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Enhancing engineering drawing skills via fostering mental rotation processes

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ABSTRACT
Engineering Drawing (ED) is one of the fundamental courses for various engineering disciplines. However, first-year engineering undergraduates often face difficulties in learning and solving ED problems that require visualisation of 3D objects. Conventional and modern teaching methods do assist the teaching-learning of a subject but do not guarantee the elimination of the learning difficulties, specifically related to visualising spatial relationships. Mental rotation (MR) skills play a major role in learning such concepts, and students should be trained for the execution of MR processes. This paper presents a 3D visualisation tool-based training programme where students practice MR processes. The training guides students through hands-on tasks, coupled with the cognitive steps of MR. We investigate the effect of the training on improving 253 engineering undergraduates' ED problem-solving performance by administering a pipeline of four research studies. Results show that the training successfully helps students in enhancing their ED problem-solving performance.

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Engineering drawing; mental rotation; spatial ability; 3d visualisation tool

1. Introduction

It is well known that freshman engineering students face difficulties in learning engineering drawing (ED) (Garmendia, Guisasola, and Sierra 2007; Upadhye, Shaikh, and Yalsangikar 2013). Some of these difficulties are the analysis of the shapes of three-dimensional objects, the interpretation and analysis of their various views, and their visualisation. These difficulties are linked to the fact that students find it challenging to learn the concepts of orthographic projections, isometric projections and to perform the transformations between two-dimensional (2D) and three-dimensional (3D) views, where it is required to identify and visualise multiple views of a 3D object (Akasah and Alias 2010; Nagy-Kondor 2007).

Conventional instruction methods of teaching ED require students to learn the ED course for a semester-long duration and involve them in doing the practice of sketching and drawing for longer durations. Such teaching techniques assist the learning of a subject but do not guarantee the elimination of the learning difficulties entirely (Akasah and Alias 2010; Kosse 2005). In modern instruction methods, instructors make use of software tools such as Computer-Aided Design (CAD), multimedia tutors, animations, and web-based instructions as a supplementary visual aid in learning (Branoff and Mapson 2009; Cincou 2013; Froese et al. 2013; Wu and Chiang 2013). These methods were useful in teaching the ED course and involve various additional activities such as content presentations with voice-over, software demonstrations, and videos of sketching. Though these techniques are useful in improving the learning of ED concepts and skills, certain difficulties remain, such as interpretation and manipulation of engineering drawings and objects

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required for performing 2D and 3D transformations (Kuang and Hu 2004). One of the potential reasons for the persistence of these learning difficulties in ED is students' poor spatial skills (Medupin et al. 2015).

Spatial skills play an essential role in learning concepts involving 3D visualisation of an object and acquiring knowledge in ED concepts. Spatial skills deal with performing the mental rotation of the objects, visualisation of the appearance of an object from different angles, and conceptualising the relation of objects in 3D space (Sutton and Williams 2007). Spatial skills have been defined in multiple ways (Buckley, Seery, and Canty 2017; Linn and Petersen 1985; Maier 1998; Mohler 2006; Sutton and Williams 2007). Linn and Petersen (1985) identified three categories of spatial skills as Spatial Perception, Mental Rotation, and Spatial Visualization. Mental rotation (MR) is an essential aspect of spatial skills and has been defined differently by various researchers. For example, Gurny (2003) described it as 'the ability to rotate an object in space mentally.' MR has also been defined as the ability to rapidly and accurately rotate a two or three-dimensional figure mentally (Ferguson et al. 2008; Nagy-Kondor 2007). While these definitions of MR are valid and somewhat similar, we adopt Maier's (1998) definition of MR as it encapsulates the essence of all the definitions and states that MR is an ability to 'rapidly and accurately rotate a 2D or 3D figure.' The nature of MR problems requires thinking in three dimensions. Solving MR problems involves performing specific cognitive steps. And to solve these MR problems, Johnson (1990) had specified six specific cognitive steps: (a) 'Form a mental representation of an object,' (b) 'Rotate the object mentally until its axial orientation allows the comparison to the standard,' (c) 'Make the comparison,' (d) 'Make a judgment,' and (e) 'Report a decision.'

This paper proposes and evaluates an instructional method known as TIMeR that stands for 'Training to Improve Mental Rotation Skills'. The TIMeR is a hands-on training programme with three phases, Preparatory Phase (Phase 1), Training Phase (Phase 2), and Transfer Phase (Phase 3). Each phase consists of different training activities that involve active manipulation of a 3D object being displayed on a computer screen. Active manipulation of a 3D object is achieved by performing various functions of the keyboard and mouse controllers within a computer-based 3D environment of Blender. The cognitive steps of MR have been used as the basis for the pedagogical design of tasks in TIMeR. We used the Blender tool as it is open-source with high-quality 3D visuals (Gumster 2003; Roosendaal 2011). It has been used for educational purposes in domains like biology (Andrei et al. 2012; Callieri et al. 2010), MR development (Kadam, Sahasrabudhe and Iyer 2012), computer science (Kadam et al. 2013; Mustaro 2011), chemical and physics lab experiments (Dere, Sahasrabudhe and Iyer 2010). Our research goal is to investigate the effect of TIMeR on students' ED problem-solving performance. To do this, we administered a pipeline of four research studies on 253 engineering undergraduates. The key results and contributions of this research include (i) TIMeR was found to be effective in improving ED problem-solving performance (ii) TIMeR was successfully integrated into an ED course.

2. Mental rotation and ED learning

Mental rotation includes visualisation of a 3D object which is complex. Therefore, performing the transformations between 2D projections and 3D views of objects becomes difficult (Akasah and Alias 2010; Jiannan 1998; Kosse 2005). Instructors also find it challenging to explain the 3D concepts of orthographic and isometric views (Khabia and Khabia 2012; Sutton, Heathcote, and Bore 2005; Upadhye, Shaikh, and Yalsangikar 2013). The persistence of these learning difficulties in ED raises the question of what are the fundamental reasons for the continued existence of such problems? One of the potential reasons is students' poor spatial skills (Medupin et al. 2015). Arrays of researchers have emphasised that spatial skills are essential for the learning of ED concepts (Alias 2000; Kadam et al. 2015; Khabia and Khabia 2012). Consequently, for the successful learning of such courses, students should be trained to acquire these skills (Alias 2000; Leopold, Gorska, and Sorby 2001; Nagy-Kondor 2007).

