Development of Creativity of Engineering Students: A Cause for Concern?

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Abstract

This research paper describes the study of how instruction in the use of an idea generation heuristic may differently influence the creativity performance of first year, third year, and postgraduate students from the same institution. Innovation and creativity are increasingly becoming important skills for engineers, but some students suffer design fixation and are unable to effectively produce solution ideas. An experiment was devised whereby students received instruction in use of an idea generation heuristic, and then spent time generating ideas to a real-world engineering-related problem. Results showed that first year students performed better than third year students, who in turn performed better than postgraduate students. These outcomes suggest that if idea generation heuristics are to be introduced to curriculum, they may be most effective if introduced in first year of study when students may be more willing to accept and utilise such creativity techniques.

Introduction

Recent reports have highlighted the need for Australian businesses to be able to innovate and think creatively in order to be able to effectively compete in the global market into the future [1, 2]. Nominally, the Australian engineering sector should be able to effectively meet this need for creativity and innovation. Having a creative and innovative demeanor is one of the expected traits of a professional engineer within Australia, as set out by the Australian engineering accreditation body, Engineers Australia [3]. It is therefore important to assess in a global context, whether Australian engineering graduates do effectively possess the required skills to be able to be creative.

Despite the need for creativity, inclusion of material that is specifically focused on the development of creativity-related skills appears to be lacking in the engineering curricula of many tertiary institutions worldwide. For example, a study of engineering curricula at an American tertiary institution found that content related to creativity was limited, and that there was specifically a lack of “instruction on generating ideas and openness to exploring ideas” [4]. A study conducted by Marquis et. al. [5] analysed the coverage of creativity-related material in a variety of disciplines of study at a Canadian university. Out of a total of 149 engineering courses that were analysed, it was found that only 1% had content that was explicitly linked to the development of creative skills. When asked about the importance of creativity as a skill for innovation, French engineering students reported that it was very important, but that the integration of creativity material within their program was incredibly limited [6]. Specifically regarding Australia, a review of Australian electrical engineering programs analysed the extent of coverage of creativity-related material from more than 20 institutions [7]. It was found that explicit coverage of creativity-related material was limited, and that explicit instruction on how students may actively enhance their creativity skills was effectively non-existent.

However, it is important to observe that this apparent widespread lack of focus on creativity material, does not necessarily suggest that engineering programs are unable to produce graduates who are more creative. Research has shown that engineering students enrolled in their fourth year of study rated their own innovation abilities at a level that was significantly higher than the level which first year students rated their own innovation abilities [8]. This suggests that students' innovation skills and their confidence in their ability to innovate were successfully enhanced over the four years of study they had completed. Other research has established findings which may support this notion. When faced with an unfamiliar, ill-defined engineering-related problem, Nazzal [9] found that students in their first year on average generated fewer solution ideas, produced ideas that utilised fewer concepts in solving the problem, and were overall less creative than students who were in higher year levels. However, other studies have produced findings which contradict these results. A study which investigated the innovation capabilities of engineering students when faced with a design related problem, found that the first-year students were on average able to develop concepts that were considered as being more innovative than their fourth-year counterparts [10]. Moreover, a recent study evaluated the critical and creative thinking of first and fourth year students through use of the Watson-Glaser Critical Thinking Appraisal (WGCTA) and the Test for Creative Thinking-Drawing Production (TCTDP) [11]. It was found that although critical thinking remained at similar levels between first and fourth years, the creative thinking skills of engineering students significantly declined between first and fourth years of study. Upon evaluating engineering students' perspectives of their problem solving capabilities, Steiner et. al. [12] found that students' confidence (self-efficacy) in their ability to solve problems declined between first and fourth year of study. These outcomes suggest that it cannot be conclusively stated whether engineering students' creativity skills improve over the period of studying a year degree, and is likely to depend on numerous contextual factors.

