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Denis Dumas[a] & Linda Schmidt[b]

[a] Department of Human Development and Quantitative Methodology, University of Maryland, 3304 Benjamin Building, College Park, MD 20742, USA

[b] Department of Mechanical Engineering, University of Maryland, 0162 Glenn L. Martin Hall, College Park, MD 20742, USA

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Relational reasoning as predictor for engineering ideation success using TRIZ

Denis Dumas[a] and Linda Schmidt[b]*

[a]*Department of Human Development and Quantitative Methodology, University of Maryland, 3304 Benjamin Building, College Park, MD 20742, USA;* [b]*Department of Mechanical Engineering, University of Maryland, 0162 Glenn L. Martin Hall, College Park, MD 20742, USA*

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With the particular technological challenges facing our twenty-first-century society, it is crucial that design engineers continue to foster the innovative potential of students, as well as identify the underlying cognitive abilities which support the innovative process. In this investigation, we examine the predictive link from an individual's analogical and relational reasoning ability to their success using the TRIZ (from the Russian acronym for 'Teoriya Resheniya Izobretatelskikh Zadatch' meaning theory of inventive problem-solving) ideation method. TRIZ instruction was shown to significantly increase the novelty of participant's generated solutions to an engineering design problem. Moreover, the degree of the increase in the novelty of a participant's generated ideas was linked to their relational reasoning ability. Specifically, those participants with greater ability to reason relationally experienced a greater increase in ideation success when using the TRIZ method. These empirical findings support existing theoretical accounts of the TRIZ method as an implicitly analogically driven design method. Implications for engineering practice and education, such as the potential to identify individuals most likely to have success in design innovation using tests of relational reasoning, as well as the potential for systematically supporting relational reasoning ability in all students, are discussed.

Keywords: drivers of innovation; theory of inventive problem-solving; design education; psychology of creativity

Today's engineers are faced with a variety of complex and demanding tasks. For example, engineers are expected to create economic prosperity both in their local communities and around the world through innovation. At the same time, fundamental constraints, such as the need to be conscious of environmental damage, complicate their undertaking. Because of expectations and pitfalls such as these, the field of engineering has and will continue to shoulder the heavy burden of moving society forward through innovation and design. As such it is the responsibility and privilege of those in the engineering design community both to innovate and to work to sustain and improve innovative ability in students and novices within the field.

In search of strategies by which to foster such an ability to innovate, a number of design engineers have turned to the cognitive science and education literatures for clarity (e.g. Fu et al. 2013; Howard, Culley, and Dekoninck 2008). For example, in a recent review, Visser (2009) argues that engineering design is a cognitive process that can be understood through the careful delineation and study of the cognitive activities that constitute the overall process. In particular,

*Corresponding author. Email: lschmidt@umd.edu

Vissers argues that design may implicate both domain-general and domain-specific cognitive processes, and that describing how these domain-general abilities manifest themselves within the specific domain of engineering design may lead to further insight into the design process.

One such general cognitive ability that has been widely implicated in the design domain is *analogical reasoning* (e.g. Ahmed and Christensen 2009; Fu et al. 2013; Linsey, Wood, and Markman 2008; Vargas Hernandez, Schmidt, and Okudan 2013; Visser 2009). In the cognitive and educational literatures, analogical reasoning is often defined as the discernment of a relational pattern of *similarity* among multiple pieces of information (e.g. Gentner 1983; Goswami 1992; Holyoak 2012). As such, analogical reasoning represents a special case of the larger cognitive construct termed *relational reasoning*, which encompasses any ability to discern meaningful patterns in a body of information, be the pattern one of similarity or contrast (Dumas, Alexander, and Grossnickle 2013). In order to reliably assess the broadly conceived construct of relational reasoning, the test of relational reasoning (TORR) was created (Alexander et al. 2015). The TORR is designed to tap multiple forms of relational reasoning, not only analogical reasoning. The other forms of relational reasoning that are measured on the TORR are: (a) anomaly, which is predicated on a relation of discrepancy or unusualness, (b) antinomy, which is defined by a relation of incompatibility between categories, and (c) antithesis, which is based on a relation of opposition or refutation. In the education literature, the multi-faceted construct of relational reasoning has been linked to achievement in a wide variety of STEM domains such as mathematics (Richland and McDonough 2010), chemistry (Bellocchi and Ritchie 2011; Trey and Khan 2008), and meteorology (Trickett, Trafton, and Schunn 2009). However, while analogical reasoning has been connected to engineering design success (e.g. Kamal, Leach, and Wissam 2012), the potentially important direct link between its broader parent construct, relational reasoning, and engineering design has not, to our knowledge, been examined.

Reflecting the previous focus within the engineering design literature on analogical reasoning, many published design methods explicitly rely on analogies to support innovation. For example, the Synectics method has long utilised four different types of analogies (i.e. direct, fantasy, personal, and symbolic) to support design success (Gordon 1961). More recently, the WordTree method was developed to aid designers in identifying salient analogies that may support the development of a novel design (Linsey, Markman, and Wood 2012). Further, the bio-inspired design movement has encouraged designers to analogically map attributes from a biological system onto their designs (e.g. Vattam, Helms, and Goel 2010). In this line of work, Sartori, Pal, and Chakrabarti (2010) have developed the SAPPhiRE model with includes four steps (i.e. formulate search objectives, search for biological analogues, analyse biological analogues, and transfer) for successfully mapping a biological analogy onto an engineering design problem. While these methods differ in important ways, they share an explicit reliance on analogical reasoning in the support the engineering design.