Gould (2012) suggests that a 'skill' contains a 'knowledge' component and a 'doing' component and is defined as 'an organized pattern of mental and/or physical activity.' To perform a skill, it is desired for the learner to possess the knowledge of what has to be done and the sequence in which it has to be done. This view, essentially, reasserts Senemoğlu's (2005) suggestion that problem-solving in any domain requires both subject matter knowledge ('knowledge' component) and selection of appropriate cognitive strategies ('doing' component) (Senemoğlu 2005). Skill training should take care of the improvement of both 'knowledge' and 'doing' components. For problem-solving in any domain, the balance of these components may differ (Gould 2012), for example, swimming will have a greater 'doing' component, whereas using a computer will have a greater 'knowledge' component. However, irrespective of the relative proportions, all skills will possess elements of each component. Therefore, to train students on ED skills, one needs to focus not only on the associated 'knowledge' components, such as conceptual understanding of views, shapes, different types of projections, and others, but also on the 'doing' component, such as mental rotation. In addition to the 'knowledge' component, our work explicitly addresses the 'doing' component of the problem-solving skill in ED to support students' ED learning.

Existing research has shown that MR has significant importance in the engineering domain and can be improved by training (Alias 2000; Khabia and Khabia 2012; Maier 1994; Norman 1994; Olkun 2003; Pillay 1994; Sorby 2009; Voyer et al. 1995). The MR training methods involve physical training (Flusberg and Boroditsky 2011), manual training (Wiedenbauer, Schmid and Jansen-Osmann 2007), computer-based training (Contero et al. 2005; Samsudin, Rafi and Hanif 2011), computer-aided design training (Sorby 2009; Kinsey, Towle, and Onyancha 2008; Martin-Dorta, Saorin and Contero 2008; Yue 2008; Godfrey 1999; Turner 1997; Gillespie 1995; Zaiyouna 1995), video games, animations (Froese et al. 2013), ED activities and many more. These existing methods were useful in spatial skills development and assessment; however, they focus on multiple spatial skills (such as visualisation, MR, paper folding) at a time, rather than on any individual skill. The focus of training and assessment on multiple skills at a time may affect the development and evaluation of an individual skill. Such training sessions had longer durations (spread over weeks), with only a few exceptions. Although many works carried out in the ED domain emphasise the importance of spatial skills, especially MR, they did not examine the effect of MR training on ED problem-solving. They just investigated the effects of different training only on spatial skills. This helped us in fine-tuning our research agenda from 'improving ED problem-solving skills with computer-based training' to a more specific research goal of 'improving students' ED problem-solving through MR training using a 3D visualization tool.' The details of how MR forms the basis of our proposed pedagogy are provided in the next section.

3. Design and development of TIMeR pedagogy

The cognitive steps involved in solving MR problems (Johnson 1990) are as shown in Figure 1. The initial step of forming the mental representation requires careful observation of an object and imagining all the aspects of a 3D form of that object. The different aspects include geometrical forms, views (top, front, side, back, and 3D), faces, shapes, edges, vertices, dimensions, and orientations. Once the mental image of an object is formed, it would require imagining different axes (x, y, and z or an arbitrary axis) to do the mental rotation. In the next step, it would be likely to have multiple mental rotations resulting in multiple mental representations of that object. The comparison and judgment steps would allow having a comparison of the current rotated mental representation of an object with the standard figure.

The key idea of TIMeR is to improve students' ED problem-solving skills by fostering their MR processes. Therefore, the cognitive steps of MR have been used as the basis for the pedagogical design of tasks in TIMeR. TIMeR pedagogy uses these cognitive steps of MR and has three phases: (i) the preparatory phase, (ii) the training phase, and (iii) the transfer phase. Each phase has a hands-on MR training activity that is tightly coupled with MR cognitive steps. Each phase is executed using

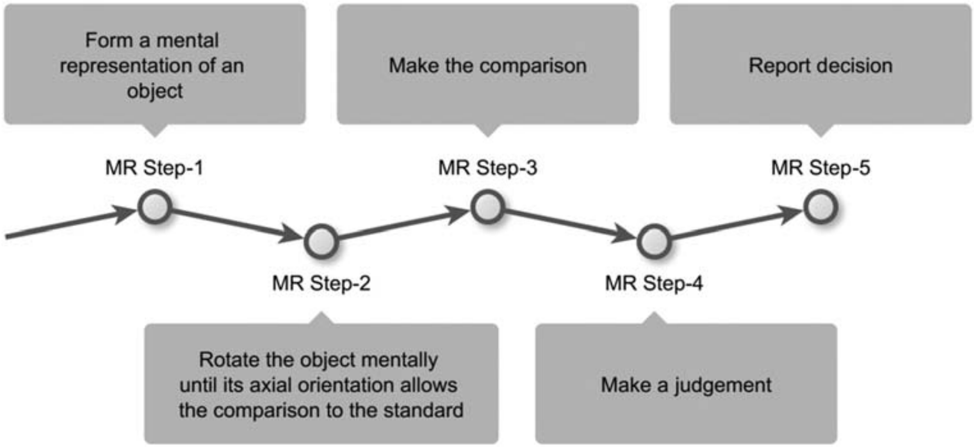

Figure 1. Cognitive steps of MR.

the instructional strategy of demo-drill-practice (DDP), which is based on demonstration and practice-based methods of teaching (Gould 2012; Kadam, Sahasrabudhe and Iyer 2012). To support the selection criteria of pedagogical elements (use of visualisation tool, interactive tasks, and instructional strategy: Demo-Drill-Practice) and also to support our findings, we have used common coding theory as a theoretical basis. As per common coding theory, the perception, execution, and imagination of movements (actions or events) are connected by a common neural representation (i.e. common code). This connection allows movements in any of the modalities (say perception) to activate movements in the other two modalities (execution and/or imagination) (Chandrasekharan et al. 2010). Mental rotation is treated as imagination or action in imagination, and as per the common coding theory, this action in imagination is triggered and hence improved by the actual actions and the perception of those actions that are performed on an object on the screen during the training. An overview of TIMeR is illustrated in Figure 2, which provides the structure of each phase, which has several elements as Prerequisite, Instructional Goal, Task, Rationale, Expected Outcome, Tools and Material, Common, and Different. These elements are explained below.

