Influence of Prior Knowledge on Students' Performance in Idea Generation: Reflection on University Entry Requirements

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CONTEXT
Creative performance of science and engineering professionals is supported by their ability to generate diverse solution ideas. The latter ability, in turn, can be influenced by numerous factors including prior knowledge and experience of the problem solver as well as by ideation heuristics she/he uses. This paper investigates the influence of prior science knowledge on the outcomes of an idea generation experiment that engaged engineering students from Australia, Czech Republic, Finland and Russian Federation in resolving the same open-ended technical problem.

PURPOSE
The outcomes of the abovementioned idea generation experiment were unexpected. Australian students proposed statistically significantly less distinct ideas than their international counterparts. Moreover, the ideas generated by the Australian students were not as broad as ideas generated by the students from the other three countries. Such poor performance of Australian students contradicted the results of the 2012 OECD PISA assessment of creative problem solving skills, which positioned Australian 15-year-olds above their international peers from Czech Republic and Russian Federation and on a par with students from Finland. The reasons for such a poor performance by Australian students required exploration.

APPROACH
In order to establish the potential reasons behind the unexpectedly poor performance of Australian students this study reflected on: (1) the results of OECD PISA 2012 assessment of student skills in mathematics, science and reading and the results of the 2012 OECD PISA assessment of creative problem solving skills; (2) performance of students from Australia, Czech Republic, Finland and Russian Federation in the abovementioned idea generation experiment; (3) reviews of educational systems of Australia, Czech Republic, Finland and Russian Federation as well as the admission requirements at universities that participated in the abovementioned idea generation experiment.

RESULTS
It was discovered that the minimum university admission requirements in science knowledge at participating universities from Czech Republic, Finland and Russian Federation were similar and substantially more demanding than that at the Australian university. All other identified factors that could have influenced the idea generation performance were evaluated and found to be insignificant. Therefore, it was concluded that the most likely reason for poor performance of Australian engineering students compared with their counterparts from Czech Republic, Finland and Russian Federation was related to significant differences in their prior science knowledge.

CONCLUSIONS
This study demonstrated that a lack of prior knowledge in science might limit creative abilities of STEM graduates. Australian STEM educators need to revisit university admission requirements and to consider establishing admission thresholds of prior science knowledge similar to those existing in other countries if we would like to see Australian graduates on par with their international counterparts.

KEYWORDS
Prior knowledge, creativity, idea generation, STEM education, engineering education.

Introduction

Importance of creativity skills for STEM graduates of the 21st Century

Creative problem solving and idea generation is an integral part of work for engineering and science professionals. The need to develop novel ways of achieving goals in engineering and scientific practice is growing due to the perpetual developments in manufacturing, technological processes, new materials, as well as due to expanding computing power and increasing internet speeds. Under such conditions of rapid change, advanced cognitive skills and specifically skills in generating creative ideas for projects in engineering and science are becoming vitally important. Companies that do not innovate effectively will likely struggle, independent of their location and their production costs. Consequently, STEM (science, technology, engineering and mathematics) educators face the challenge of how best to instil advanced cognitive skills in their students over the three to five years of their university study.

Creative problem solving: standing of Australian Engineering students

The outcomes of the most recent OECD (Organisation for Economic Cooperation and Development) Programme for International Student Assessment (PISA) of students' skills in creative problem solving (PISA 2012 creativity skills assessment), which engaged 85 thousand 15-year-olds from 44 countries, established that Australian 15-year-olds performed above the OECD average and only lagged behind their counterparts from Singapore, South Korea, Japan, China and Canada (OECD, 2014a).

A recent study by Belski et al. (2015) which compared outcomes of idea generation of students who had just started their engineering study in Australia, Czech Republic, Finland and Russian Federation (the 2015 idea generation experiment) discovered that performance of future engineers did not follow the PISA 2012 creativity skills assessment. Based on the PISA 2012 creativity skills assessment, Australian students were expected to outperform students from Czech Republic, Finland and Russian Federation or at least perform on par with their international counterparts. Nonetheless, Belski et al. (2015) reported that Australian students generated less ideas then their peers and that these ideas were less broad than that of their counterparts from the other three countries.