Creativity has been demonstrated to be highly domain-specific and that the creativity a person demonstrates is not simply transferrable between domains [13]. This suggests that the definition of creativity is also domain-specific. Specific to the domain of engineering, it has been proposed that creativity depends on the ability to generate novel ideas which are non-obvious to experts in the field and which may be implementable at some current or future point of time [14]. The creative potential that a person possesses is linked to their ability to think of novel and unobvious solutions when faced with a problem which is not familiar to them [15], highly aligning with this proposed definition. As a result, the process of idea generation and the way in which a person conducts the idea generation process heavily influences their creative performance. In regards to the idea generation process, this is an area where many engineering students may find it hard to perform effectively. When faced with an unfamiliar problem, many engineering students may find it difficult to employ their divergent thinking skills and conceptualise ideas which are different from the first idea which comes to mind (either through ability or unwillingness to consider other ideas), or be able to produce ideas which use a variety of concepts to try and resolve the problem [16-18]. This phenomenon is known as design fixation. Results found by Nazzal [9] suggest that the divergent thinking skills and ability of engineering students to overcome design fixation, increases between the first year and following years of study. In the interest of further enhancing the creativity skills of engineering students, this raises the question of how the skills of first-year students may be enhanced to try and make them able to produce more ideas, and produce ideas that are more varied in their suggested solutions. One potential way may be found in the introduction of training in idea generation heuristics. An experiment conducted by Belski et. al. [19], established that exposing first-year students to simple idea generation heuristics was sufficient to enhance their idea generation performance. Moreover, this finding was replicated using first year students from several countries [19], and students of both undergraduate and postgraduate year levels [20]. This suggests that providing training in the use of idea generation heuristics may be one approach (though certainly not the only way) for enhancing students' creativity skills, by providing them with structured methods of searching for alternative solution ideas.

The aim of this study was to establish whether the year level (i.e. first year, fourth year) in which an engineering student is exposed to and learns about creativity heuristics, is critical to how effectively the student may be able to apply such creativity heuristics. Students who are in higher year levels have a greater level of domain knowledge which may enhance creativity when faced with relevant problems. However, it is possible that students in later years of study may be more hesitant to learn about or use idea generation heuristics if they have not already been expected to learn about them. Contrary to what may be expected, research has determined that it is actually more effective to provide instructional techniques to people who have less relevant experience (or expertise), than people who have higher levels of relevant experience. This phenomenon, known as the expertise reversal effect, outlines that instructional techniques are most effective when applied to inexperienced learners [21].

If upon exposure to a suitable idea generation heuristic, it is established that students who are in their later years of study perform more effectively in relation to their first year counterparts, this would suggest that senior students do not suffer the expertise reversal effect and are able to effectively learn about and use idea generation heuristics. Conversely, if the idea generation performance of students decreases or remains similar between first and subsequent years of study, this may suggest that students in later years of study may be more hesitant towards using heuristics. In order to enhance creativity through use of heuristics, students may therefore need to be exposed to heuristics earlier in their program of study, when they may be more willing to learn and apply such heuristics. This study addresses this issue though use of an experiment designed to answer this question. Outcomes, implications and limitations of the study are discussed.

Methodology

In order to observe how the introduction of a heuristic may influence the idea generation performance of students from different year levels, engineering students from first year, third year, and postgraduate years who were enrolled at the same Australian tertiary institution were investigated. All students were from the discipline of electrical engineering. By ensuring that all first and third year students are from the same institution and same discipline of engineering, it is possible to directly compare how enrolled students' performance changes over the course of (partially) studying a four-year engineering degree. Postgraduate students however, do not necessarily complete their undergraduate studies at the same institution, and may therefore have different experiences to students who had completed their undergraduate students at the same institution. Nonetheless, the postgraduate group was incorporated to see how students, who have more experience in studying, may compare to the third year students.

The experiment took place in first, third, and postgraduate (first year of a two year masters degree) tutorial classes that were related to engineering design. As part of the content for these tutorials, students were involved in an idea generation activity that was designed to expose them to learning an idea generation heuristic. The activity was not assessed, and did not count towards the final mark for the overall course. At the beginning of each of the classes, students were made aware that they would be involved in the idea generation activity. In addition, students were made aware that a research experiment was being conducted (exact details about the experiment were not provided, as their performance may have been influenced), and that they were able to voluntarily participate by handing their activity worksheet to the tutor at the conclusion of the class. Students were instructed not to write any personal identifiable information on their activity worksheets, to ensure anonymity. In total, 26 first year, 34 third year, and 27 postgraduate students returned their activity worksheets to the tutor for analysis. These numbers constituted approximately 90% of the students from each year level enrolled in the tutorial classes.