The **Prerequisite** is the prior condition mandatory for participating in the TIMeR phases. For participating in the preparatory phase, the student must complete the pretest. For participating in the Training Phase, it is mandatory to complete the preparatory phase. Similarly, to participate in the transfer phase, it is mandatory to complete the training phase. An '**Instructional Goal'** in TIMeR phases (in Figure 2) describes what students should be able to do after undergoing a distinct unit of instruction in that phase. A '**Task'** is the training activity to be accomplished for achieving an instructional goal within the scope of a particular TIMeR phase. The approximate time required for task execution is shown in the bracket. The training phase has single or multiple tasks, where the main task is broken down into subtasks for achieving the goal. Each TIMeR task has a specific '**Rationale,'** which is the logical basis for a course of actions involved in that task. An '**Expected Outcome'** indicates what the TIMeR phase is intended to achieve in terms of students' learning and behaviour after the completion. The '**Tool and Material'** are the training tools and training materials provided to the students to accomplish the training task. Students were provided with a computer having a Blender tool installed, Blender executable files of 3D objects created in Blender, and the instruction hand-outs. '**Instructional Strategy'** indicates the instruction method used to execute the TIMeR tasks to meet the various instructional goals. We have used Demo-Drill-Practice (DDP) for executing all tasks, where the tasks were demonstrated and assisted by the instructor (*Demo*), followed by the students performing the practice (*Drill*). The *Demo* part ensures students acquiring the knowledge required to perform the task. The *Drill* part ensures

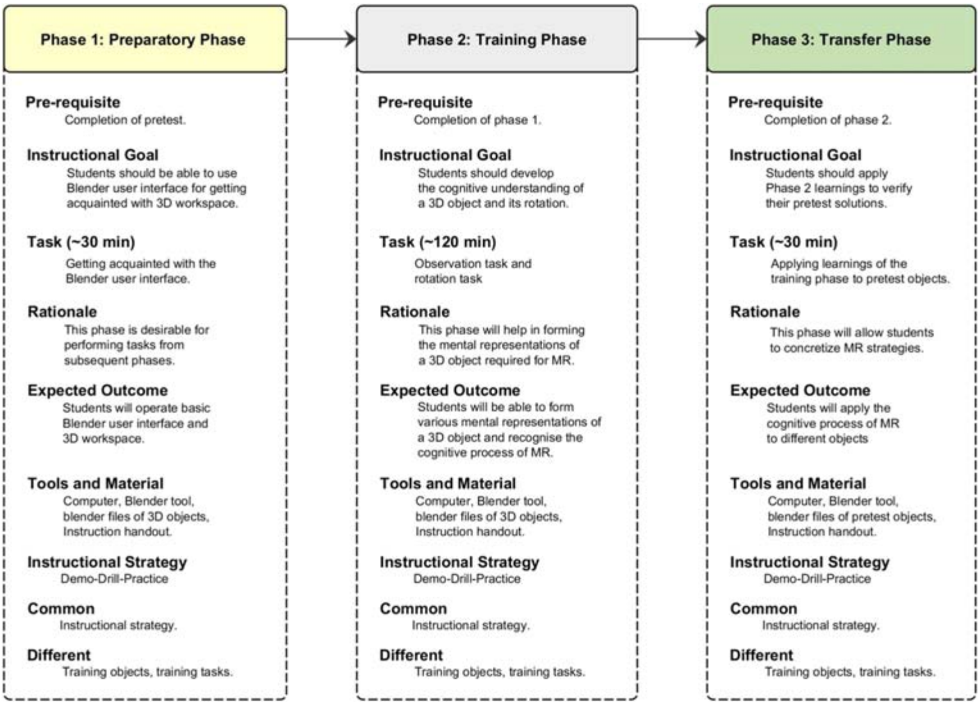

Figure 2. TIMeR overview.

students perform the task sequentially by repeating it instantly as they see the demo, which also ensures the retention of the mental representation acquired during the demo part. Finally, the *Practice* part ensures that students have performed a sufficient amount of rehearsal of the task. '**Common'** indicates the things that are common in all three phases, whereas '**Different'** indicates the things that are not common in all three phases.

4. Research methodology

We administered a pipeline of four quantitative research studies, as shown in Figure 3, to answer the research question (RQ): How effective is TIMeR for improving engineering undergraduate students'

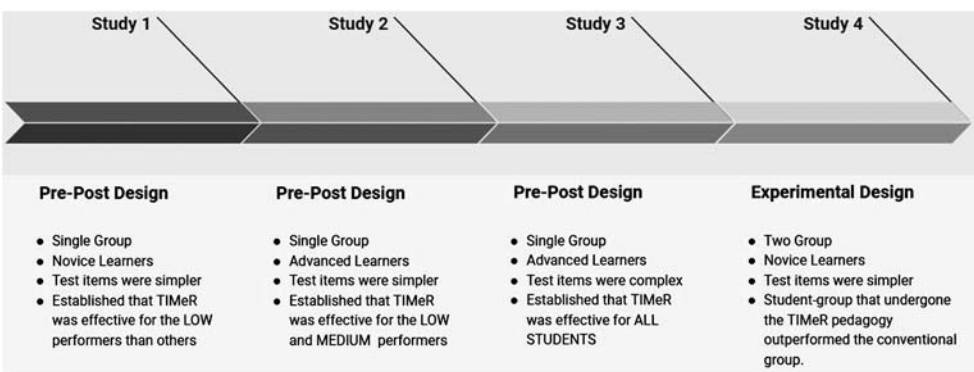

Figure 3. Overall research design.