In contrast to these explicitly analogical design methods, the TRIZ method (from the Russian acronym for ‘Teoriya Resheniya Izobretatelskikh Zadatch’ meaning theory of inventive problem-solving) relies on analogies implicitly in the form of *inventive principles* (Altshuller and Shulyak 2002; Orloff 2006; Rantanen and Domb 2002). These innovative principles were developed by Genrich Altshuller, who generalised them from patents issued in the former USSR (Altshuller and Shulyak 2002). Some examples of inventive principles offered in TRIZ are: segmentation (no. 1), change dimensionality (no. 17), feedback and (no. 23), phase transitions (Altshuller and Shulyak 2002). Importantly, each of these inventive principles are broadly applicable, and, in theory, must be relationally mapped onto the particular problem at hand. In this way, TRIZ inventive principles cognitively operate as far-field analogies (Vargas Hernandez, Schmidt, and Okudan 2013). Indeed, the TRIZ method is often described as a design-by-analogy method (e.g. Jeong and Kim 2014).

Importantly, while each of the methods previously mentioned (i.e. Synectics, WordTree, SAPPhiRE, and TRIZ) are ideation methods used to aid design engineers, they differ on some important aspects. First, while other ideation methods were explicitly designed to require relational thinking, it cannot be said that TRIZ was designed with any particular cognitive abilities in mind (Altshuller and Shulyak 2002). Therefore, while other ideation methods have potentially highly predictable cognitive foundation, the mental abilities which predict TRIZ success remain less understood. Second, TRIZ has been an established ideation method in the engineering community for some time, and it remains probably the most widely used systematic ideation method in practice (Charyton 2014). Therefore, an understanding of the cognitive abilities associated with TRIZ may potentially inform the work of many design engineers.

Crucially, TRIZ has repeatedly been empirically demonstrated to improve design results both in working professional engineers (e.g. Okudan, Ogot, and Shirwaiker 2006; Orloff 2006) and in engineering students (e.g. Vargas Hernandez et al. 2010; Vargas Hernandez, Schmidt, and Okudan 2013). A notable study on the impact of TRIZ training studied 219 design engineers in a major international engineering firm (Birdi, Leach, and Wissam 2012). In this investigation, 123 engineers received training and displayed better short-term performance in creative problem-solving than a non-trained group of 96 engineers. Over the long term, TRIZ-trained engineers 'had better levels of idea generation at work, and this was due to improvement in both creative problem-solving skills and motivation' (Birdi, Leach, and Wissam 2012, 322). In another investigation, Vargas Hernandez and colleagues found that TRIZ instruction led to a significant improvement in engineering students' ability to effectively redesign a biomass oven to reduce harmful emissions (Vargas Hernandez et al. 2010). Later, the same research team found that TRIZ instruction led to similarly significant gains in students' ability to redesign traffic lights to reduce snow build-up (Vargas Hernandez, Schmidt, and Okudan 2013). Each of these studies, among others, have repeatedly demonstrated the effectiveness of the TRIZ method to improve ideation in engineering design.

However, while the TRIZ method has been empirically validated in its ability to improve design, and has been theoretically described as an analogical design process, TRIZ's reliance on analogical reasoning has not to our knowledge been empirically demonstrated. Moreover, examination of the link between the broad construct of relational reasoning, which includes analogical reasoning as a sub-form, and engineering design success has never been attempted.

It is important to fill these observed gaps in the engineering design literature for three principal reasons. First, without empirical evidence concerning the cognitive abilities associated with TRIZ success, it is unclear whether or not TRIZ can or should be accurately described as an analogically based design method. Relatedly, knowledge of the cognitive processes required for TRIZ success would allow engineering instructors to more adequately tailor their instruction to support the thinking strategies most associated with ideation and TRIZ success. Finally, both in engineering education and professional practice, the identification of individual engineers who are more or less likely to successfully ideate in a given context has become an important endeavour in the innovation-driven economy of the twenty-first century (Charyton 2014). Therefore, the identification of psychological constructs and corresponding psychometric measures that predict ideation ability and TRIZ success is potentially applicable in a variety of professional and education settings.

Therefore, in this first-of-its-kind investigation, we pose two explicit research questions. First, as in other studies of the TRIZ design method, will TRIZ instruction be effective at increasing the novelty of engineering design students' problem solutions? Second, what cognitive variables (e.g. relational reasoning) are predictive of the increase in novelty of problem solutions observed for each participant?

Importantly, while some previous investigations of TRIZ have utilised a between-subjects study design to assess the effectiveness of TRIZ instruction (e.g. León-Rovira, Heredia-Escorza, and Río 2008), our particular research questions pertaining to the cognitive change in an individual student associated with TRIZ requires the measurement of participants' ideation both before and after TRIZ instruction. Therefore, a within-subjects design must and will be used to answer our research questions. Moreover, a within-subjects design alleviates potential confounding factors associated with between-subjects designs, such as the non-equivalency of comparison groups on potentially salient cognitive variables. With these specific research questions posed, and their implications for study design considered, we undertook this investigation.

Method

Participants

Nineteen graduate students at the University of Maryland (13 male; 68.4%) participated in this study. At the time of their participation, students were enrolled in a mechanical engineering graduate design course at the university, and were recruited for participation in this study in that course. Participants ranged in age from 22 to 32 years old, with a mean age of 24.86 years old (SD = 2.15). The sample was highly diverse, with 36.8% ($n = 7$) of the students reporting their ethnicity as White, 15.8% of students reporting their ethnicity as African American/Black ($n = 3$); 21.1% of students reporting their ethnicity as Hispanic/Latino ($n = 4$); and 21.1% reporting their ethnicity as Asian ($n = 4$). Also, 78.9% of the sample reported English as their first language ($n = 15$). Participants reported a mean grade point average of 3.22 (SD = .42) on a four point scale, with grade point averages (GPAs) ranging from 3 to 4.

Measures

Traffic light problem

In order to save energy, many communities in the USA have installed traffic lights using LED bulbs in place of traffic lights using incandescent bulbs because LED lights required less energy to operate (Ramde 2009). Much of the energy savings associated with LED bulbs comes from LED bulb's lower heat production as compared with traditional incandescent bulbs (Ramde 2009). Unfortunately, during winter storms, snow and ice can build up on the lights because the heat generated by the LED bulbs in the lights is insufficient for melting. This situation represents a design trade-off, in which a design change leads to unintended consequences, and made national news because of traffic accidents. One Associated Press news article describing the problem was made into a handout and given to participants in this study (Ramde 2009). Figure 1 is a picture of this situation, such as the one disseminated to students participating in this study.