The methodology used in this study was based upon the procedure used by Belski et. al. [19], with some changes. In order to carry out the experiment, it was necessary to select a heuristic that students would be exposed to. In the study by Belski et. al. [19] students were exposed to one of two idea generation heuristics, Random Word by Edward de Bono [22] and the Fields of MATCEMIB (Mechanical, Acoustic, Thermal, Chemical, Electric, Magnetic, Intermolecular, Biological) technique and asked to generate as many ideas as possible over a period of 16 minutes. The Fields of MATCEMIB is one of the heuristics from the Theory of Inventive Problem Solving. The study by Belski et. al [16] repeatedly demonstrated that exposing students to either heuristic enhanced their performance, relative to a control group. However, the Fields of MATCEMIB technique was found to be more effective than Random Word technique. Substance-Field (Su-Field) Analysis is a heuristic that is based upon the Fields of MATCEMIB technique. Research has demonstrated that providing students with instruction in the use of Su-Field Analysis and subsequently engaging them in an idea generation activity lead to significantly higher performance in a further idea generation activity that was conducted 12 weeks later, compared to a control group who were not shown the technique or involved in the first activity [23]. This suggests that learning the technique has measurable long-term benefits.

To conduct the experiment an instructional video showing how to apply the Su-Field Analysis technique and a worksheet template which guided students through applying the Su-Field Analysis technique, were required. The video was designed to demonstrate the application of the Su-Field Analysis technique by means of an example problem (how to remove annoying flies in the vicinity), and was 15 minutes in duration. The worksheet template consisted of several steps, which followed the process outlined in the video. The process suggests a person to consider how each of the eight fields of MATCEMIB may be used to resolve the problem, one at a time. Each of the fields contains a set of relevant concepts, hints or analogies, which are used to try and trigger new ideas. To aid students to be able to focus on one concept at a time, the fields and each concept were set out sequentially, one per line. Space was provided between each of the concepts to allow students space to write their ideas. The overall template was 4 pages in length, and there were a total of 40 concepts presented for students to consider.

When using the Su-Field Analysis methodology, designers always deal with the same eight fields and related concepts; hints are not specifically created for the problem being resolved. Su-Field Analysis is designed to help a person to resolve problems of technical or physical nature, and therefore it is expected that a person would use the technique when resolving a problem of this type. The number of concepts proposed for a user to consider while generating ideas for each field is as follows: Mechanical - 8, Acoustic – 3, Thermal – 5, Chemical – 6, Electric – 5, Magnetic – 4, Intermolecular – 4, Biological – 4. Two examples of concepts from the Thermal field include “utilisation of fire, burning, heat treatment” and “phase/state change (melting, boiling, and their opposites, solidification and condensation; sublimation), thermal expansion”, while two examples of concepts from the Chemical field include “usage of catalysts, inhibitors, indicators” and “processes of dissolving, crystallisation and polymerisation”. As a practitioner considers each concept, they may use a simple diagram to help them illustrate the current situation. The generic diagram consists of 3 circles and 3 lines (see left side of Figure 1). The left circle illustrates the object to be influenced (e.g. barnacles). The right circle illustrates an object that will be introduced to the scenario (e.g. a hammer). The top circle outlines which field of MATCEMIB the introduced object will use to resolve the problem (e.g. mechanical field, application of direct force causing the barnacles to break and fall off).

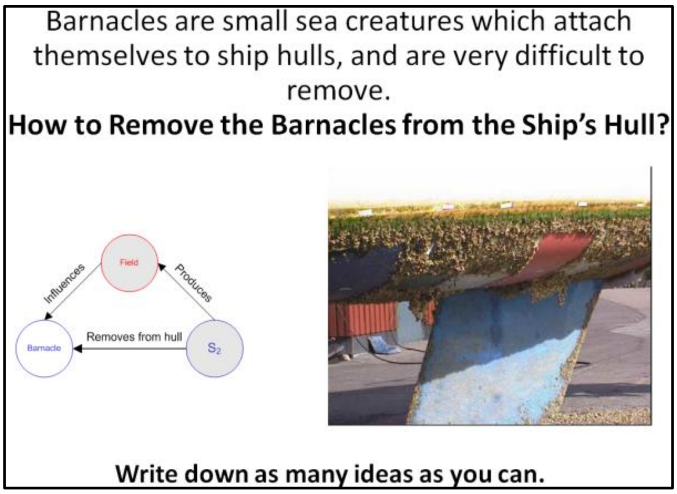

Figure 1: Problem presented to students. Diagram on the left shows application of the idea generation technique (Su-Field Analysis)

The procedure for carrying out the experiment was as follows. First, students were shown the instructional video, so that they were aware how to apply Su-Field Analysis. Following this, worksheet activities were handed to all students in the class. Students were then shown the problem shown in Figure 1 and were allocated a time of 16 minutes to individually write down as many ideas as they could to resolve the problem. Students were instructed to work individually, and not to discuss the problem or potential solutions during this time period. Upon completion of the activity, students were able to voluntarily hand their worksheets back to the tutor for later analysis.