ED problem-solving performance? The first three studies had a single-group pretest-posttest design, and the last study had a two-group experimental design. The single-group pre–post design enabled us to investigate the change in the performance of the same set of participants due to TIMeR, while the two-group design enabled us to compare the performance of students in the treatment (TIMeR) group and the students in the control group (conventional instruction) to confirm the effect of TIMeR. It should be noted that in each of the four studies, there were incremental variations in design to cater to our research inquiry path. Study 1 was to test the effect of TIMeR on novices, while Study 2 assessed the effects on advanced learners. Study 3 was also administered with advanced learners but used complex test-items to investigate if the effect of TIMeR was also on the high-performers. This could not have been tested in the first two studies that had test-items too easy for the high-performers to show any pre–post gain. Study 4, on the other hand, had helped us validate causality, i.e. the pre–post gains in the first three studies were caused due to TIMeR. We discuss each of these studies in the subsequent sections.

4.1. Participants

Across the four studies, a total of 253 students participated (156 novice and 97 advanced learners). The novice learners were the first-year engineering undergraduates who were learning ED. The advanced learners were second-year engineering undergraduates who had prior knowledge of ED. We used a convenient sampling technique, ensuring equal distribution by random assignment as applicable to individual studies.

4.2. Instruments and data collection

The instruments used in the pretest and posttest of the first, second, and fourth studies were taken from Spatial Visualization Ability Test Instrument (SVATI), (Alias 2000). SVATI is a set of multiple-choice questions, and we considered only ED problems from the test set. The problems involved in all of the tests were: (a) Conversion of isometric view to orthographic views, (b) Conversion of orthographic views to an isometric view.

4.3. Data analysis procedure

The quantitative analysis was performed in the form of descriptive analysis such as means, standard deviations, and learning gains. For deciding which statistical test to be used for comparing the means, we tested the data for normality using Shapiro-Wilk's test of normality (Shapiro and Wilk 1965; Razali and Wah 2011). We performed t-test analysis for normal data, and Mann–Whitney test or Wilcoxon test as per the suitability of the research design and sample size of the individual studies. For analysis, we used the significance level of 0.05 (5%). We also computed learning gains (Marx and Cummings 2007) and the effect sizes (Cohen, Manion and Morrison 2007), to get a measure of gains in the pre to post-test performance and a measure of how important a gain is.

5. Study 1: evaluating the effect of TIMeR on novice learners

Study 1 aimed at testing the effectiveness of TIMeR on the ED problem-solving performance of novice learners who were 114 first-year engineering undergraduates. This study follows a single-group pretest-posttest design, as shown in Figure 4. The study started with a fifteen-minute ice-breaker activity emphasising the importance of MR skills by practicing an ED problem. The training session (TIMeR, as presented in Figure 2) was administered for three-hours. Pretest and posttest were administered for fifteen-minutes with four ED items from SVATI. A sample problem is shown in Figure 5. Students had to solve the test individually. After the pre and post-tests, students were given fifteen-minutes to think about the test problems, their solutions, and to reflect (in a written

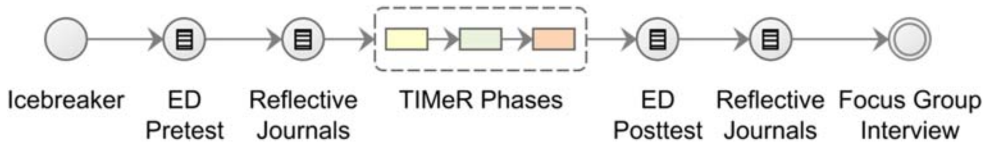

Figure 4. Research design used in Study 1, 2 and 3

form) about the difficulties faced while solving the test. At the end of the study, few students volunteered to participate in a focus-group interview. It should be noted that the analysis of the qualitative data obtained from journal writing and interviews are out of the scope of this research paper. The 3D primitive objects were used as the training objects for the first two phases of TIMeR. For the transfer phase, ED objects (Figure 6) from the pretest were used. For instance, the pretest object from Figure 5 is modelled in Blender and shown in Figure 6 (d), using a Quad-View feature.

For each of the pretest and posttest, out of the four assessment items, the first two were on (i) Conversion of isometric view to orthographic views. The other two items were on (ii) Conversion of orthographic views to an isometric view. Each question weighed one mark.

5.1. Study 1 results

We performed a quantitative analysis of the pretest and posttest for all 114 students. Based on the normality test results, we chose to use the Wilcoxon Signed Rank Test to see how significant the improvement in students' scores is. For our analysis, we used the significance level of 0.05 (5%). We also determined the effect size of the improvement and computed average gain (Marx and Cummings 2007). To look into the effects at a more granular level, we performed the same analysis separately for the students at different pretest-achievement levels: low, medium, and high. The minimum and maximum achievable score for the pretest is zero and four, respectively. To decide the three achievement levels based on the pretest score, we formed three clusters by dividing the maximum score (four) with desired levels (three). It resulted in three ranges of scores, that are between 0 to 1.33 (low-performers), between 1.34 to 2.66 (medium-performers), and between 2.67 to 4 (high-performers). Table 1 provides the quantitative results of Study 1.