Scoring of generated problem solutions was done based on the *novelty* of ideas. Novelty is a characteristic of each generated concept, and is a measure of the frequency of that idea generated relative to all the ideas generated by the entire group of subjects for the method under consideration (Shah et al. 2003). Thus, the fewer the number of subjects generating the same idea, the higher its novelty score. Determining novelty requires that each idea or concept is coded according to the scientific principles behind its operation and the type of working principle the physical form of the concept would take. All concepts generated during the experiment, regardless of method used, comprise the design space of possible solutions for the sample of participants. A 'genealogy tree' is built to represent the characteristics of each idea in the solution space. A tree is generated for each basic function that branches into different scientific principle categories. Each physical principle node branches into different working principles that can be

Figure 1. A snow-covered LED traffic light, such as the one included in the Traffic Light Problem (colour online).

used to instantiate the concept. Some example physical and working principles used in this study are shown in Table 2.

In this investigation, each generated problem solution was coded based on the physical and working principles it utilised. In our coding, the physical principles participants used to solve the traffic light problem were (a) mechanical (e.g. using a windshield wiper to wipe away the snow), (b) heat (e.g. using electrical resistance coils to melt the snow), (c) tribology (e.g. lubricating the bulbs so snow will slide off), (d) chemical (e.g. spraying antifreeze on the bulbs), and (e) optical (e.g. adding more LEDs so light will be bright enough to shine through snow). Combinations of each of these physical principles (e.g. mechanical and chemical) were also coded. Specifically, this coding was done independently by the first and second author, with a high level of inter-rater reliability ($\kappa = .86$). After coding was complete, the novelty value of each generated problem solution is calculated based on the variety of working principles represented by the set of ideas and the number of each idea belonging to a specific working principle. The formula for the novelty score of idea *c* is based on the work of Shah et al. (2003) and is shown below.

$$\text{Novelty score }(c) = \frac{\begin{array}{c}\text{(Total number of ideas generated/}\\ \text{Total number of ideas at working principal branch of c)}\end{array}}{\text{Total number of working principal branches for dea set}}.$$

The quantity of problem solutions was also saved in the data set for later analysis, and calculated by counting the number of solutions a participant generated.

Test of relational reasoning

The TORR ($\alpha = .83$) is a graphical reasoning test with 32 items. The TORR has been empirically observed to be highly internally consistent and reliable, as is evidenced by its alpha level (.83). Also, the TORR has demonstrated high levels of predictive validity, as it predicts scores on measures such as the SAT, and IQ tests (Alexander et al. 2015). Further, The TORR is designed to limit the need for participant prior knowledge and language ability, and principally taps fluid intellectual processing (Alexander et al. 2015). The TORR includes four scales of eight items, each designed to capture one of the four forms of relational reasoning (i.e. analogy, anomaly, antinomy, antithesis). An example analogical reasoning item from the TORR is included in Figure 2. In this item, the matrix format requires participants to infer the salient pattern both across the rows and down the columns in order to ascertain which of the answer choices is correct. In this investigation, the TORR was administered to participants during class, in paper and pencil form. Participants were given as much time as they needed to complete the TORR, with no participant taking more than one hour.

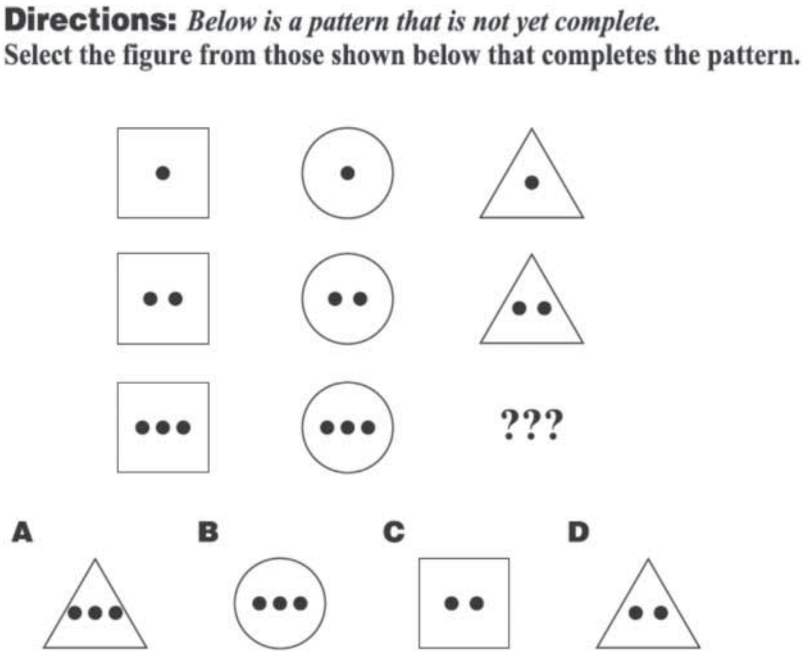

Figure 2. Analogical reasoning TORR item. In this item, the matrix format requires participants to infer the salient pattern both across the rows and down the columns in order to ascertain which of the answer choices is correct. Here, the correct answer is A, because the pattern dictates that the answer choice must be triangular, and contain three dots.