Each of the worksheets that had been returned to the tutor was then independently assessed by three evaluators. As carried out in the study by Belski et. al. [19], student ideas were assed according to the number of independent idea they had generated (related to idea fluency), and the breadth or diversity of ideas they had proposed (related to idea flexibility). These are metrics that are commonly used for assessing divergent thinking and creative performance [23, 24]. Charyton and Merrill [25] specifically suggest idea fluency, idea flexibility and originality as metrics for assessing the creative performance of engineering students. Idea fluency was established for each student by counting the distinct number of ideas that had been proposed. Ideas were considered distinct if the method of resolving the problem was different. For example, using a high powered pressure washer (pressure force) and a vacuum (suction) were considered as distinct ideas, whereas hitting the barnacles with hammer and hitting the barnacles with a chisel were considered the same idea. To establish idea flexibility, the eight fields of MATCEMIB were used as categories. In addition to counting the number of distinct ideas, evaluators assigned each idea to one (or more) of the eight fields of MATCEMIB. Idea flexibility was then established as the number of fields of MATCEMIB the student had used in the generation of all their ideas. Therefore, idea fluency had no maximum range, while idea flexibility was limited to a maximum value of eight. The evaluation of the three assessors was then checked for inter-rater reliability. Results showed that agreement was high, with values of Cronbach's alpha above 0.9 for idea fluency and idea flexibility. The values of idea fluency and flexibility for each student were then set as the average of the values independently allocated by the three assessors.

Results

Analysis showed that the mean number of ideas generated for first year students was 10.53, while third year students generated an average of 6.75 ideas, and postgraduate students 4.35 ideas. Regarding the diversity of ideas proposed (using the eight fields of MATCEMIB as categories), first year students used an average of 4.96 fields, while third year students used 4.50, and postgraduate students used 3.81 fields on average. Using the Shapiro-Wilk test of normality it was established that the distributions for the number of ideas generated by first year students, and number of MATCEMIB fields used by third and postgraduate students were not normally distributed ($p<0.05$). Therefore, non-parametric tests were used to test for significance between all groups.

Table 1: Students' performance in the idea generation task

Group	N	Number of Ideas Generated Mean (Std. Dev.)	MATCEMIB Fields Used Mean (Std. Dev.)
First Year	26	10.53 (6.81)	4.96 (2.01)
Third Year	34	6.75 (3.98)	4.50 (1.91)
Postgraduate	27	4.35 (2.48)	3.81 (1.55)

Considering the number of ideas generated and diversity of ideas proposed, statistical significance between the three groups was tested using the non-parametric Kruskal-Wallis Test of significance. Results showed significance between the groups for number of ideas generated ($p<0.001$), but not the diversity of ideas proposed. Post-hoc analysis using the Mann-Whitney U Test of significance established significance between all groups for the number of ideas generated. Results of these calculations can be observed in Table 2.

Table 2: Statistical significance and effect size between groups for number of ideas (fluency)

Group 1	Group 2	p-value	z-value	Cohen's d
First Year	Third Year	0.035	-2.105	0.71
Third Year	Postgraduate	0.014	-2.464	0.72
First Year	Postgraduate	0.000	-4.098	1.24

In addition to statistical significance, effect sizes were also calculated for the number of ideas generated in order to better comprehend the scale of the difference in performance between groups. Effect sizes with a value of Cohen's d between 0.2 and 0.5 are considered small, while values between 0.5 and 0.8 are considered medium, and values greater than 0.8 are considered large [26]. Effect sizes of 0.5 or higher are generally regarded as demonstrating that there is a practical significance in the difference between achievement levels [26]. For the number of ideas generated, medium effect sizes were established between first and third year students, and third and postgraduate year students (see Table 2). A large effect size was established between first and postgraduate year students.

