International Journal of Engineering Education Vol. 29, No. 5, pp. 1248–1259, 2013
Printed in Great Britain

0949-149X/91 $3.00+0.00

Cultivating Imagination in Entry-Level Civil Engineering Students: Exploring the Effects of an Innovative Instructional Model*

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Imagination, the limitless ability to form mental images and concepts through thinking, is inherent in human cognition as the basis for the creative activities and inventions that have driven human technological and engineering innovations. Imagination should be cultivated in the process of preparing future engineers. This study develops an imagination instructional model for entry-level engineering college students. Three features of imagination: possibility, connectivity and boundary-crossing, are established as the theoretical basis for an instructional model called IDEAL. This model was implemented in an introductory engineering course and its effect was evaluated. The results showed that: (i) The IDEAL model significantly increased students' overall imagination, and more especially, (ii) it significantly enhanced students' boundary-crossing capacity. This study makes contributions to current engineering education by first exploring the inherent features of imagination, constructing a workable instructional model for the cultivation of imagination, implementing the model to an introductory engineering course and showing its effect.

Keywords: engineering education; imagination; possibility; connectivity; boundary-crossing

1. Introduction

1.1 The need for imaginative engineers in a changing world

The rapid development of civil engineering has helped to make our lives more convenient than ever before. Infrastructure and public facilities, including buildings, airports, tunnels, dams, bridges, roads, and such, have become symbols of our advanced civilization. However, civil engineering has traditionally emphasized durability, solidity, and safety in the design and supervision of construction projects. Consequently, extensive professional knowledge and skills are the assumed prerequisites of a civil engineer. However, the rapid pace of globalization has increased and diversified the requirements for living spaces, buildings and public facilities. These changes are in turn affecting the field of civil engineering and the role of civil engineers [1].

Hence, to remain globally competitive, engineering firms rely heavily on creative individuals and teams to develop new products and drive the field forward. Taurasi [2] noted that 65% of engineers agreed that they needed to be more creative and innovative to be globally competitive. In fact, many engineering tasks require the engineer to employ great creativity to come up with imaginative and innovative projects to solve challenging problems. Therefore, traditional engineering education, which focuses mainly on mathematics and physics, is no longer sufficient for addressing the needs of modern engineers. There is a greater emphasis on the need for improving the imaginative/creative capacities of engineering students [3].

1.2 Challenges for engineering education

Since engineering is going to be more complex in the future, finding a method of teaching creativity to students has become a key concern in engineering education [4–5]. Zampetakis *et al.* [6] stated that 87% of current engineering students agreed that creativity was a prerequisite skill for engineering, and 77% said that they would like to take a course in creative problem solving. However, it is found that although engineering students have an increasing interest in creativity, the traditional engineering curriculum still emphasizes the basic sciences, such as physics, mathematics and mechanics, at the expense of the kind of problem solving that is specific to engineering [7]. Moreover, as the traditional training models for undergraduates have always been instructor-centred and knowledge-

* Accepted 10 May 2013.

based, students tend to be passive, unimaginative, overcautious, alienated and unconcerned with problems encountering [8–12]. For this reason, our educational system ought to train students to be active, imaginative, perceptive and adventurous. In response to current trends, recent reforms on engineering education have focused on infusing engineering curricula with more creative thinking. Many colleges have reformed their engineering curricula by providing more creative project-based design courses [13–18].

Although there is an increasing intent to provide more courses on creative problem solving and product design, there is, in general, a lack of specific emphasis on developing the imaginative capabilities of engineering students, despite several requests that this objective be incorporated into engineering curricula [19–20]. It is suggested that a rich imagination is an essential antecedent for creative processes to occur [21]. Some even claim that one's capacity for imagination reflects one's creative potential [22]. Therefore, in terms of cultivating creativity, imagination is an important antecedent that should be seriously studied and discussed [23]. Modern engineering education should foster the imaginations of engineering students.

Furthermore, it is found that innovative design courses have traditionally been offered only at the upper levels. In traditional engineering education, the freshman year is typically the cognitive stage, which involves encoding a skill or learning a set of facts relevant to the skill. During this stage, students are taught mathematical skills such as calculus, the principles of physics such as Newton's laws, and the fundamentals of engineering such as the strengths of materials and fluid mechanics. The advanced design courses are often offered as upper division capstone courses for senior students. Few introductory cornerstone courses have been offered for freshmen [7].

Some researchers have found that senior students are equipped with a wider reservoir of professional knowledge and skills than freshmen and are better prepared than freshmen for creative application of such knowledge to solving problems [9, 24–25]. Others have claimed that, since imagination is an innate endowment and cannot be taught, freshmen might be more inclined to employ creative imagination than their senior counterparts [7, 26–28] because they are less bounded by the fixed framework of professional training and skills. Still others have argued that imagination/creativity *can* be taught [25, 29], so it would be advisable to cultivate such an important capacity in the early stages of engineering education. We conclude that it is important to cultivate the imaginations of freshman engineering students in entry-level courses.