The differences in idea generation performance in the 2015 idea generation experiment and in the PISA 2012 creativity skills assessment may be related to various factors. Some of these factors were discussed by Belski, Livotov and Mayer (2016). In general there are seven main factors that could have contributed to the unexpectedly lower student performance during the 2015 idea generation experiment. These factors are: (a) differences in prior science knowledge of the student participants, (b) differences in their experiences, (c) dissimilarity in their creativity skills, (d) differences in student motivation during idea generation, (e) differences in experimental conditions, (f) cultural and language differences, and (g) the influence in the treatment that the experimental groups were under.

This paper analyses possible reasons for poor performance of Australian engineering students compared with their counterparts from Czech Republic, Finland and Russian Federation that were reported by Belski et al. (2015).

Methodology and Results

In order to establish the likely causes of the unexpectedly poor performance of Australian students compared to their peers from Czech Republic, Finland and Russian Federation this study reflected on three different kinds of information: (1) results of OECD PISA 2012 assessment of student skills in mathematics, science and reading (OECD, 2014b); (2) performance of students from Australia, Czech Republic, Finland and Russian Federation who participated in the 2015 idea generation experiment reported by Belski et al. (2015); (3) reviews of the educational systems in the four countries as well as the university admission requirements at the universities that participated in the 2015 idea generation experiment.

Student Performance: PISA 2012

In order to assess the influence of prior science knowledge on idea generation, data from the OECD PISA 2012 assessment of skills in mathematics, reading and science (PISA 2012 general skills assessment) (OECD, 2014b) was analysed. This assessment engaged a subset of around 510 thousand students from a population of approximately 28 million 15-year-olds, in the schools of the 65 participating countries. It was anticipated that the results achieved by countries in the PISA 2012 general skills assessment could be used as a reliable indicator of science knowledge of secondary school graduates in each country. Table 1 presents the 2012 PISA general skills assessment findings on the performance of students from the four countries together with the findings of the PISA 2012 creativity skills assessment (OECD, 2014a).

Table 1: 2012 PISA performances in Maths, Science, Reading and Creative Problem Solving

Country/Subject	Mathematics (max: 613)	Science (max: 570)	Reading (max: 580)	Creative PS (max 562)
Australia (Victoria)	504 (*499*)	521 (*516*)	512 (517)	523
Czech Republic	499	508	493	509
Finland	519	545	524	523
Russian Federation	482	486	475	489

The first three columns in Table 1 show the mean scores achieved by the students from each country for mathematics, science and reading (including the score for reading for the students from the state of Victoria in Australia) that were explicitly published in the PISA 2012 general skills assessment report. Table 1 also presents the scores for mathematics and science achieved by the students from the state of Victoria (in italic). These latter scores for mathematics and science were calculated by the authors using Tables I.5.1a and B2.I.1 from the PISA 2012 general skills assessment report (OECD, 2014b). The maximum scores in each subject shown in Table 1 correspond to the maximum mean scores achieved in each subject by the students from the country which performed the best in this subject from all countries which participated in the OECD assessment.

The fourth column in Table 1 presents the mean scores in creative problem solving of the 15-year-olds from the four countries (OECD, 2014a). The maximum score in creative problem solving shown in Table 1 corresponds to the maximum mean score achieved by the students from the country which performed the best in this subject from all countries which participated in the OECD assessment.

As presented in Table 1, 15-year-olds from Finland performed well above their peers from the other three countries in all three areas of general skills assessment. Students form Russian Federation achieved the lowest scores in all areas. Their scores in mathematics, science and reading were substantially below that of the students from the other three countries. It can be noticed that mathematics and science performance of school students from Czech Republic was close to that of Australians and very similar to that of Victorians.

Data on student performance in creative problem solving presented in Table 1 suggest that the 15-year-olds from Finland and Australia performed better than students from Czech Republic and much better than students from Russian Federation.