As Sorby (2009) and Voyer and Saunders 2004 suggested that MR skills are needed for solving specific ED problems, we hypothesised that the TIMeR session should have been beneficial for improving students' ED problem-solving performance. Study 1 has proved this hypothesis by showing that for the whole class, there was a significant improvement in the ED problem-solving performance. However, when we looked at a more granular level, we found that TIMeR was significantly beneficial for the low-performers only (with a large effect size). Still, we cannot conclude the same for the medium and high-performers from the result, as for the medium-performers the effect was positive (with a small effect size) but not statistically significant. For the high-performers, the result was negative (with a small effect size) but not statistically significant. With this evidence, we claim that the TIMeR session has a significantly positive effect on the improvement of low-

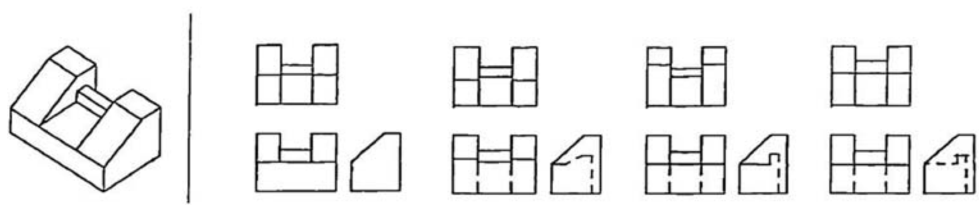

Figure 5. ED sample pretest item (reproduced from SVATI, Alias 2000).

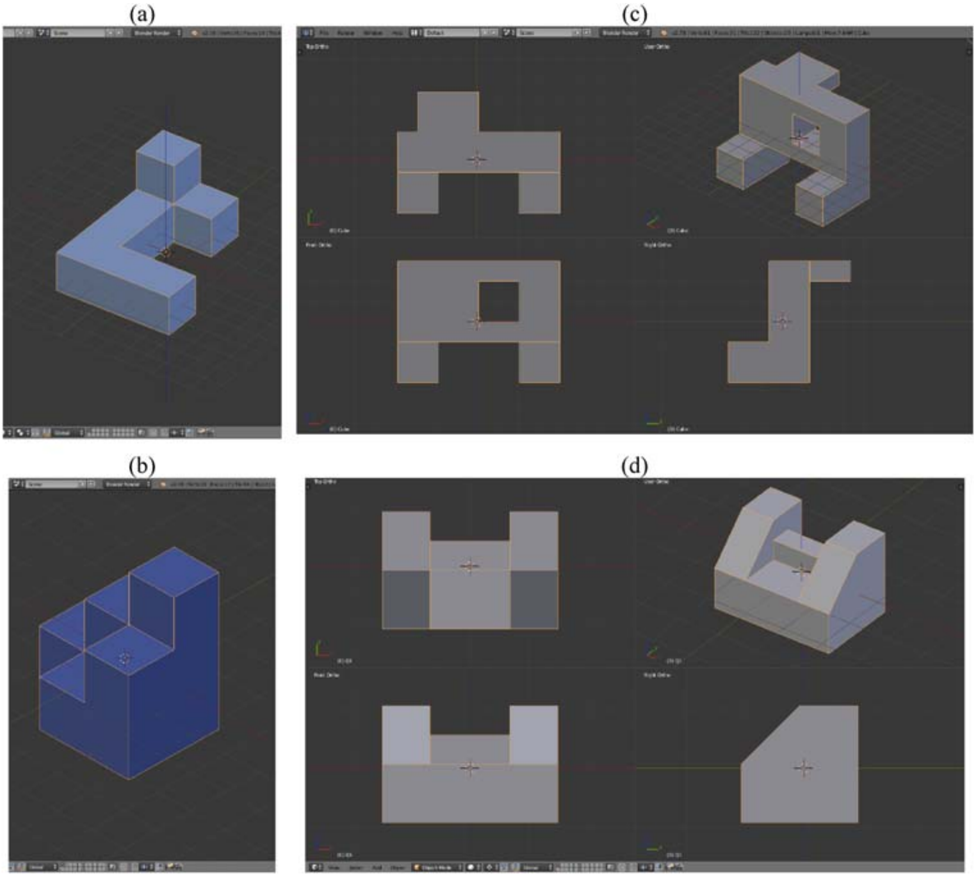

Figure 6. ED practice objects.

performers' ED problem-solving performances. The results from the study until this point could not provide us with any conclusive inference about the effect of TIMeR pedagogy on the medium and high-performers. In Study 2, we focus on advanced learners who have already studied the ED course before. We would be focusing on the advanced learners with a conjecture that most of the advanced learners should fall in the category of medium and high-performers.

6. Study 2: evaluating the effect of TIMeR on advanced learners

This study aimed at testing the effectiveness of TIMeR on the ED problem-solving performance of the advanced learners. We repeated the research procedure of Study 1 with advanced learners. The participants in this study were 59 s-year engineering undergraduates, and these students have

Table 1. Results – Study 1.

	Overall	Low-Performers	Medium-Performers	High-Performers
N	114	32	43	39
Pretest mean	2.07	0.71	2.00	3.28
Posttest mean	2.49	2.25	2.13	3.07
p	0.001	0.000	0.420	0.102
Effect size r	0.21 (med)	0.55 (large)	0.08 (small)	0.18 (med)
Learning gain	0.22	0.46	0.06	−0.29

completed the ED course in their previous academic semester. The research study design applied for Study 2 was a single-group pretest-posttest.

6.1. Study 2 results

We performed the data analysis by following the same method as in Study 1. Table 2 provides the quantitative results of Study 2 for the overall class and for different pretest achievement levels where low, medium, and high-performance criteria were the same as in Study 1.