Therefore, the purpose of this study was, first, to explore the features of imagination; then, based on our findings, to develop a workable instructional model and apply it to a freshman engineering course; and finally, to assess its effectiveness in improving students' capacities for imagination.

2. Exploration and cultivation of imagination

2.1 Exploring the features of imagination

Imagination is the first step of all creative activities, so it should be vigorously studied and discussed. However, previous studies of human cognition have mainly focused on critical thinking, problem solving and creative thinking [30–32]. Little research has gone into the essence and characteristics of imagination, let alone to developing a concrete guiding model to cultivate it. Based on an extensive literature review, we concluded that imagination is a mental process characterized by the following three key features: possibility, connectivity and boundary-crossing.

2.1.1 Possibility

One feature of imagination is that it allows consideration of alternative possibilities. Imagination is based not only on actual experiences, but also on experiences that have never taken place [31, 33]. It is the capacity to open the mind and imagine possible alternatives, including alternative values, perceptions and/or aesthetics. It provides a licence to create experiences and possibilities [31]. Therefore, possibility is an important characteristic of imagination.

2.1.2 Connectivity

Another characteristic of imagination is connectivity. Imagination is the unifying force of the mind, the force that relates diverse cognitions, affections, experiences and memories to one another [33–34]. Psychologists have suggested that the process of imagining involves the creation of imagery through connecting multiple sources of ideas and images [35–36]. Li [37] believed that imagination operates through the reprocessing of existing memories to connect new images of things and events. Shen and Li [38] asserted that imagination unrolls when one's brain formulates new images, through the reprocessing of old images. Chen [39] suggested that imagination performs the operation of recombining existing images in the brain to make a new image. The aforementioned discourse implies that imagination, as a special and complicated thinking activity based on old cognition, affection and experience, generates new content through constituting, transforming and developing multiple memories and images. In this sense, imagination is a process of connecting.

2.1.3 Boundary-crossing

Boundary-crossing is another key characteristic of imagination. There are two distinct types of imagination: inventive and radical [31, 33]. The former is related to old memories or existing experiences, whereas the latter refers to the creation of experiences or phantasms that are not represented in any experience. Therefore, imagination may cross the boundaries from the inventiveness of previous experiences to the boundless territory that exists neither in reality nor in prior perceptions and experiences [35, 40]. It is a unique human mental process that constantly strives to cross the boundary of existing worlds. It is a bridge to connect the real to the unreal, from the known to the unknown, and thus imagination is oftentimes fanciful and fantastic [30, 32].

2.2 Cultivation of imagination

In sum, imagination is characterized by possibility, connectivity and boundary-crossing. An important question thus follows: Can imagination be cultivated? Could students be guided to develop their mental capacities for generating alternative ideas, to connect perceptions/experiences/affections, and to project their imaginings into the wild horizon of the unknown? For new learners, the root of the difficulty in imagining lies in the lack of a tangible process with concrete and clear guidance to follow in becoming engaged in the act of imagining.

The process of imagining is often cast as an innate endowment, flashes of inspiration, or even the illusions of a chaotic mind [39]. Thus, it is concluded, it is impossible to cultivate. However, some scholars have claimed that design abilities, including imagination, can be articulated, and that educational programs can develop these abilities in students [25, 29]. The authors take a similar stand that, as with any human cognitive faculty, imagination can be developed, nurtured and even trained. If we can unravel the features of the mental process of imagination and construct a procedure to facilitate such a process, then the cultivation of imagination becomes possible. Based on the above three characteristics of imagination, we propose an instructional model of imagination called IDEAL, which is intended to enhance individuals' capacities to construct possibilities, connect perceptions and ideas, and to cross the boundary from the known to the unknown.

3. The IDEAL model and the Think-Pad

Based on the three features of imagination, a training process that guides students to initiate, develop and link alternative uncommon and even non-existent ideas was constructed. It is called the IDEAL model because it consists of four stages: Initiation (I), Development (DE), Alternatives (A), and Links (L).

To make the IDEAL process tangible and operational in the instructional process, an instructional toolkit called the Think-Pad was developed. On the Think-Pad, three layers of concentric circles are provided for students to develop their ideas, from the common in the inner circle, to the uncommon in the intermediate layer, to the non-existent in the outer layer (Fig. 1).