Shapebuilder

Because the TORR is a graphical measure that requires the mental manipulation of visual figures, the visuo-spatial working memory capacity of participants may affect their ability to score highly on the TORR (Logie 2003). So, in this analysis, we controlled for visuo-spatial working memory capacity through the use of the Shapebuilder task (Sprenger et al. 2013). Because Shapebuilder is not a selected-response measure, the alpha statistic of internal consistency is inappropriate. However, Shapebuilder has demonstrated strong test-retest reliability ($r = .75$), as well as validity in a variety of contexts (Sprenger et al. 2013). The Shapebuilder task requires participants to maintain a mental representation of serially presented shapes (e.g. circle, square, or triangle) and recall those shapes in sequential order. In addition to order of presentation, the various shapes differed in number displayed, their colour, and their location on a grid. Each participant has 15 minutes to be presented with varying serially presented strings of shapes. Each shape in a string correctly recalled earns a participant a certain amount of points, calculated based on the number of varying dimensions associated with that shape. The Shapebuilder task is then scored automatically. Because of its interactive nature, Shapebuilder is necessarily administered to participants on a computer. In this investigation, participants completed the Shapebuilder task outside of class via the internet. A screenshot of the Shapebuilder task is included in Figure 3.

Uses of objects task

The uses of objects task (UOT), a psychometric test that requires participants to generate multiple original uses for a given every day object, was utilised in this study. The UOT has been widely used in research on creativity for many years (Guilford 1950; Hudson 1968; Torrance 1998). Indeed, the UOT is perhaps the most psychometrically studied of all creativity measures, with strong predictive validity ($r = .48$), as well as reliability coefficients ($r = .93$)

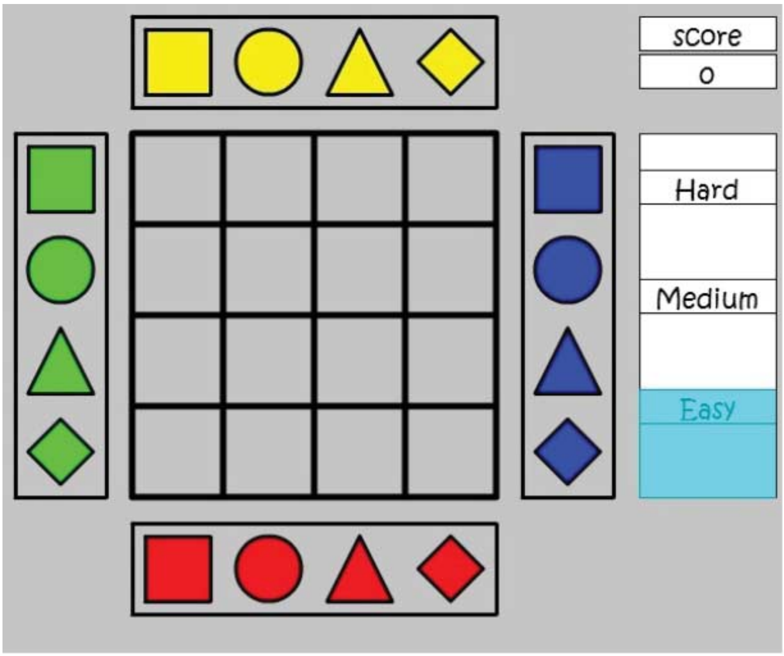

Figure 3. Shapebuilder task screenshot. In this task, the programme presents sequences of shapes appearing in the matrix. Participants are asked to remember the colour and location of sequences of shapes. Points are earned for every shape in a sequence remembered correctly (colour online).

reported in the research literature for more than half a century (Torrance 1998). In this study, the UOT was administered to the participants in class, and the object for which participants generated uses was a tin can. Participants were given 10 minutes to think of as many original uses for a tin can as they could. Afterwards, the number of uses each participant produced was tallied, and the total count was used as their score for the UOT.

Procedure

Individual difference measures

Prior to receiving TRIZ instruction and completing the traffic light problem, participants completed the TORR, Shapebuilder, and the UOT. These measures assess *individual differences* in the way students cognitively process information (i.e. relational reasoning ability, visuo-spatial working memory capacity, and creativity). As previously mentioned, the TORR and the UOT were both administered to participants during class in paper and pencil form, while Shapebuilder was completed outside of class via the internet. In subsequent analyses, these measures are used as predictors of a participant's performance on the traffic light problem both before and after TRIZ instruction.

TRIZ instruction and traffic light problem

In this study, a repeated measures design was utilised to investigate the effect of TRIZ instruction on ideation performance with the traffic light problem. As previously discussed, a within-subjects design is the only way to validly investigate the cognitive changes associated with TRIZ instruction, because measures of the same participants both before and after TRIZ are required in order to assess change. Further, because a within-subjects design was used, methodological concerns

Table 1. Ideation task activities implemented during this study.

Activity	Subjects do test of unusual uses	Present design Task	Subjects ideate on Ad-Hoc basis	Data collected on site	TRIZ lecture	Subjects ideate using TRIZ	Data collected on site	Subjects repeat Ideation task using TRIZ in a homework assignment	Data submitted in 1week
Time allowed	10 minutes	5 minutes	10 minutes		50 minutes	30 minutes		Suggest 2-hour limit	
Materials provided	Form with task statement	1 page description	1 page of instructions		Copy of slides	1 page of instructions and TRIZ material[a]		Nothing[b]	
Location	Classroom setting in a contiguous time period							Subjects' homes	

[a]TRIZ contradiction matrix and description of TRIZ inventive principles.
[b]The TRIZ lecture includes a website for online access to TRIZ inventive principles (www.triz40.com).

about the equivalency of participants in comparison groups are alleviated, because the pre- and post-TRIZ groups are composed of the same participants, and are therefore equivalent on all variables except their exposure to TRIZ. In this way, cognitive changes associated with TRIZ instruction can be investigated. Specifically, prior to any TRIZ instruction, the traffic light problem was introduced to the participants with a one-page description and a short discussion to assure that the task is clear. At this point, the participants had only a writing instrument and blank paper; there was no access to external resources (i.e. internet, texts, etc.).