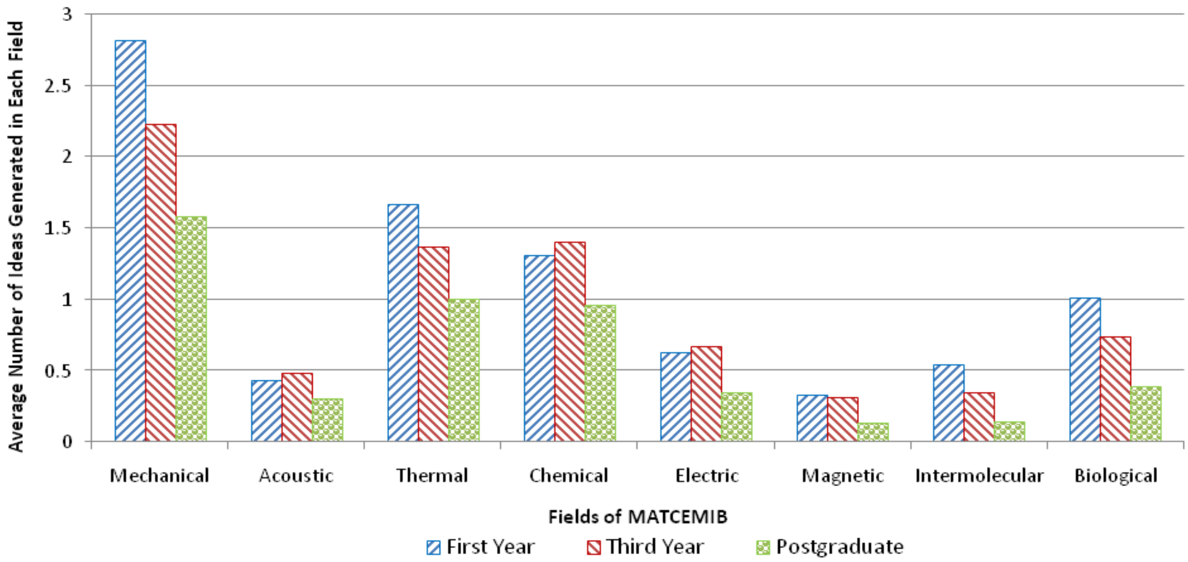

Figure 2: Average number of ideas generated in each field of MATCEMIB by each year level

Figure 2 shows the number of ideas generated in each field of MATCEMIB by each year level. As may be expected, students from all year levels utilized the Mechanical, Thermal and Chemical fields the most. Many of the ideas proposed by students overlapped between the groups, and reflected familiar methods for cleaning, such as use of chemicals, and manual removal. Example ideas generated by first year students include “use force at an angle (chisel+hammer) to chip barnacles off the hull”, “use hydrochloric acid to dissolve the barnacles“, “move ship to the arctic so barnacles freeze to death” and “pass current through hill, electrocuting the barnacles”. Examples of ideas generated by postgraduate students include “spray toxic gas that has a reaction with the barnacles”, “introduce a bacteria or living organism that can destroy the barnacles” and “burn barnacles through use of fire”.

Discussion and implications

The outcomes of this study delivered results which were rather unexpected. Results showed that when provided with instruction in the use of an idea generation technique and faced with an ill-defined engineering-related problem, the number of ideas proposed by third-year students was significantly lower than first-year students, with medium effect size. Likewise, the number of ideas proposed by postgraduate students was lower than that of third-year students, although it is important to note that the postgraduate students may not have completed their undergraduate studies at the same institution and may therefore have different experiences what graduates of the same institution may have. Despite the fact that the number of ideas greatly varied between year levels, the breadth (or variety) of concepts that were used in the generation of these ideas was only significant between first-year and postgraduate students. This suggests that the heuristic may have aided students of lower year levels produce more ideas, but that several of these resulting ideas may have utilised similar areas of knowledge, or solution concepts.

The finding that students in higher year levels produced fewer ideas may suggest that engineering students who are in higher year levels may be more reserved, and are more unwilling to write down ideas they consider as being less suitable. This may suggest that students of higher year levels may be more likely to engage in self-critiquing their ideas before writing them down, compared to first-year students. This outcome was in spite of the instructions provided to students at the start of the idea generation phase of the experiment, whereby they were encouraged to write down all ideas they were able to think of regardless of how crazy or outlandish they may seem to be.