3.1 Initiation

Initiation, the first stage of the IDEAL model, is intended to guide individuals to start from scratch, to go from having no ideas to generating various ideas. In fact, when one tries to imagine new ideas or possibilities, the most difficult part is usually deciding how to approach the issue. Once an initial idea is in place, others can usually follow more easily. Therefore, Initiation prompts one to start from scratch. In this stage, initial images/ideas are in

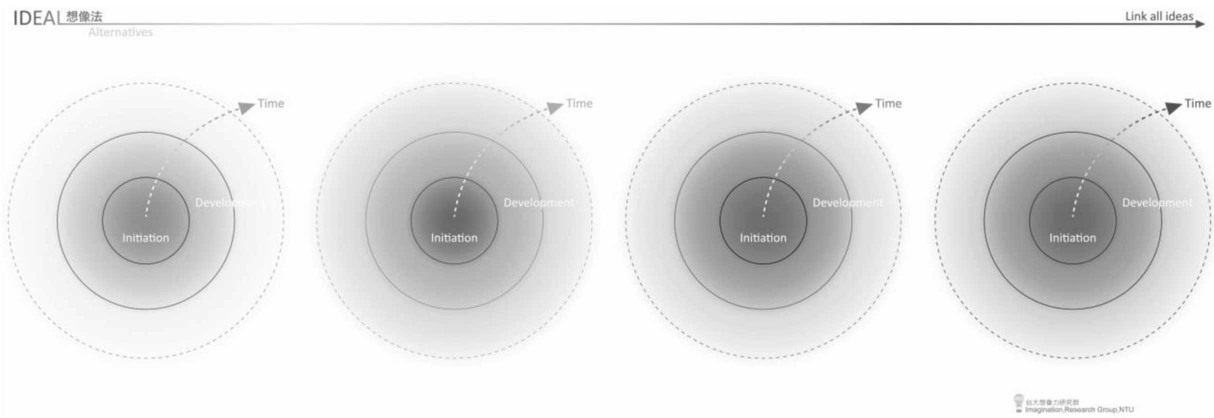

Fig. 1. IDEAL Think-Pad.

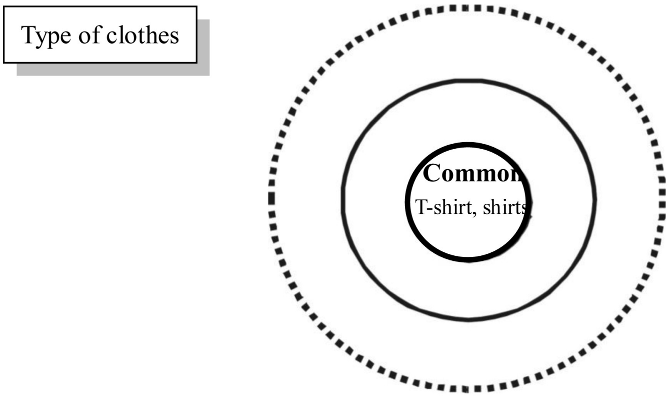

Fig. 2. Initiation: From no ideas to various ideas.

place that can inspire the imaginers to jump into a variety of new possibilities. In other words, this stage cultivates individuals' ideas with one feature of imagination, Possibility.

In our study, when demonstrating the use of the IDEAL Think-Pad, we provided students with an example of inventing clothes for the year 2060. Based on the IDEAL model, we divided the process of imagining such clothes into four stages: Initiation, Development, Alternative and Links. We started from the Initiation stage by guiding students to start thinking from the inner circle about the common types of clothes, such as T-shirts and button-down shirts (Fig. 2).

3.2 Development

After the initial ideas are in place, it is important to further expand the original ideas. The Development stage is intended to guide the process of expanding ideas. In this stage, original ideas are spread to form multiple new ideas. Many times, there are gaps between the ideas in the first stage and the goal; therefore, we have to develop these initial ideas into more feasible alternatives by dissociating, associating, recomposing, exaggerating or transforming them into more possibilities across different boundaries. In this stage, the original ideas are developed into some boundary-crossing new ideas and images, and individuals are guided to develop ideas with the three features of imagination: Possibility, Connectivity and Boundary-Crossing.

By using the IDEAL Think-Pad, students were guided to draw ideas on the second layer of the concentric circle to develop new ideas or images that were more 'uncommon' from those initial common ideas in the first layer of the circles. Back to our example of inventing clothes for the year 2060, in the second circle, uncommon but existing ideas for clothes were thus generated, including spacesuits and superhero suits. Students were further guided to draw ideas in the third layer of circles, crossing the boundary of the known. Using the example of future clothes, ideas that are non-existent, such as a 'liquid suit', were presented at this level (Fig. 3).

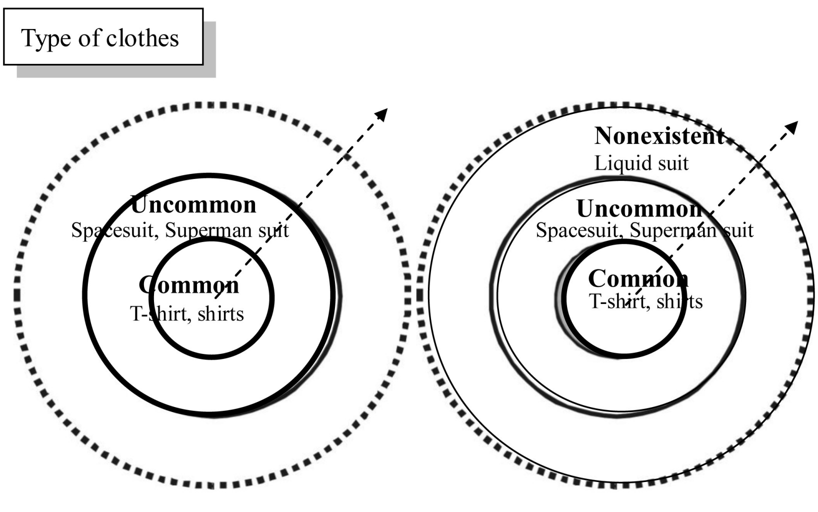

Fig. 3. Development: Expanding ideas.