After this initial ideation period, the participants received instruction on the TRIZ method, and received the official TRIZ instructions and material. TRIZ instruction was carried out by students' engineering professor, a tenured scholar at a large research university. Instruction lasted approximately one hour, and included detailed discussion of how to effectively use TRIZ materials. Moreover, the students observed a worked-example of the TRIZ method, and instruction did not end until all participants reported an understanding of the TRIZ materials and how to use them. Finally, participants revisited the traffic light problem with explicit instruction to apply the TRIZ method to their ideation process. Since the TRIZ process requires substantial time, participants were instructed to use a larger block of time in an informal setting to fully apply the TRIZ contradiction matrix to the traffic-light problem. At the next class meeting, participants submitted their TRIZ-based problem solutions to the researcher. This procedure is visually outlined in Table 1.

Results

Efficacy of the TRIZ instruction

In order to examine the effectiveness of the TRIZ instruction, the average novelty of problem solutions put forward by this sample of participants before and after TRIZ instruction was examined. Table 2 holds examples of novelty scores associated with certain problem solutions generated by participants in this study. Further, Figure 4 depicts an example drawing of a problem solution created by a participant in this sample. Specifically, this example depicts a traffic-light

Table 2. Example traffic-light solutions and corresponding novelty scores.

Scientific principle class (no. of branches in class)	Heat (4 branches)		Chemical (2 branches)	Mechanical (14 branches)		
Working principle in embodied concept	Electrical resistance		Antifreeze	Pressure		Vibration
Concept idea (all imply controllers that activate the concept at start of storms)	Add heating elements to the light fixture	Add incandescent bulbs to lights	Spray defrosting liquid on bulbs	Add blowers to lights	Add vacuum to lights	Vibrator on light to shake off debris
No method novelty score (instances)	0.24 (17)	1.022 (4)	1.022 (4)	1.022 (4)		0.817 (5)
TRIZ novelty score (instances)	0.306 (11)	1.682 (2)	0.673 (5)	0.561 (6)		0.420 (8)

Note: The coded principles that appear in this table are examples and not an exhaustive list. Therefore, not all coded principles appear in this table.

design which is relationally mapped onto previous 'barber-pole' design. In regards to this example solution, the TRIZ principle of 'inversion' is noted as the inspiration for the solution. The participant linked the working principle of a rotating design to the idea of a barber pole. Here it may be reasonable to infer that the student drew an analogy between a traffic light and other devices that display coloured signals, such as a barber pole. That, combined with the student's knowledge of centrifugal force, and the antinomously reasoned idea that the required spinning to generate such force was not incompatible with the main function of a traffic light (i.e. directing traffic with coloured lights), allowed for the creation of this idea via relational thought.

Before TRIZ instruction, the mean novelty score for problem solutions generated for the traffic light problem by participants in this sample was .82 (SD = .34). After TRIZ instruction the problem solutions generated by the same group of participants had a mean novelty score of 1.22 (SD = .65). A repeated-measures analysis of variance (ANOVA) confirms that the increase in mean novelty of problem solutions after TRIZ instruction was significant [$F(1, 18) = 8.79$, $p = 0.008$, $\eta_p^2 = .33$]. This effect is visually depicted in Figure 5. This main effect of increased novelty of problem solution after TRIZ instruction is in line with the findings of previous studies of TRIZ effectiveness (e.g. Vargas Hernandez et al. 2010; Vargas Hernandez, Schmidt, and Okudan 2013).

Interestingly, while the mean novelty of problem solutions significantly increased after TRIZ instruction, the mean quantity of problem solutions generated slightly decreased, although the decrease was not significant. Specifically, before TIZ instruction, participants generated 5.11 (SD = 1.62) problem solutions on average, and after TRIZ, participants generated 4.47 (SD = 2.41) problem solutions on average. As previously stated, this difference was not significant [$F(1, 18) = 1.046$, $p = 0.320$].

Predictors of TRIZ success

In order to ascertain the degree to which the observed significant gains in novelty of solutions to the traffic light problem associated with TRIZ instruction relied on particular cognitive variables, the predictive relation between participants' scores on the three individual difference measures (i.e. TORR, Shapebuilder, and UOT), and their level of increase in novelty of problem solutions was examined. First, the change in novelty for each participant was calculated by subtracting