From Table 2, we can see that only 7 out of 59 students (i.e. 11.9%) fell in the low-performers group. Low and medium-performers together form only 25% (15 out of 59) of the whole sample, and 75% fell in the high-performers. It was contrary to the experiences in Study 1, where the high-performers were just 34% of the total sample. This indicated that our decision of choosing 'advanced learners' to study more about the high-performers was right. The results for the low-performers, however, with a small sample size of 7, again corroborate the findings of Study 1 by showing that the low-performers' performance improved significantly. The results concerning the medium-performers have shown significant improvement, which is an encouraging result about the effect of TIMeR. On the other hand, the 44 high-performers did not show any significant increase or decrease in their performance. This has again strengthened the claim that TIMeR pedagogy is effective for the low-performers and has also left the question about the effects of TIMeR on the high-performers unanswered. The 'no-effect' results in Study 1 and Study 2 about the effect of TIMeR on the performance of the high-performers may be due to two possible reasons: (i) either TIMeR pedagogy really does not have any effect on the high-performers, or (ii) the assessment items are too simple to gauge the effect on them. In the next study, we explore the second reason. We repeated the same procedure with a new set of assessment items, which were more complex to be answered.

7. Study 3 – Evaluating the effect of TIMeR on advanced learners with complex assessment items

Similar to Study 2, the purpose of this study is to investigate the effectiveness of TIMeR on the ED problem-solving performance of advanced learners. The only difference from Study 2 is that we have used a different assessment instrument where the questions are more complex, as they need to be answered in the form of making drawings instead of answering MCQs. For example, students are shown an isometric view of an object and have to draw various orthographic views for the same. For Study 3, we followed the same research and training procedure as in Study 1 and Study 2. The participants in this study were 38 s-year engineering undergraduates. These students had completed the ED course in their previous academic semester.

7.1. Study 3 results

Study 3 results are shown in Table 3. This study has revealed a new result about the effect of TIMeR on advanced learners. The minimum and maximum achievable score for the pretest and posttest is

Table 2. Results – Study 2.

	Overall	Low-Performers	Medium-Performers	High-Performers
N	59	7	8	44
Pretest mean	2.983	1.000	2.000	3.477
Posttest mean	3.288	2.857	3.500	3.318
p	0.068	0.026	0.014	0.289
Effect size r	0.167 (small)	0.596 (large)	0.612 (large)	0.113
Learning gain	0.299	0.619	0.75	−0.30

Table 3. Results – Study 3.

	Overall	Low-Performers	Medium-Performers	High-Performers
N	38	12	26	0
Pretest mean	2.81	1.25	3.53	-
Posttest mean	3.76	2.83	4.23	-
p	0.001	0.002	0.030	-
Effect size r	0.386 (medium)	0.622 (large)	0.300 (medium)	-
Learning gain	0.182	0.234	0.155	-

zero and eight, respectively. To decide the three achievement levels based on the pretest score, we formed three clusters by dividing the maximum score (eight) with desired levels (three). It resulted in three ranges of scores, that are between 0 to 2.66 (low-performers), between 2.67 to 5.33 (medium-performers), and between 5.34 to 8 (high-performers). The results show a significant positive effect of the TIMeR pedagogy on these learners. It should be noted that we did not get any students in the high-performers category. This shows that the new assessment instrument was difficult for all of the participants.

The primary objective of this study was to examine the effect of TIMeR on the 'high-performers.' But the 'high-performers' that we were interested in were those who performed 'high' according to the original assessment instrument, i.e. multiple-choice questions, as in the first two studies, and not according to the new instrument, i.e. drawing questions. We could not use the original instrument (MCQ) as the pretest in this study because we wanted to keep the test-items difficult to answer. Therefore, the only way to understand the effect of TIMeR on the 'high-performers' we were interested in was to use the finding from Study 2 that most (75%) of the advanced learners fell in the high-performers category. With this, we can comfortably assume that the advanced learners in the current study should have mostly fallen into the high-performers' category, had there been the original assessment instrument used in the pretest. So, we use the results for all of the advanced learners in Study 3 to comment on the effect of TIMeR on high-performers. The significant positive effect of the TIMeR pedagogy on these advanced learners shows that TIMeR has positive effects on the ED performance of even high-performers. Still, the effects on them are evident only when we use difficult assessment instruments.

8. Study 4 – integrating TIMeR in an ED course

Though we had significant results for single-group pretest-posttest research design in the first three studies, we didn't administer any experimental research design to help us compare the effect of TIMeR with the effects of traditional ED instruction. In Study 4, we integrate TIMeR in an ED course and administer a two-group posttest research inquiry. The specific objective of the study was to compare the effectiveness of TIMeR with that of the traditional instruction on the ED problem-solving performance of novice learners. Moreover, Study 4 also presents a design of how one can integrate TIMeR in an ED course.

The participants in this study were 42 first-year engineering undergraduates. The experimental and control groups were created by randomised assignment. We refer to the group of participants who received TIMeR training as the TIMeR group, and another group of participants who received conventional classroom teaching, as the control group. The group size was 21 each. Three students from the TIMeR group and five from the control group could not attend all the sessions, resulting in the actual group size of 18 and 16, respectively.

Procedure for the Experimental Group: The procedure for the TIMeR group is shown in Figure 7. We conducted two implementations of TIMeR. For each implementation, we split TIMeR training into two sessions. We did this splitting because we wanted to accommodate and execute the study in the in-situ conditions similar to conventional instructions, where instruction requires two sessions

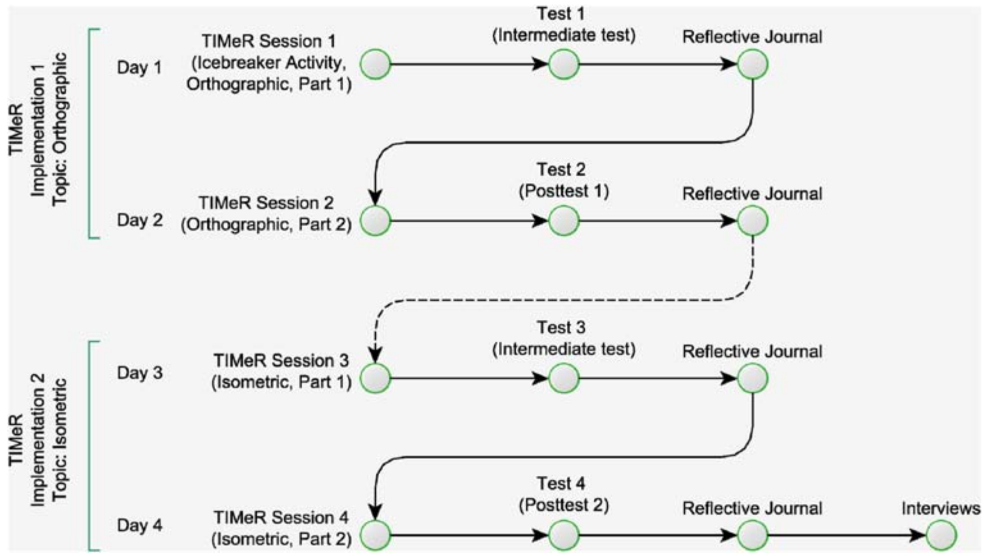

Figure 7. Instructions for TIMeR group.