3.3 Alternative

Students may sometimes get stuck in the process of Development if they only think from one perspective because the gap between the start and the goal can be too vast. Thus, based on the principle of 'possibility,' the Alternative stage guides students to launch a new beginning by taking an alternative perspective, starting at a new point, or regarding the goal as the start, so that new ideas will again flourish. Each new perspective can be taken as a fresh start, and the imaginers are encouraged to repeat the stages of Initiation and Development to combine and recompose ideas/images. In this way, the stages of the cycle of Initiation, Development, and Alternative reinforce each other and bring students to new horizons of imagining. This stage cultivates individuals' ideas with one feature of imagination: Possibility.

Returning to our example of inventing clothes for the Year 2060, in the third stage, new concentric circles were provided to further initiate and develop new ideas from alternative perspectives. In addition to the original 'types' of clothes, students were encouraged to think about alternative aspects of clothing, including the materials and functions of clothing. In terms of materials, the common ideas of 'cotton' and 'linen' can be further developed into the uncommon 'silica gel' and even transformed into a non-existent material such as 'anti-gravity metal.' In terms of function, the common idea of 'dress up' can be further developed into the uncommon one of 'fireproof' and even transformed into a non-existent function such as 'fly' and 'change shape' (Fig. 4). In this way, students are guided to initiate and develop new ideas from the common to the unknown by adopting alternative perspectives.

3.4 Links

Lastly, it is not enough to just initiate, alternate and develop one's ideas. Based on the principle of 'connectivity,' the final stage of Links is introduced to teach students to link ideas from the starting point to the goal with elaborate storylines and portrayals. During the first three stages, many ideas are generated and developed; students are encouraged to choose and link potential ideas by composing and decomposing different images/ideas into coherent storylines to reach the goal. In fact, they are encouraged to come up with multiple storylines and portrayals to solve the problem from different angles. Moreover, by comparing these varied solutions, one possible 'best' solution may be attained. This last step accomplishes the entire imagining process of IDEAL. This stage cultivates individuals' ideas with the three features of imagination: Possibility, Connectivity and Boundary-Crossing. It should be noted that, as the last step of the IDEAL model, it could also serve as the starting point for another round of imagining through Initiation, Development, Alternative and Links to cope with a new situation, or to solve a new problem. Back to our example of inventing clothes for the year 2060, at the fourth stage, all aspects (types, materials and functions) were linked as a whole to help create a well-narrated storyline for the clothing of 2060, which is portrayed as a 'flying liquid suit made of anti-gravity metal', as Figs 5 and 6 show.

To sum up, the IDEAL model and its Think-Pad transforms the abstract principles of possibility, connectivity and boundary-crossing of imagination into a well-structured and easy-to-follow procedure to facilitate the process of individuals' imagining. It is concrete, concise and operational and may be applied to a variety of instructional contexts to stimulate and facilitate learner's imaginations. It can be well applied to the context of engineering education, as described in the next section.

4. Research method

4.1 Research purpose

In order to examine if the IDEAL model with its instructional toolkit, the Think-Pad, is workable and effective for enhancing engineering students'

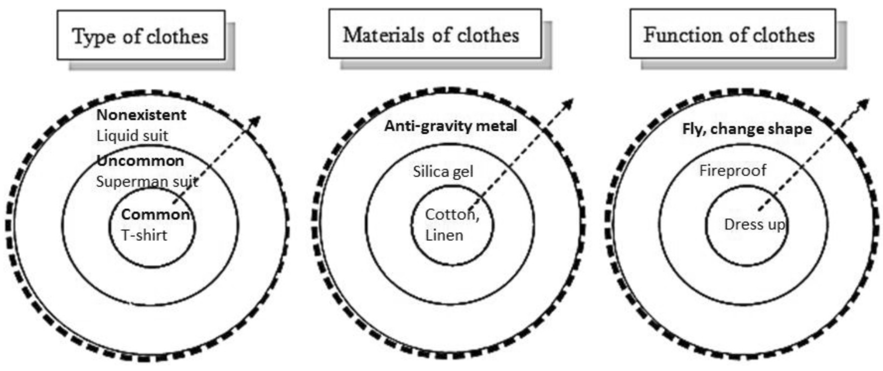

Fig. 4. Alternatives: Change a direction or find a new start.