Student performance: Idea Generation

In 2014 – 2015, students, who had just commenced their university study in Australia, Czech Republic, Finland and Russian Federation, participated in the same experiment (Belski et al., 2015). All students were enrolled at technical universities: Royal Melbourne Institute of

Technology (RMIT) in Victoria, Australia, Brno University of Technology (BUT) in Czech Republic, Lappeenranta University of Technology (LUT) in Finland and Komsomolsk-on-Amur State Technical University (KNASTU) in Russian Federation.

At each university students were recruited from four tutorial groups: one group was deployed as the control group and the other three acted as the experimental groups. After two minutes of problem introduction, all students were given 16 minutes of tutorial time to individually generate as many solution ideas as possible for the same problem (to remove the limescale build-up in water pipes).

Students from the Control groups were not influenced by any ideation methodology. Students from the experimental groups were told that during their idea generation session they would be shown some words. No explanation on what these words would be and what to do with them were given. The first of the three experimental groups was the 'Random Words group'. Students from the Random Word groups were offered eight random words (the same set of words translated into the language of each country). These eight words were shown to students one by one for two minutes each. Students in the other two experimental groups were shown one of the words that in their language identified the names of the eight fields of MATCEMIB (Mechanical, Acoustic, Thermal, Chemical, Electric, Magnetic, Intermolecular, Biological) every two minutes. The eight fields of MATCHEMIB belong to the ideation heuristic of systematised Substance-Field Analysis and are used by problem solvers as prompts during idea generation (Belski, 2007). One group were only shown the names of each of the eight fields (the MATCEMIB group), another (the MATCEMIB+ group) – the names of each field together with some words (in small font) that illustrated the interactions relevant to the particular field (e.g. friction, direct contact, collision, wind, etc. – for the Mechanical field). Each word was shown to the students in the experimental groups for two minutes, meaning that they devoted exactly 16 minutes to the idea generation activities as did their peers in the Control groups.

In order to judge the performance of students from different countries, this study compared the average numbers of ideas generated by students from the four countries as well as the differences in breadth of these ideas as reported by Belski et al. (2015). More specifically, only differences in performance of students from the Control groups, as well as of students from the MATCEMIB+ groups were investigated. Numbers and breadth of ideas generated by the students from the Control groups were compared because it was anticipated that differences in their performance were not related to any experimental treatment. In essence, performance of the Control groups represented the outcomes of idea generation under usual day-to-day problem solving conditions. Students from the Control groups could be considered to generate ideas in similar conditions to that of the participants of the PISA 2012 creativity assessment. Therefore, their performance was expected to match that of the 15-year-old participants from the PISA 2012 creativity assessment from their country. On the other hand, students from the MATCEMIB+ groups were compared because they were exposed to the strongest experimental treatment. They had been shown the sets of words (a field name and a list of field interactions) that could have reminded them of various natural principles that could be used for cleaning limescale from water pipes. It was anticipated that students with higher prior knowledge in science would be familiar with more of these natural principles and would propose more and broader solution ideas than students will lesser prior knowledge in science. Therefore, the outcomes of idea generation of students from the MATCEMIB+ groups were expected to demonstrate the depth of science knowledge acquired by them during secondary schooling more accurately than the results of any other group.

Table 2 depicts the performance of students from the Control groups and the MATCEMIB+ groups that participated in the idea generation experiment reported by Belski et al. (2015).

For each participating country Table 2 shows the number of students that submitted their idea generation sheets (N), the average number of distinct ideas generated by students in each group (Mean), and the average breadth of these ideas (Breadth). The breadth of ideas for a group was calculated as the average number of fields of MATCEMIB that were behind the principles of cleaning limescale, that the ideas proposed by each student from this group were based upon (Belski et al., 2015).