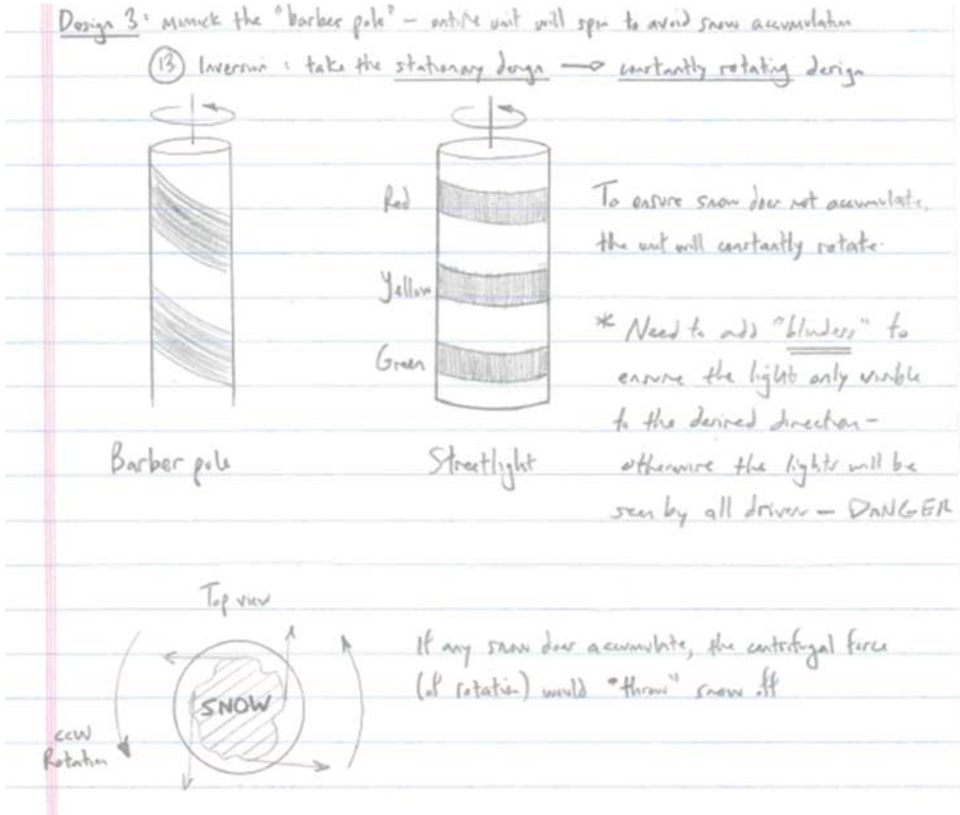

Figure 4. Example solution to traffic light problem: 'the barber-pole' utilising a mechanical physical principle and a rotation working principle.

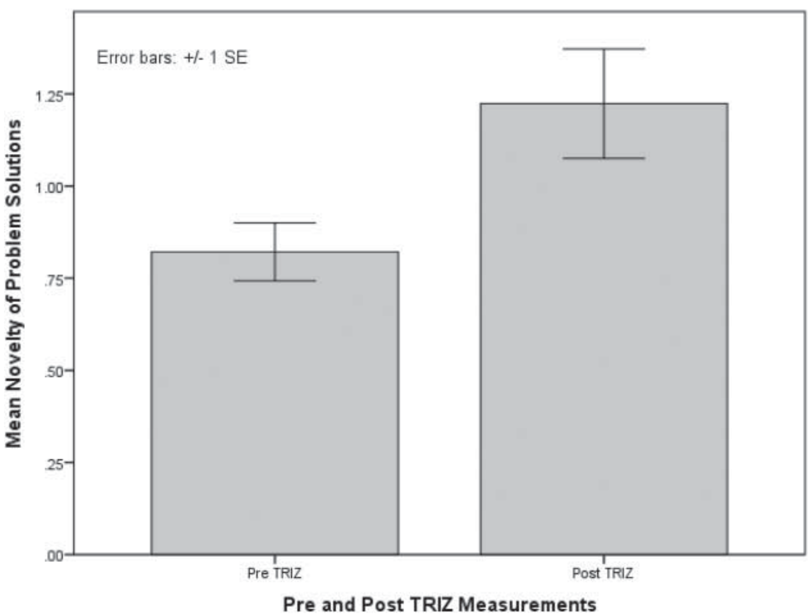

Figure 5. Mean novelty of problem solutions before and after TRIZ instruction.

Table 3. Descriptive statistics and bivariate correlations among individual difference measures.

	Mean (SD)	TORR	Shapebuilder	UOT	△Originality
TORR	22.62 (4.06)	1.00			
Shapebuilder	1293.91 (327.61)	.452*	1.00		
UOT	16.52 (4.18)	.378	.138	1.00	
△Originality	0.47 (.37)	.605**	.319	.210	1.00

*$p < .05$.
**$p < .01$.

Table 4. Standardised and unstandardised coefficients, standard errors, and significance tests for each variable in the regression model.

	Standardised β	Unstandardised β	Standard error	t	p
TORR	.84	.093	.03	2.99	.01**
Shapebuilder	.08	.012	.01	0.33	.74
UOT	.37	.017	.01	1.65	.12
Gender	.29	.025	.02	1.24	.23
GPA	.34	.035	.02	1.32	.21
Language background	.11	.016	.01	0.45	.58

their pre TRIZ novelty score from their post TRIZ novelty score. This variable, *change in novelty of problem solutions*, was saved in the data set. In this sample, the average increase in novelty of problem solutions was .47 (SD = .37). Table 3 includes descriptive statistics, as well as bivariate correlations among each of the measures used in this analysis. Based on these bivariate correlations, it was determined that multi-collinearity was not a threat to the power of this analysis, because the only predictor variables that were significantly correlated were the TORR and Shapebuilder, and then the correlation was only moderate in strength ($r = .45$). Moreover, the moderate magnitude of the standard deviations associated with each of the variables, as well as visual inspection of scatterplots, ensured that outliers were not unduly effecting the outcome of this analysis.

A multiple linear regression model was run in which participants' scores on the TORR, Shapebuilder, and the UOT were used to predict the change in the novelty of their problem solutions. The potentially important demographic variables of gender, first language, and university GPA were also included in the model, as a way to control for potentially important demographic effects. This multiple linear regression model significantly predicted participants' change in novelty of problem solutions associated with TRIZ instruction [$F(6, 12) = 3.31$, $p < .048$, $R^2 = .40$]. This R-square value of .4 implies that 40% of the variance in participants' ability to generate novel solutions to the traffic light problem was accounted for by the variables in our regression model. In the social or cognitive sciences, this proportion of variance accounted for is widely considered to be high, because complex cognitive processes are inherently difficult to predict (Lorch and Myers 1990).

Consistent with the hypothesis that the observed significant gains in the novelty of problem solutions after TRIZ instruction rely on students' relational reasoning ability, the TORR was the only significant predictor of change in novelty of problem solutions in the linear regression model [$\beta = 0.84$, $t = 2.99$, $p = 0.01$]. Standardised coefficients, standard errors, and accompanying significance tests associated with each variable in this model are available in Table 4.

Interestingly, the unstandardised coefficient associated with the TORR in the regression model was .093. So, when holding visuo-spatial working memory capacity, creative ability, gender, first language, and GPA constant, every point increase on the TORR predicted an increase in the novelty of solutions to the traffic light problem of .093 on average. In other words, relational reasoning ability as measured by the TORR significantly predicts gains in novelty of problem solutions while other individual differences in cognition and demographics do not, implying that the TRIZ ideation method relies crucially on relational and analogical ability.