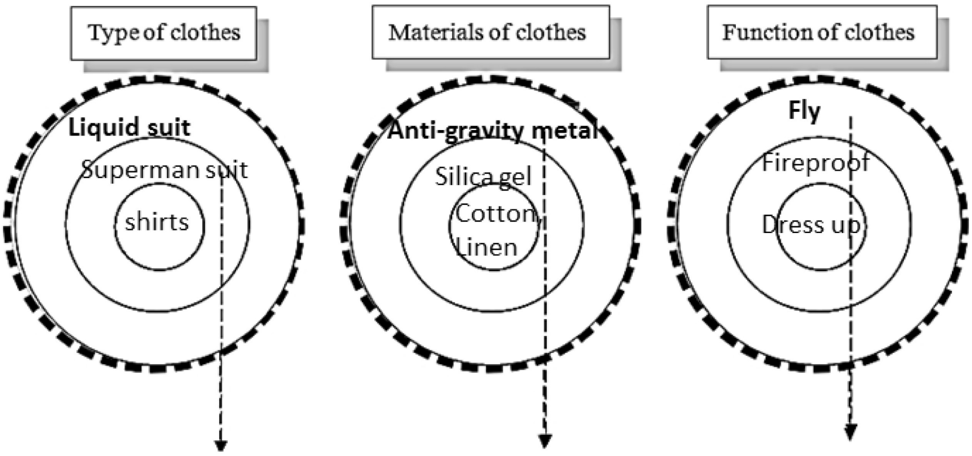

Fig. 5. Links: Link all ideas to achieve the goal.

capacities for imagination, an instructional experiment was conducted. The research questions are:

1. Is the IDEAL model an effective method to enhance students' imagination?
2. Is the IDEAL model effective in increasing students' capacities for possibility, connectivity and boundary-crossing?

4.2 Research design

This study used a field quasi-experimental design. The participants were 86 civil engineering freshmen who took the required entry-level course 'Conceptual Design Studio' at a comprehensive university in Taiwan (National Taiwan University—NTU). This course, which lasted for 15 weeks, was divided into four units: architecture, hydraulics, structural engineering and transportation. Each unit lasted for three weeks. Students were given relevant lectures and instructions on the topics. During in-class discussions, students were requested to give free rein to their imaginations to complete innovative tasks with their team partners. They were asked to accomplish two open-ended innovative tasks/projects during the first and second halves of the semester. Students were randomly assigned into one of two classes: the experimental class, with a total of 44 students, and the control class, with a total of 42 students. Students in each class were further randomly divided into 15 and 14 teams consisting of 2–3 students. Students in the experimental group were provided with and guided by the IDEAL Think-Pad, which they used to help them develop and link ideas throughout their discussions and completion of the projects. In contrast, students in the control group had to solve the problem without the guidance of the IDEAL Think-Pad.

4.3 Design of instruction

In class, four classic international and domestic projects of civil engineering, including the Sydney Opera House, the Yuan-Shan-Tzu flood diversion, the Golden Gate Bridge, and the Taiwan High Speed Rail, were provided as a prompts for students to learn about the process of developing innovative architecture, hydraulic, structural and transportation engineering projects. During the first and second halves of the semester, two open-ended innovative projects were provided for student teams to accomplish: a hydraulic construction task/project and a bridge construction task/project.

4.3.1 Project 1: Hydraulic

In the hydraulic task, students had to 'solve the flood problem in residential Area B, which often suffers from floods'. The Yuan-Shan-Tzu flood

Fig. 6. The final product of clothes for the Year 2060, composed of a liquid suit, anti-gravity metal and fly (source: the official site of the movie *Fantastic Four—Rise of the Silver Surfer*).

diversion in Taipei, which has been regarded as a classical innovative project for flood prevention, was provided as a reference. A film about hydraulic construction, featuring a mayor who wanted to hire an engineering project team to solve the flood problem in the area, was also provided to simulate students' thinking about the scenario. We invented a fictitious map on which the residential Area B was downstream of a winding river. The river, which had changed directions many times, flowed through residential Areas D, A, C, and then to B, and there were farms and mountains in the middle and a lake and the sea nearby. Students were instructed to come up with new ways to prevent flooding again in the area, since many of the traditional measures had failed. The experimental group was furnished with the IDEAL Think-Pad to develop and link ideas, whereas the control group was not.

4.3.2 Project 2: Bridge

Based on the conception of the Golden Gate Bridge, students were asked to work as a construction team and build a bridge connecting Town B to either City L, a cultural capital with rich academic and cultural resources, or City K, a populous economic capital where many technology companies resided. B was a lone town without connections to City K or City L; therefore, it needed to be connected in order to prosper through trade or tourism with either city. However, the difference in elevation between City L and Town B was large, and there were also historical remains in the middle that had to be preserved. On the other hand, a deep ocean trench lying between City K and Town B was difficult to cross over. Students had to decide which locations to connect with a bridge, based on their preferences for the destination and the difficulty of the task. They had to imagine new ways to connect these unconnected areas because previous attempts had failed. The experimental group was guided by the IDEAL Think-Pad to develop ideas to build a connection, whereas the control group was not.

