected that the distribution of results for the subject should compare with alternative elective subjects. Nevertheless, more than 70 students enrolled, with many of them acknowledging that the course was not expected to be easy. A spot check of the visualisation skill development of about half of the class, using the oscillating MCT, midway through the course nevertheless showed a significant increase in abilities.

In 1997, the enrollment was again about 70 students, and the 'right hand' version of the MCT was used to assess the skills of the cohort both before and following the course. Once again, the students undertaking the course showed significant improvement over the control group. This was the first occasion that the control group showed a significantly lower skill, and much greater standard deviation than the test group, so the results must be treated with some caution. It appeared that the volunteer students who undertook the MCT were of an unusually lower ability than the test group. Notwithstanding this observation, it is quite likely that the modified MCT used in the testing programme depressed the scores by one to two points at the pre-test, as had been expected.

In 1998 the 'oscillating' test was used, and the results again showed that the students undertaking the course in spatial visualisation improved their MCT score significantly above the practice effect. Although there were 50 students enrolled in 1998, timetabling problems meant that only 21 undertook both pre and post tests on the MCT. This year was slightly unusual in that both the experimental and the control groups showed atypically high improvements in their MCT scores. This repeated the effect seen in 1996, and suggests that the 'oscillating' MCT has a high test-retest effect, as well as a greater sensitivity to improvements in spatial skill. The relatively small sample size in 1998 means that this observation needs to be checked carefully.

4.2. Visualisation Skills of Undergraduates

It appears that visualisation skill can be developed through a special course. However since it was not certain that the normal engineering course does not achieve a similar outcome as an indirect effect of the conventional teaching programme, a check of final year student skill was conducted.

While 55 first year engineers scored an average of 15.4 (standard deviation of 5.3) on the standard MCT in 1995, 31 final year mechanical engineering students scored an average of 15.8 (standard deviation of 4.8). The difference is too small to be statistically significant, and could in any case be explained by the normal increase in spatial skill with increasing age for this sample. The increase appears to be much less than the adjusted improvement made by the group of students undertaking the special course, described above.

It may be of passing interest to note that a group of 24 first year Industrial Design students at Monash (selected into the course largely through their high quality graphics work) scored a mean of 15.9 (standard deviation of 4.1) on the MCT: again not significantly better than the engineering students. This indicates that graphics skill alone does not improve visualisation skill as measured by the MCT, even though they are related 'right brain' skills [3].

5. Conclusion

The testing of undergraduate students at Monash University has indicated the following factors:

- First level engineering students are unlikely to possess specially higher spatial skills than the general population. Furthermore, the spatial skill of students entering industrial design were also unexceptional.

- Spatial skills are not measurably developed by a conventional mechanical engineering undergraduate course.
- A special course with about 50 contact hours appears to have been successful in developing visualisation skill in first level engineers. There is some evidence that freehand drawing of three dimensional objects, in orthogonal, isometric and perspective views makes a major contribution to the development of spatial skill.
- A modification of the Mental Cutting Test (MCT) which rearranges the pictorial presentation of the cut object, may reduce the score obtained by weaker visualisers, and therefore allow a greater improvement for those tested as their ability increases. This modified MCT may provide a more sensitive measure for visual skill.

References

[1] E.S. Fergussen: *Engineering and the Mind's Eye*. MIT Press, Boston, USA, 1992.

[2] I.E. Aust: *Careers in Engineering*. IEAust/DEET, Canberra, Aust., 1995.

[3] B.W. Field: *Why do we only Educate Half the Engineer*. Proc. 7th Annual Conv and Conf AaeE, Melbourne 1995, pp. 350–354.

[4] W.P. Lewis, J.G. Weir, D.G. Hook, E.V. Mochel: *Education in 3-D Geometry and Modelling*. Int J. Engg. Educ. **6**, 531–547 (1990).

[5] G.V. Page, J.A. Tomas: *On the Development of a Visualisation Course for Engineers*. Proc. 5th ICECGD Melbourne 1992 (unbound).

[6] B.W. Field: *A Course in Spatial Visualisation*. Proc. 6th ICECGDG Tokyo 1994, 257–261 (1994).

[7] S.S. Marlor, B. Gimmestadt: *An Introduction to 3-D Spatial Visualisation — A Pre-Graphics Course*. Proc. 6th ICECGDG Tokyo , pp. 820–824.

[8] Y.S. Kim, M. Astley, F. Pariente, H. Zhao: *Instructional software development for visual reasoning: the first phase*. Proc. 6th ICECGDG Tokyo 1994, 276–280.

[9] K. Suzuki, K. Shiina, K. Makino, T. Saito, T. Jingu, T. Jingu, N. Tsutsumi, S. Kashima, M. Shibata, H. Maki, E. Tsutsumi, H. Isoda: *Evaluation of Students' Spatial Abilities by a Mental Cutting Test*. Proc. 5th ICECGDG Melbourne 1992, 277–281.

[10] D.J. Magin, A.E. Churches: *Reliability and Stability of Two Tests of Spatial Abilities*. Proc. 6th ICECGDG Tokyo 1994, 801–805.

[11] B. Edwards: *Drawing on the right side of the brain*. Harper-Collins, London 1992.

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