Table 2: Idea generation performances: Control and MATCEMIB+ groups (Belski et al., 2015)

Group Information	Australia			Czech Republic			Finland			Russia		
	N	Mean	Breadth	N	Mean	Breadth	N	Mean	Breadth	N	Mean	Breadth
Control	21	2.02	2.05	18	**3.56**	***2.53***	8	**5.81**	2.75	21	**4.32**	***2.57***
MATCEMIB+	18	5.13	4.44	18	***6.92***	4.56	6	**9.67**	***6.00***	23	***6.62***	***5.59***

Due to the absence of normality in distributions of some groups in Mean and Breadth, a non-parametric Mann-Whitney U Test was used for analysis. Statistically significant differences in performance were only observed between the Australian groups and the same groups from other countries. The values of the Mean and the Breadth presented in bold text in Table 2 correspond to statistically significant difference of these values with the corresponding values of the Australian group. The **normal bold** font in Table 2 identifies statistical significance of $p<0.001$; the ***italicised bolded*** font a $p<0.05$. Differences in performance between the same groups (Control or MATCHEMIB+) from Czech Republic, Finland and Russian Federation were not statistically significant.

Educational System and University Admission Requirements

The authors also explored relevant information on secondary education in each of the four countries as well as on university admission requirements for all four universities that participated in the 2015 idea generation experiment reported by Belski et al. (2015). This information is presented in Table 3.

Table 3: Country's position in secondary education as well as university admission requirements

Information / Country	Soundness of school education (world position)			University Admission	
	MBCtimes.com (2016)	*Worldtop20.com (2015)*	*OECD 2015*	*Study Prerequisites*	*Entry Examinations*
Australia	15	Outside 20	14	GS, M, S*	RMIT: N/A
Czech Republic	19	Outside 20	21	GS, MM, SM	BUT: M, S
Finland	5	6	6	GS, MM, SM	LUT: M, S
Russia	13	5	34	GS, MM, SM	KNASTU: M, S

The first three columns in Table 3 show the ranking of school education system in Australia, Czech Republic, Finland and Russian Federation by different assessors: MBCtimes.com, Worldtop20.com and OECD (Hanushek & Woessmann, 2015). The forth column presents information on general admission requirements for admission into engineering degree programs at each participating university. The term 'GS' (graduation score) in the fourth column means that in order to be admitted, student had to achieve some minimum secondary school graduation score that evaluates overall secondary school performance (GS has different name and different meaning in each country). The term 'M' means that completion of a mathematics subject was required, but there was no performance threshold for admission. The term 'S*' means that completion of subjects in science (physics or chemistry) was not compulsory, but was treated as advantageous for admission. The terms 'MM' (mathematics mark) and 'SM' (science mark) respectively indicate the existence of threshold marks in school mathematics and science for admission to university. The last, fifth, column in Table 3 contains information on specific entry examinations that the students from the four participating universities had to sit and pass at the relevant university in order to be admitted. RMIT admission did not require any additional examination. Admissions to BUT and KNASTU were conditional on passing written entry examinations in mathematics (‘M’) and science (‘S’) – usually physics or chemistry. Students admitted to LUT could be divided into three categories. About a third of them were admitted solely on the basis of their outstanding secondary school performance in mathematics, physics and chemistry. All other students sat entry examinations in mathematics, physics and chemistry and were admitted either on their high overall score of school marks plus entry examination results or due to their exceptional performance on the entrance examinations in all three subjects.

The data on the soundness of secondary schooling from Table 3 correlates with the data from PISA 2012 general skills assessment that is shown in Table 1. Two of the three assessment sources in Table 3 positioned Finland above the rest of the three countries. This agrees with the top performance of Finnish 15-year-olds in mathematics, science and reading presented in Table 1. Australian secondary schooling was assessed in Table 3 just above that of the Czech Republic. This is also in agreement with data from Table 1. The position of secondary schooling of Russian Federation presented in Table 3 is more diverse. WorldTop20.org assessed it as a little better than that of Finland (WorldTop20.org, 2013); MBCtimes.com positioned it under Finland, but above Australia and Czech Republic (MBC Times, 2016); OECD report – well below all the other three countries, as was the PISA 2012 skills assessment (see Table 1).

It is also clear from Table 3 that the university admission requirements are similar in Czech Republic, Finland and Russia. In order to be admitted to the universities which participated in the 2015 experiment, almost all school graduates from these countries had to demonstrate appropriate performance in mathematics and science (physics and/or chemistry), as well as to pass entry examinations. RMIT, like the majority of Australian engineering schools only required school study in mathematics (no performance threshold) for admission and did not make studies in physics and chemistry compulsory. Instead, applicants to engineering degrees who studies physics and/or chemistry at school were given additional marks to their school graduation score (GS in Table 3) that could help them to be admitted if their original graduation score (GS) was below the GS threshold.