4.4 Group work on projects

When student teams were assigned the projects, they devoted themselves to a discussion session, with the purpose of brainstorming their ideas of designing the bridge and flood prevention devices. Students in the experimental group used the IDEAL Think-Pad to help them cultivate and link boundary-crossing ideas throughout their discussions and completion of the projects. They followed the guidance of the concentric circles of the Think-Pad, from the common, unreal to the non-existent, and alternate between different aspects of flood prevention. In contrast, students in the control group had to complete the project without the help of IDEAL Think-Pad throughout their discussions. In group discussion, they tried to build on each other's ideas and shared the common goal in completing their works. After a full discussion session, they were given a period of time to draft out their ideas on project worksheets. After they had completed the worksheets, they were asked to present and share their products in front of the class. During the entire period, the instructor and teaching assistants provided help and comments whenever necessary to facilitate group discussion and work.

4.5 Measurement

To evaluate the progress of the students' imaginations during the instructional process, the researchers developed two assessment instruments. One was the 'Imagination Rating Scale' for group projects. This scale assessed the level of imagination demonstrated in the group projects. The other was the

Table 1. Imagination Rating Scale for group projects

Features	Dimension		Criteria	Score
Possibility	Multiple perspectives	Ideas / Projects feature multiple perspectives.	Higher: 7~10 Medium: 4~6 Lower: 1~3	1~10 (Total score: 9~90)
	Multiple functions and values	Ideas / Projects have multiple functions and values.		
	Multiple options	Ideas / Projects can be replaced by other ideas for the same purpose.		
Connectivity	Form connectivity	The form and structure of ideas / projects are impressive and appropriate.		
	Functional connectivity	The functions of ideas / projects are strongly tied to their purposes.		
	Social connectivity	Ideas / Projects conform to social needs.		
Boundary-crossing	Transcendental imagination	Ideas / Projects are the products of imagination unbounded by reality.		
	Infinite in need	Ideas / Projects are the products of an infinite imagination and address unknown human needs.		
	Fictionalization	Ideas / Projects are the products of imagination through fictionalization.		

'Individual Imagination Scale', which evaluated individual students' imaginativeness at the beginning and the end of the course.

4.5.1 'Imagination Rating Scale' for group project

The researchers developed the Imagination Rating Scale to evaluate the imaginativeness of students' work on the two projects. Each of the three features of imagination—possibility, connectivity and boundary-crossing—was further divided into three sub-categories to fully evaluate the imagination deployed in the students' group projects (Table 1). The possibilities consisted of multiple perspectives, multiple functions and values, and multiple options. Connectivity consisted of the form connectivity, functional connectivity, and social connectivity. Boundary-crossing was composed of transcendental imagination, infinite in need, and fictionalization.

Each dimension was rated from 1 to 10 in terms of students' performance (1–3 being low performance, 4–6 being medium, and 7–10 being high). Total scores ranging from 9 to 90 were used as the scores of the imagination employed in students' group projects. A higher score on this scale indicated that a product showed a higher level of imagination. A group of four experts in the fields of civil engineering, education and psychology were invited to evaluate the students' group projects. A double-blind design was applied: all the groups' works were mixed together for evaluation, without differentiation between the experimental and control groups. In this way, it was ensured that the ratings would not be contaminated by the raters' presumptions about the characteristics of the experiment and control groups. Kendall's W test was employed to evaluate consistency among the evaluators. The reliabilities (Kendall's W) among all the evaluators for both projects were fairly high (Hydraulic = 0.871, Bridge = 0.856).

4.5.2 Individual Imagination Scale

To understand how the IDEAL Think-Pad affects students' imaginativeness at the individual level, we further developed the Individual Imagination Scale. A group of four experts in engineering, education and psychology developed initial questionnaires of 60 items. A pilot test was conducted with a group of 310 college students with primarily science and engineering backgrounds. Items were revised based on the results of item analysis and factor analysis, and each item had good discrimination. The students scored each item on a 4-point Likert-like scale (1 being Never Done, and 4 being Always Done). A final revised scale included 37 items featuring the three elements of imagination. Possibility featured 10 items composed of two dimensions: alternative and future perspective, such as 'I would think of all kinds of alternative possibilities to solve a problem.' Connectivity featured 14 items composed of three dimensions: irrelevant connectivity, multiple connectivity and image connectivity, such as 'I would integrate all the social needs when

Table 2. Comparison of overall imagination for group projects

Task	Group	*N*	*Mean*	*SD*	*t*
Hydraulic	Experimental	15	35.15	9.61	3.82**
	Control	14	23.68	6.03	
Bridge	Experimental	15	40.36	12.29	4.06***
	Control	14	24.52	8.14	