Implications and conclusion

After observing the results of this investigation, it is apparent that both of our research questions can be generally answered in the affirmative. As with other studies of the TRIZ methodology (e.g. Vargas Hernandez et al. 2010; Vargas Hernandez, Schmidt, and Okudan 2013), this examination has shown that TRIZ instruction made a significant difference in the novelty of problem solutions generated on a design task. Moreover, this study was the first to empirically demonstrate, through the regression analysis presented earlier, that the gains in the novelty of problem solutions associated with TRIZ instruction are predicted by relational reasoning ability.

These findings have a number of particular implications both for practicing engineers engaged in ideation and innovation professionally, as well as for engineering education, in which the ability to ideate and innovate is being fostered. For example, because relational reasoning ability predicts ideation success with the TRIZ method, assessments of relational reasoning like the TORR may be fruitfully utilised to identify individuals most likely to be successful innovators (i.e. those with high-levels of relational reasoning ability). It is reasonable, for example, that score on the TORR, among other potential measures, may be used to determine the need for specific training in recognising relations among engineering parameters in different devices or identifying TRIZ as a preferred ideation method for a group. However, further research may be necessary to fully determine the breadth of the applicability of the TORR to engineering design, and how best to tap the predictive potential of relational reasoning ability in design engineers. Moreover, because multiple effective ideation methods are currently utilised in engineering design practice, understanding the cognitive requirements for success in each of these methods in order to better tailor instruction to particular students – and not impose a ‘one-size fits all’ model of innovation – may be an important next phase in this line of inquiry.

Importantly, many currently used ideation methods (e.g. bio-inspired design and WordTree) explicitly rely on analogical thought, and as such have specific supports for relational reasoning built in. However, other highly effective ideation methods, such as the TRIZ method examined here, implicitly rely on analogical and relational reasoning. In consequence, the supports for relational thought in the TRIZ method are less explicitly explained to students. Given the findings from this investigation, making strategies for think relational thinking while ideating highly explicit (i.e. specifically directing students to relate inventive principles analogically to the problem at hand) may support ideation in engineering students. In the cognitive science and education literature, explicit support for relational reasoning has improved students’ performance on demanding tasks within STEM fields (Dumas, Alexander, and Grossnickle 2013). This leads to the hypothesis that, while relational reasoning ability does certainly predict ideation in engineering students, careful instruction on relational reasoning strategies may boost the innovative abilities of all students. In fact, studies within the educational literature have repeatedly shown that such explicit reasoning instruction can improve the performance of students at a wide variety of levels, and across many domains of learning (e.g. Tzuriel and Shamir 2010; White and Caropreso 1989). While it is likely that such instructional intervention may be effective within the field of engineering design, further research is needed to test this hypothesis.

One important aspect of this investigation is its repeated-measures design, which, as mentioned before, offered a valid way to assess changes in participants’ ideation before and after

TRIZ. In this design, in an effort to hold every potentially confounding variable constant, students generated solutions to the same design problem (i.e. the traffic light problem) both before and after TRIZ instruction. However, one difference between the pre- and post-TRIZ ideation sessions was the time-limit imposed on them. Specifically, pre-TRIZ, participants were given 10 minutes to generate problem solutions. However, after TRIZ, the first ideation session of 30 minutes was inadequate for generating solutions. This finding is consistent with previous investigations using TRIZ, which find that the TRIZ method is much more time-intensive than brainstorming alone (e.g. Vargas Hernandez, Schmidt, and Okudan 2013). Thus, the ideation session was repeated in an informal setting, and participants were free to take as much or as little time as they felt they needed, although the instructions suggested participants impose a two-hour time limit. Importantly, because of the significant predictive relation between the individual difference variables included in our regression model (i.e. visuo-spatial working memory, creativity, and relational reasoning) and the gain in novelty of problem solutions associated with TRIZ instructions, we can conclude that these gains were likely *not* due to the increased time allotment. Specifically, an individual participant's relational reasoning ability, creativity, or visuo-spatial working memory capacity, is likely to be statistically independent of their willingness to spend time on the traffic light problem. Indeed, this has been repeatedly found in empirical investigation in the cognitive sciences (e.g. Bunge et al. 2005; Krawczyk 2012). In other words, we have no reason to believe that those with higher or lower scores on any of the individual difference measures would have been any more or less diligent about the traffic light problem outside of the controlled setting. Therefore, the variables in our regression model, which significantly predicted gains in novelty of problem solutions associated with TRIZ, are independent, or unrelated to the amount of time spent on the ideation task. Thus, the observed predictive ability of these variables is unaffected by any differences in time-on-task within our sample, and differences in time-on-task are not relevant when interpreting the results of our presented analysis.

In this study, we have demonstrated the efficacy of the TRIZ method to positively affect the novelty of problem solutions in an engineering design task. Importantly, because of previous research in the ideation literature that shows more novel ideas tend to produced later in an ideation session (e.g. Basadur and Thompson 1986; Kohn, Paulus, and Choi 2011) the causal link between TRIZ and improved novelty is not clear-cut in these results. However, because of the established effectiveness of TRIZ in the engineering design literature, this study is highly informative about when, and for whom TRIZ is an effective ideation method, as well as what cognitive abilities predict that efficacy. Specifically, we have shown that these gains in novelty can be significantly predicted using measures of participants' cognitive abilities, especially relational reasoning. Further, this study is the first to bring the broadly conceived cognitive construct of relational reasoning, and the TORR, to bear on the domain of engineering. With the predictive power of relational reasoning within engineering design now identified and established, the door has been opened for further investigations into the ways this fundamental ability relates to other tasks within the field of engineering. Moreover, the results of this study imply that the ongoing interdisciplinary collaboration between those in the cognitive sciences, and those within the engineering community, may continue to yield productive and important insights into the ways engineers think, learn, and solve problems crucial to our contemporary society. For our part, we have established that relational reasoning may be a critical cognitive ability predictive of ideation success, and a powerful tool for the field of engineering in the twenty-first century.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ahmed, S., and B. T. Christensen. 2009. “An in Situ Study of Analogical Reasoning in Novice and Experienced Design Engineers.” *Journal of Mechanical Design* 131 (11), article id 111104 (9 pp.). doi:10.1115/1.3184693.