Reflecting upon the expertise reversal effect, it is apparent that under certain circumstances students may suffer from this phenomenon when introduced to the proposal of learning idea generation techniques. Contrary to what might have been expected, first-year students may have been able to apply the technique more effectively than students in higher year levels as they had less experience in solving related problems. The level of information provided in the worksheet templates was extensive, with approximately forty concepts, hints or analogies which make up part of the fields of MATCEMIB, being suggested. Students in lower year-levels may have found it easier to accept the instructions and suggests that were provided to them, and been able to more effectively perform idea generation as a result.

In regards to the issues of developing the creativity of engineering students within Australia and helping to overcoming the issue of being unable to diversity students' thinking, the outcomes of this study suggest that instruction in idea generation heuristics may be most effective if applied to students in the first or second year of study in an undergraduate degree. If students are taught specific methods that are designed to help them broaden their thinking procedures in their earlier years of study, this may be beneficial in two ways. First, it may help to directly overcome the issue that students in first year have been shown to generate ideas that are fewer in number and utilise less diversity in generating the concepts to resolve the problem [9]. Second, if students are taught how to apply idea generation heuristics early on in their studies while they are more susceptible to being able to make use of such information, this may help to further improve their level of creativity in their later years of study. Research has shown that under the correct circumstances, instruction in idea generation heuristics can lead to measurable influences on future performance [23]. It is in the interest of engineering educators to work out how use of such heuristics may most effectively be integrated into the engineering curriculum.

A limitation of this study is that the quality of ideas was not assessed. It is possible that although first-year students were able to propose a greater number of solution ideas, these ideas may not be considered as 'useful' or of as high a 'quality'. While the quality of ideas is important and may have in hindsight provided further insight into the thought processes that students of different year levels undertake during idea generation, the primary focus and scope of this study was on assessing whether the introduced heuristic was able to influence metrics that are relevant to divergent thinking skills of students, namely idea fluency and idea flexibility.

Reflecting upon the proposed definition of creativity in the domain of engineering [14] it is questionable whether assessing idea feasibility or usefulness is appropriate, as ideas which may not be considered implementable at the current point of time may be implementable in the future. There is also issue with measuring idea quality as different researchers may employ different interpretations of what quality actually means. For example, Nazzal [9] measured the overall quality of students' idea generation performance (rather than quality of each idea) using a metric specifically called 'quality'. When analysing the quality of each independent idea, Saad et. al. [27] consider that idea quality is related to the originality of the ideas, while others have considered idea quality to be linked to solution effectiveness [28] or originality and feasibility [29]. Reflecting on the various methods of assessing idea quality, Saad et. al. [27] conclude that "the plethora of methods for assessing idea quality explains why the findings are equivocal when compared against idea quantity results".

Nonetheless, it is important to consider these findings in the context of other research regarding the relationship between quantity and quality of ideas. Regarding the number of generated ideas, Adánez [30] found that in a brainstorming context there was a very strong correlation (R^2=0.893) between the number, and quality of the proposed ideas, although this study involved groups rather than individuals. Although there was an overall positive relationship between the number of ideas generated and the number of ideas that were considered as having a high quality, one study found that there were diminishing returns on idea quality as the number of ideas proposed by a group increased [31]. Other researchers have arrived at other conclusions, however. Girotra et. al [32] established that when product design students were engaged in hypothetical scenarios of designing specified product types for a student market, the mean quality of ideas actually decreased as the number of ideas increased (although groups were again assessed, rather than individuals). When faced with an ill-defined engineering problem, Nazzal [9] established that on an individual level there was no correlation (R^2=0.02) between the number of ideas generated and the quality of students' overall idea generation performance (as opposed to average quality of each idea), but that the number of ideas was significantly correlated to overall creativity (R^2=0.39). Overall, these studies suggest that there is not a single clear relationship between the number and quality of ideas produced during idea generation, as the relationship can change depending on the study that is referenced.

Future research may attempt to build on the findings of this study by investigating any potential relationship between the quantity of ideas and the quality of ideas that are proposed by students of different year levels, when-faced by an ill-defined engineering-related problem. This may provide further insight into the thought processes of students during idea generation, how this may relate to the issue of design fixation, and how idea generation heuristics may able to be most effectively utilised.

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