of regular lab hours for the same ED topic. The first of the two sessions administered the preparatory and training phase of TIMeR pedagogy, and the second session administered the transfer phase of the TIMeR pedagogy. The overall study was conducted in four regular lab sessions of two hours each per day. We administered two assessments in each implementation: one after the first session that we refer to as 'intermediate test,' and the other after the second session that we refer to as 'posttest.' We administered the intermediate tests (Test1 and Test3) in the two implementations such that the students can use test-items from the intermediate tests as practice problems in phase 3 of TIMeR. The second assessments (Test2 and Test4) were used as the posttests and were administered at the end of each implementation. In addition to the TIMeR sessions and the assessments, students were also asked to write their journal entries about challenges in problem-solving.

Procedure for the Conventional Group: The conventional group students received two implementations of the conventional teaching of ED in four sessions on four separate days (Figure 8). The duration of each session was approximately two hours. Similar to the experimental group, Implementation 1 (sessions 1 and 2) used problems on 'orthographic projection,' while Implementation 2 (sessions 3 and 4) used problems on 'isometric projections.' At the end of every session, we conducted the same tests on ED problems. Here again, after each test, we collected students' reflective journals to understand their perceptions of the learning difficulties in ED while solving the tests. Additionally, at the end of all sessions, we conducted students' interviews to get a deeper understanding of learning difficulties.

The data for both the groups were gathered in the form of performance scores of tests of ED problems which were SVATI and ED exercise book questions (Bhatt 2011, Earle 1967, 1968, 1969; Sorby, Wysocki and Baartmans 2003). A total of four tests were conducted, and each test consisted of four items. Test1 and Test2 had questions on orthographic projections, where for a given isometric view, students must identify the correct set of orthographic views. Test3 and Test4 had questions on isometric projections, where for a given set of orthographic views, students must identify the correct isometric view. For each correct answer, they got one mark. Test duration was twenty-minute.

We performed a quantitative analysis by first doing the normality test. Since the data showed no normal distribution, to test the differences between two independent groups (TIMeR and Conventional group), we performed the non-parametric Mann–Whitney test. We calculated the means, standard deviations, effect size, and learning gain. To see if there is a significant difference between the

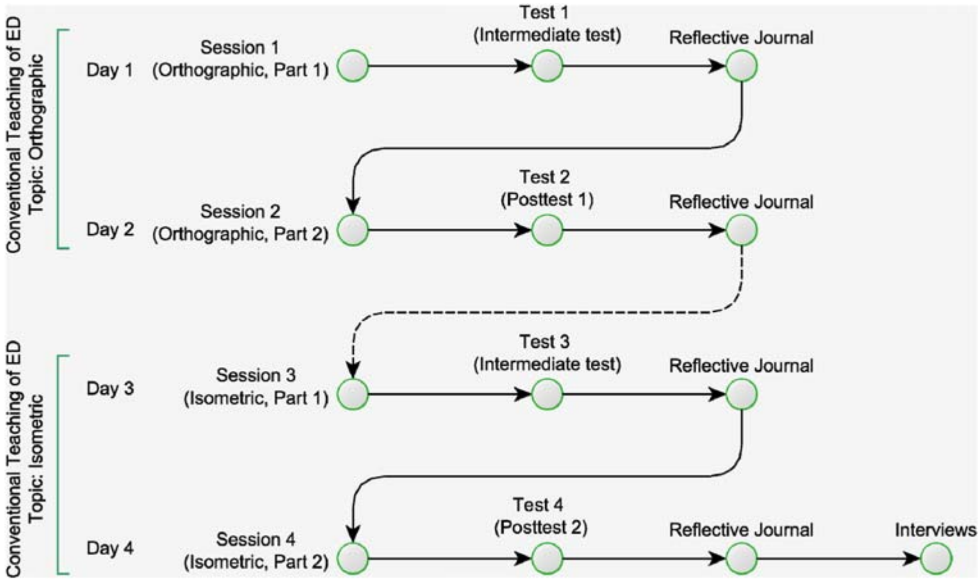

Figure 8. Instructions for conventional group.

performance of two tests for each topic, we also performed a Wilcoxon signed-rank test within the group for both the groups. For our analysis, we used the significance level of 0.05 (5%). Tables 4 and 5 provide the quantitative results of Study 4 for between-group and within-group, respectively.

In the current study, it has been shown that only partial execution of a TIMeR session cannot give the desired improvement, as the TIMeR group did not score statistically better than the conventional group in the intermediate tests (Table 4). Another usefulness of the results of the intermediate test is that they validate the fact that both the TIMeR group and the conventional group were equivalent, and the random assignment has produced the desired group equivalence.

Table 4. Results of Study 4 (between group).

	Test1	Test2	Test3	Test4
TIMeR Group (Mean)	4.00	7.44	5.77	7.00
Conventional Group (Mean)	3.87	6.12	4.75	4.25
p	0.834	0.036*	0.150	0.000*
Effect size *r*	0.036	0.359	0.246	0.673
	Small	Medium	Close to medium	Large

Table 5. Results of Study 4 (Within group, topic-wise).