** $p < 0.01$; *** $p < 0.001$.

Table 3. Comparison of each feature of imagination for group projects

Task	Wilks' λ	Multivariate *F*	Feature	Group	*N*	*Mean*	*SD*	Univariate *F*
Hydraulic	0.54	7.20**	Possibility	Experimental	15	10.30	3.35	1.54
				Control	14	8.93	2.50	
			Connectivity	Experimental	15	11.50	2.46	1.65
				Control	14	10.36	2.33	
			Boundary-crossing	Experimental	15	13.35	6.89	22.33***
				Control	14	4.39	1.72	
Bridge	0.53	7.38**	Possibility	Experimental	15	11.18	4.74	9.64**
				Control	14	6.79	2.43	
			Connectivity	Experimental	15	14.67	4.13	3.71
				Control	14	11.81	3.84	
			Boundary-crossing	Experimental	15	14.62	5.80	19.43***
				Control	14	5.93	4.72	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

imagining.' Boundary-crossing featured 13 items composed of three dimensions: fantasy, fictionalization, and role projection, such as 'I would day dream.' The internal consistencies (Cronbach's a) of the three features were all fairly high (Connectivity = 0.878, Boundary-crossing = 0.824, Possibility = 0.858).

5. Results

5.1 Overall imagination for group projects

A t-test was used to test if overall imagination scores for group projects between the experimental group and the control group differed. The results indicated that the overall imagination scores of the experimental group were significantly higher than those of the control group in the Hydraulic (t = 3.82, $p <$ 0.01) and Bridge (t = 4.06, $p < 0.001$) projects (see Table 2).

5.2 Each feature of imagination for group projects

MANOVA was used to test if each feature of imagination between the experimental group and the control group differed. The results showed that, in general, the scores of the experimental group were higher than those of the control group. Moreover, the mean differences between the groups were significant in the Hydraulic works and the Bridge works (Wilks' λ = 0.54, F = 7.20, $p < 0.01$; Wilks' λ = 0.53, F = 7.38, $p < 0.01$). In the Hydraulic works, the boundary-crossing scores of the experimental group were significantly higher than those of the control group (F = 22.33, p < 001). In the Bridge works, the possibility and boundary-crossing scores of the experimental group were significantly higher than those of the control group (F = 9.64, $p < 0.01$ F = 19.43, p < 001) (see Table 3).

5.3 Overall and each feature of individual imagination at post-test

ANCOVA was used with statistical control to exclude the overall difference in individual imagination capacity at pre-test. The adjusted mean score was then compared with the test if the true mean of overall individual imagination in the experimental group was higher than that of the control group at the end of the course. Results indicated that the overall imagination score of the experimental group was higher than that of the control group (F = 4.80, $p < 0.05$) (see Table 4).

One-way MANCOVA was used with statistical control to exclude the differences in individual imagination capacity at pre-test. The adjusted mean scores were then compared to test if the true mean of each feature of individual imagination in the experimental group was higher than that of the control group at the end of the course. Results indicated that the mean differences among the three imagination features were significant (Wilks' λ = 0.85, F = 3.11, $p < 0.05$). Furthermore, the experimental group's scores on the three imagination features were all higher than those of the control group. Boundary-crossing in particular showed significant differences between the two groups (F = 7.26, $p < 0.01$) (see Table 5).

5.4 Each feature of individual imagination between pre-test and post-test

A paired t-test was used to test if overall imagination and each feature of individual imagination improved in the experimental and control groups over time, from the start to the end of the class. It was found that for the experimental group, overall imagination scores on the post-test were higher than those on the pre-test (t = 3.93, $p < 0.001$). In

Table 4. Comparison of overall individual imagination at post-test

Levene	Group	*N*	*Mean*	*SD*	*Adj–Mean*	*F*
1.72	Experimental	31	3.00	0.36	2.97	4.80*
	Control	30	2.75	0.42	2.77	

* $p < 0.05$.

Table 5. Comparison of each feature of individual imagination at post-test

Wilks' λ	Multivariate *F*	Feature	Group	*N*	*Mean*	*SD*	*Adj–Mean*	*Univariate F*
0.85	3.11*	Possibility	Experimental	31	3.15	0.42	3.13	1.00
			Control	30	3.00	0.54	3.02	
		Connectivity	Experimental	31	2.94	0.38	2.93	3.24
			Control	30	2.73	0.46	2.75	
		Boundary-crossing	Experimental	31	3.07	0.48	3.05	7.26**
			Control	30	2.73	0.51	2.75	

* $p < 0.05$, *** $p < 0.001$.