Discussion

Influence of the Seven Factors

Let us now separately consider the influence of each of the above-mentioned seven factors on performance of students that participated in the 2015 idea generation experiment (Belski et al., 2015).

Prior Knowledge in Science

The data on educational systems provided in Table 3 suggest that the school graduates from Finland are likely to be better educated than their counterparts from the other three countries. Also the information offered in Table 3 suggest that the overall difference in secondary schooling in Australia, Czech Republic and Russian Federation is unlikely to differ much. At the same time, the distinction in admission to engineering degrees between RMIT and the other three universities suggests that RMIT students are less likely to have as much knowledge in science compared to their peers from LUT, BUT and KNASTU. The latter three universities admitted school graduates with high marks in school mathematics and science and only after passing entry examinations in these subjects. RMIT neither had any threshold requirements in mathematics and science, nor conducted entry examinations in these subjects. Therefore a conclusion can be drawn that the student participants from RMIT were likely to have significantly lower science knowledge than their counterparts from LUT, BUT and KNASTU.

It needs to be noted, that a small percentage (<5%) of the students that participated in the experiment in Australia and Czech Republic were graduates of secondary schools outside Australia or Czech Republic. Therefore it is possible that they could have had different levels of knowledge in science to the country graduates. Due to the small percentage of foreign school graduates, it was unlikely that their idea generation results could have significantly influenced the overall results of Australian students and students from Czech Republic.

Student Experience

Over 90 per cent of students admitted to each of the four degrees in the year of the 2015 idea generation experiment came directly from secondary school and were 18 to 19 years of age. About five per cent of admitted students were adults over 25 years of age. Clearly, students who grew up in different countries have somewhat different experiences. Nonetheless, years of primary and secondary schooling that occupied their time for 11 to 12 years were similar and did not allow them to have significant time for experiences outside of schools. Therefore, since the majority of the students that participated in the experiment enrolled into university directly from secondary school, it was concluded their prior experiences were similar and were unlikely to influence their idea generation performance significantly.

Creativity Skills

It is impossible to make an accurate assessment of the creativity skills of students from the four counties that participated in 2015 idea generation experiment from the data available. Nonetheless, it is hard to suggest any practical reason that led to the observed poor performance of Australian students in idea generation.

The outcomes of 2012 PISA creativity skills assessment presented in Table 1 suggest that two to three years prior to leaving secondary school, the 15-year-olds from Australia and Finland were more creative than their counterparts from Czech Republic and Russian Federation. It is possible that over the last two or three years of secondary schooling Czech and Russian students could have significantly improve their creativity skills. This possibility, though, is highly unlikely. Most of the subjects taught over the last two to three years of secondary schooling are discipline specific and do not focus on creativity skills. Hence, it is highly unlikely that the Australian participants of the 2015 idea generation experiment significantly lagged behind the students from the other three countries in creativity.

Student Motivation During Idea Generation

All participants in the 2015 idea generation experiment were recruited during scheduled tutorial classes. Students who did not want to participate in idea generation were allowed to leave and/or not to submit their work. In essence, students participated in the experiment willingly. Also, they were treated in exactly the same way by their tutors, who used the same Power Point slides (translated into appropriate languages) to conduct the experiment. Therefore, although it cannot be completely excluded, it is difficult to find a reason for students from different countries to have significantly different motivation during the idea generation sessions.

Differences in Experimental Conditions

As it has already been discussed, all students from the same group (Control or MATCHEMIB+) were treated in the same way. It is possible that the time of day when the tutorials were held could have influenced the outcomes of idea generation. It is also possible that the difference in room size, temperature and lighting conditions could have influenced student performance. Nonetheless, all tutorial sessions were held in appropriately sized, heated and well-lit tutorial rooms. Therefore, the abovementioned factors do not seem to be a likely reason for the observed significant differences in student performance.