	Orthographic Projection		Isometric Projection	
	TIMeR Group	Conventional Group	TIMeR Group	Conventional Group
N	18	16	18	16
Test1	4.00	3.87	5.77	4.75
Test2	7.44	6.12	7.00	4.25
p	0.001*	0.010*	0.022*	0.449
Effect size r	0.575	0.454	0.382	0.133
	Large	Close to large	Medium	Negative
Learning gain	0.86	0.55	0.54	−0.15

The analysis of the tests for both implementations shows that the students who undergo the TIMeR sessions have outperformed the conventional group students (Table 5). This has further corroborated the results obtained in all previous studies that the TIMeR pedagogy is effective in improving students' ED problem-solving performance. This time it is more effective than the conventional teaching method. This study has demonstrated one instance of how to integrate TIMeR in a regular ED curriculum. Normally, a single implementation of full TIMeR pedagogy takes around three hours. We see that, in the current implementations, we split the TIMeR implementation into four sessions. We also see that if students have undergone the preparatory phase once, they get familiarised with the 3D environment of Blender. Hence, the next implementations of TIMeR do not need the preparatory phase again.

9. Discussion and conclusion

This research was set to evaluate the training effectiveness in improving students' performances in ED problem-solving. The results from Study 1 have demonstrated that TIMeR was significantly effective only for the low-performers and not for the medium and high-performers. Therefore, Study 1 could not help infer anything certain about the effects of TIMeR on the majority of the cohort (medium and high-performers). Study 2 has re-confirmed the 'no-effect' on the high-performers that we found in Study 1. However, this time it was effective for the medium-performers, in addition to the low-performers. These non-significant effectiveness results for the high-performers could have been due to two possible reasons – either the TIMeR was ineffective for high-performers, or the high-performers found the test-items in the pre and post-tests so simple that they could have performed equivalently in the pre and post-tests irrespective of TIMeR intervention. To address these speculations, we used complex pre–post test items that were difficult for all of the advanced learners in Study 3. The pretest results of Study 3 have shown that the test-items were complex enough for all advanced learners, as none of the participants could achieve high performance scores. The results of Study 3 showed that TIMeR has significant positive effects on the students of all performance levels. Finally, Study 4, with an experimental design, showed that TIMeR is significantly more effective in improving students' ED problem-solving performance for the treatment group as compared to the conventional ED-training group. All the four studies together confirm that TIMeR improves ED problem-solving skills for students from all performance strata (low, medium and high). These results address the gap in the literature (Froese et al. 2013; Norman 1994), where training is effective only for the low-performers.

Looking closely at the learning activities in TIMeR with the theoretical lens from cognitive science, we can get a possible explanation of why the Blender-based MR training (TIMeR) enhances students' MR process. MR is essentially an imagination process where one needs to visualise rotations of a 3D object. If we wish to improve students' MR processes, one of the ways is to make them foster and practice these imagination actions. But, how does the students' interaction with the activities in TIMeR foster these imagination actions? One of the plausible explanations comes from the research studies in the field of cognitive science and neuroscience that have provided a model of cognition where a common coding in the brain is shared by perception, execution, and imagination of movements (Decety 2002; Hommel et al. 2001; Prinz 1992). This common coding allows any one of these movements to generate the other two movements automatically (Chandrasekharan et al. 2010; Decety 2002; Hommel et al. 2001; Sebanz, Knoblich, and Prinz 2005; Wohlschläger 2001). The TIMeR tasks require learners to perform the cognitive actions of observing (*perceiving*) rotation of 3D objects and performing (*executing*) rotation of 3D objects, by active manipulation of 3D objects through controllers (mouse and keyboard), in the demo, drill and practice stages across different phases of TIMeR. We see that the demo stages in TIMeR have made the students watch (*perceive*) the demonstration of MR tasks, shown by an instructor, that allows them to perceive the process involved in MR. During the drill stages in TIMeR, the students perform (*execute*) the MR task using a keyboard and mouse; and at the same time, they also observe (*perceive*) it on the computer screen. During the practice stage, they repeat all the training actions of the drill stage but on different objects, which again allows them to perform the *execution* and *perception* of the MR task. Given the theoretical lens of *common coding*, the repeated practice of *perception* and *execution* of rotation of 3D objects throughout the TIMeR session lead to the repeated activation of the *imagination* of rotation of 3D objects in students' minds. The repeated activation of *imagination* further influences other activities, for example, performing similar tasks (such as other phases of TIMeR) or solving the posttest (such as MR problems). The results of this research are in line with the common coding theory where the MR is treated as 'imagination' or 'action in imagination', which is fostered by the actual actions (training tasks) that are performed on the objects (using controllers) on the screen. This explains how the learning activities in TIMeR reinforce the imagination tasks in the student that further helps improve the problem-solving performance.

We successfully operationalised the cognitive steps of MR into TIMeR tasks so that the mental process can be viewed as well as carried out by utilising the 3D tool and controllers. It supports the user in visualising the representations, which are difficult to do so without any medium. Several implications related to MR training emerged from this paper, as this operationalisation would be useful for the researchers and the teachers, which they can adapt to MR skill training. It would be beneficial for students to understand the underlying mechanism of visualisation skills similar to MR. It would also be useful for the developers for the design and development of teaching-learning environments similar to TIMeR. In addition to the ED concepts, our training method would be useful for learning all the other topics where 'mental rotation' is involved. For example, 3D transformation topics in computer graphics, computer-based 3D modelling, mechanical engineering, and stereochemistry concepts.

Overall, the research results provided an insight into how different learners in different categories, novice and advanced, and low, medium and high-performers, demonstrate the effects of TIMeR. The future work here is to implement the training method to a large-scale spatial skills development programme for first-year engineering students. A possible and needed extension of this research would be to do an in-depth investigation into the student behaviour using high granular data collection, such as tracking their eye movement while they interact with the computer screen during TIMeR tasks.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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