Table 6. Overall imaginativeness and each feature of individual imagination between pre-test and post-test

Group	Feature	Time	*Mean*	*SD*	*T*
Experimental $N = 31$	Overall	Pre-test	2.75	0.38	3.93***
		Post-test	3.00	0.36	
	Possibility	Pre-test	2.98	0.46	1.82
		Post-test	3.15	0.42	
	Connectivity	Pre-test	2.62	0.44	4.77***
		Post-test	2.94	0.38	
	Boundary-crossing	Pre-test	2.73	0.48	4.75***
		Post-test	3.07	0.48	
Control $N = 30$	Overall	Pre-test	2.64	0.32	1.28
		Post-test	2.75	0.42	
	Possibility	Pre-test	2.89	0.40	1.09
		Post-test	3.00	0.54	
	Connectivity	Pre-test	2.55	0.41	1.89
		Post-test	2.73	0.46	
	Boundary-crossing	Pre-test	2.66	0.40	0.80
		Post-test	2.73	0.51	

***$p < 0.001$.

addition, all three imagination feature scores of the post-test were higher than those of the pre-test. More notably, connectivity ($t = 4.77$, $p < 0.001$) and boundary-crossing ($t = 4.75$, $p < 0.001$) were significantly higher at post-test. For the control group, although all three imagination features scores on the post-test were higher than those on the pre-test, none of the mean scores of imagination showed statistical significance ($p > 0.05$) (see Table 6).

6. Discussion

6.1 Summary

Our findings showed that the IDEAL model is effective in increasing engineering students' capacities for imagination. We found that the experimental group's imagination scores for the group projects were significantly higher than those of the control group. Furthermore, the experimental group's individual imagination scores were also higher than those of the control group at the end of the course. This indicated that the IDEAL Think-Pad could effectively increase the imaginativeness of the students, both as a group and as individuals.

Furthermore, among the three features of imagination, boundary-crossing stands out as the most conspicuous feature that makes a difference. For both group projects and individual performances, there were significant differences in terms of imagination between the experimental and control groups. In addition, the imagination scores of the experimental group at post-test were significantly higher than the scores at pre-test, especially in terms of boundary-crossing and connectivity, whereas the imagination scores of the control group did not significantly increase. These results indicated that the IDEAL model did make a difference to students' imaginative capacities, especially in the aspect of boundary-crossing. The reason why students improved significantly on boundary-crossing may be the design of the IDEAL Think-Pad, which was intended to guide students to cross the borders of concentric circles step-by-step, moving from the common to the unusual to the non-existent. These results indicated that the IDEAL Think-Pad does work to enhance students' boundary-crossing abilities.

As mentioned above, in the past, imagination was often cast as an innate endowment, flashes of inspiration, or even the illusions of a chaotic mind. However, this study shows that imagination is a capacity that can be nurtured and taught. Previous literature on imagination is often characterized by philosophical theorizing and anecdotal inferences of individual cases, whereas this study was based on empirical research with a view to establishing a theoretical model of imagination, namely, the IDEAL model, and an instructional tool, the IDEAL Think-Pad. It is found that the IDEAL Think-Pad can enhance freshmen engineering students' capacity for imagination.

Engineering education for freshmen has traditionally emphasized skill-based knowledge such as physics or mathematics. We have challenged this approach by demonstrating that students' imaginations should be more highly valued. Ideally then, in the future, students' imaginations could be infused with more design-based knowledge or experiences, and they should feel they have more freedom to try to design innovative and creative styles. If their interests and passions for imagining are stimulated, the instructor can expect them to feel more motivated to learn.

6.2 Limitation and future study

This study used a field-based quasi-experimental design. Although the researchers controlled some variables, there were still many other external confounding variables that might have influenced the results. For example, students might have attended a sports-based physical education class prior to the class, which would have made it difficult for them to concentrate. Some of the students simply declined or were too passive to join in the task-solving discussions. Future studies should therefore make a greater effort to maintain the motivation of the participants when designing such experiments.

The subjects of this study were freshmen majoring in civil engineering. Future research could recruit students with different majors, college or vocational students, or high school students to contextualize different personalities and thought patterns. Cross-school or cross-field subjects would also deepen our understanding of the workings of the IDEAL model and its effects on diverse groups of students with different backgrounds.

In the future, it would be interesting to further investigate what triggers imagination. Imagination can be triggered by images, senses or emotions, and it can be stimulated through fantasy, fictionalization, or role projection. All of these are important factors in the imagining process. Hence, future research could add these factors to the original three features of imagination and revise the IDEAL model. For example, we could provide sensory stimulation through music and images to trigger individual imaginations, or we could create a story-based scenario as a tipping point to trigger imagination through fictionalization and projection. We could then guide users to enter the scenario and imagine themselves as one of the characters, thereby allowing them to become emotionally invested in the problem prior to applying the IDEAL Think-Pad process.

7. Conclusions

In conclusion, the present study developed an imagination instructional model for entry-level engineering college students. Three features of imagination: possibility, connectivity and boundary-crossing, were established as the theoretical basis for our instructional model, called IDEAL. The model was implemented in an introductory engineering course and its effect was evaluated. The results showed that: (i) The IDEAL model significantly increased students' overall imaginativeness, and more especially (ii), it significantly enhanced students' boundary-crossing capacity. This study made contributions to the current engineering education by first exploring the inherent features of imagination, constructing a workable instructional model for imagination cultivation, implementing the model to an introductory engineering course and showing its effect.

Acknowledgement—This research is sponsored by National Science Council, R.O.C. (NSC-100-2511-S-002-015-MY2; NSC-100-2511-S-002-016-MY2).

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