Cultural and Language Differences

Indeed, students from the four countries differed considerably in their language and cultural upbringing. There are, though, minimal reasons to suspect that these differences could have impeded creativity skills of Australian students and made them less creative than their peers from the other three countries. This conclusion is fully supported by the high performance of

Australian 15-year-olds in 2012 PISA creative skills assessment. If it was indeed, any cultural and language differences that reduced the ability of Australian students to think creatively, it would be evident in their PISA performance. In essence, the outcomes of the 2012 PISA creativity skills assessment presented in Table 1 support a conclusion that it is unlikely that cultural and language differences made Australian participants of the 2015 idea generation experiment the least creative.

Influence of Experimental Treatment

The data presented in Table 2 confirm the significant influence of the experimental treatment on idea generation performance. Students from the MATCEMIB+ group in each country generated statistically significantly more and broader ideas than their countryman from the Control group (Belski et al., 2015). This study, though, compared performance of students from the groups that were treated identically. Therefore, a conclusion can be drawn that the same groups in different countries were under similar conditions during their idea generation performance.

The Prior Knowledge Factor

Analysis of the reasons which may have contributed to the unexpectedly poor performance of Australian students in the 2015 idea generation experiment established that prior knowledge in science is likely to be the main factor.

Statistically significant differences in the number of distinct ideas and the breadth of these ideas generated by the Australian students and their counterparts from Czech Republic, Finland and Russian Federation can be easily explained by the differences in prior knowledge in science. The breadth of ideas can be treated as a measure of the extent to which proposed ideas of limescale removal were based on different principles of operation. Clearly, students who had studied science in the final years of high school would be aware of more physical and chemical principles. They would also be in a better position to suggest diverse ideas than students with lesser science knowledge. For example, students who were not very familiar with electricity, would have been unable to generate ideas for cleaning limescale that are 'electric' in nature. Therefore, the more knowledge in science possessed by a student, the broader her/his ideas were expected to be. This expectation is fully supported by the data on the breadth of ideas shown in Table 2. Practically speaking, Australian students from the Control group suggested ideas to clean limescale that belonged to only two principles of operation: removing limescale mechanically and dissolving it chemically. Students from the other three Control groups proposed ideas based on more principles of operation (with Czech and Russian students statistically significantly outperforming Australians in breadth).

The breadth of ideas generated by students from the MATCEMIB+ groups repeated the pattern for the difference in the breadth of ideas generated by students from the Control groups. Again, Australian students lagged behind the students from the other three countries with Finns and Russians being statistically significantly ahead of Australians.

The data on the number of distinct ideas generated by the students from the same group also support the findings that are based on breadth. Australian students from both the Control group and the MATCHEMIB+ group generated statistically significantly fewer ideas than their international counterparts from the same group from each of the three countries.

The significant influence of prior science knowledge on performance of student participants in the 2015 idea generation experiment is not surprising. Authors from many fields of research have reported on the positive influence of prior knowledge on performance. Arentz, Sautet and Storr (2013) established that participants with appropriate prior knowledge were significantly more likely to discover the arbitrage opportunity. Brockman and Morgan (2003) showed the important role of prior knowledge on innovativeness during new product development. Over the last four decades numerous authors have established the importance of prior knowledge for effective learning (e.g. Bloom, 1976; F. Dochy, de Rijdt, & Dyck, 2002; F. J. Dochy, 1992). Many previous studies on learning have concluded that prior knowledge explained at least 30 per cent of the variance in study results (F. Dochy et al., 2002). Moreover, prior knowledge was found to be the best predictor of learning gains (F. Dochy et al., 2002).

Conclusions

This study established that the most likely reason for poorer performance of Australian engineering students compared with their counterparts from Czech Republic, Finland and Russian Federation was due to significant differences in their prior science knowledge. STEM professionals of the 21st Century are required to generate abundant creative ideas quickly. This study demonstrates that a lack of prior knowledge in science could limit creative abilities of Australian STEM graduates.

It seems timely for Australian STEM educators to reconsider university admission requirements and to establish admission thresholds of prior science knowledge similar to that existing in other countries if we would like our graduates to compete on a world level.

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