Alexander, P. A., D. Dumas, E. M. Grossnickle, A. List, and C. M. Firetto. 2015. “Measuring Relational Reasoning.” *The Journal of Experimental Education* 83: 1–33. doi:10.1080/00220973.2014.963216.

Altshuller, G., and L. Shulyak. 2002. *40 Principles: TRIZ Keys to Technical Innovation*. Worcester, MA: Technical Innovation Center.

Basadur, M., and R. Thompson. 1986. “Usefulness of the Ideation Principle of Extended Effort in Real World Professional and Managerial Creative Problem Solving.” *The Journal of Creative Behavior* 20 (1): 23–34.

Bellocchi, A., and S. M. Ritchie. 2011. “Investigating and Theorizing Discourse During Analogy Writing in Chemistry.” *Journal of Research in Science Teaching* 48 (7): 771–792. doi:10.1002/tea.20428.

Birdi, K., D. Leach, and M. Wissam. 2012. “Evaluating the Impact of TRIZ Creativity Training: An Organizational Field Study.” *R&D Management* 42 (4): 315–326.

Bunge, S. A., C. Wendelken, D. Badre, and A. D. Wagner. 2005. “Analogical Reasoning and Prefrontal Cortex: Evidence for Separable Retrieval and Integration Mechanisms.” *Cerebral Cortex* 15 (3): 239–249. doi:10.1093/cercor/bhh126.

Charyton, C. 2014. *Creative Engineering Design Assessment: Background, Directions, Manual, Scoring Guide and Uses*. New York: Springer Science.

Dumas, D., P. A. Alexander, and E. M. Grossnickle. 2013. “Relational Reasoning and its Manifestations in the Educational Context: A Systematic Review of the Literature.” *Educational Psychology Review* 25: 391–427.

Fu, K., J. Chan, J. Cagan, K. Kotovsky, C. Schunn, and K. Wood. 2013. “The Meaning of “Near” and “Far”: The Impact of Structuring Design Databases and the Effect of Distance of Analogy on Design Output.” *Journal of Mechanical Design* 135: 021007-1-12. doi:10.1115/1.4023158.

Gentner, D. 1983. “Structure-Mapping: A Theoretical Framework for Analogy.” *Cognitive Science* 7: 155–170.

Gordon, W. 1961. *Synectics: The Development of Creative Capacity*. New York: Harper & Brothers.

Goswami, U. 1992. *Analogical Reasoning in Children*. Hove: Lawrence Erlbaum Associates.

Guilford, J. P. 1950. “Creativity.” *American Psychologist* 5: 444–454.

Holyoak, K. J. 2012. “Analogy and Relational Reasoning.” In *The Oxford Handbook of Thinking and Reasoning*, edited by K. J. Holyoak and R. G. Morrison, 234–260. New York: Oxford University Press.

Howard, T. J., S. J. Culley, and E. Dekoninck. 2008. “Describing the Creative Design Process by the Integration of Engineering Design and Cognitive Psychology Literature.” *Design Studies* 29 (2): 160–180.

Hudson, L. 1968. *Frames of Mind: Ability, Perception and Self-Perception in the Arts and Sciences*. Oxford: W. W. Norton.

Jeong, C., and K. Kim. 2014. “Creating Patents on the New Technology using Analogy-Based Patent Mining.” *Expert Systems with Applications* 41 (8): 3605–3614. doi:10.1016/j.eswa.2013.11.045.

Kamal, B., D. Leach, and M. Wissam. 2012. “Evaluating the Impact of TRIZ Creativity Training: An Organizational Field Study.” *R&D Management*, 42 (4): 315–326.

Kohn, N. W., P. B. Paulus, and Y. Choi. 2011. “Building on the Ideas of Others: An Examination of the Idea Combination Process.” *Journal of Experimental Social Psychology* 47 (3): 554–561. doi:10.1016/j.jesp.2011.01.004.

Krawczyk, D. C. 2012. “The Cognition and Neuroscience of Relational Reasoning.” *Brain Research* 1428: 13–23. doi:10.1016/j.brainres.2010.11.080.

León-Rovira, N., Y. Heredia-Escorza, and L. M. L.-D. Río. 2008. “Systematic Creativity, Challenge-Based Instruction and Active Learning: A Study of Its Impact on Freshman Engineering Students.” *International Journal of Engineering Education* 24: 1051–1061.

Linsey, J. S., A. B. Markman, and K. L. Wood. 2012. “Design by Analogy: A Study of the WordTree Method for Problem re-Representation.” *Journal of Mechanical Design* 134: 041009-1–12. doi:10.1115/1.4006145.

Linsey, J. S., K. L. Wood, and A. B. Markman. 2008. “Modality and Representation in Analogy.” *AIEDAM* 22 (2): 85–100.

Logie, R. H. 2003. “Spatial and Visual Working Memory: A Mental Workspace.” In *Cognitive Vision: The Psychology of Learning and Motivation*, edited by D. E. Irwin and B. H. Ross, Vol. 42, 37–78. San Diego, CA: Academic Press.

Lorch, R. F., and J. L. Myers. 1990. “Regression Analyses of Repeated Measures Data in Cognitive Research.” *Journal of Experimental Psychology: Learning, Memory, and Cognition* 16 (1): 149–157. doi:10.1037/0278-7393.16.1.149.

Okudan, G. E., M. Ogot, and R. Shirwaiker. 2006. “An Investigation on the Effectiveness of Design Ideation using TRIZ.” Proceedings of IDETC/CIE 2006 Design Education Conference, Philadelphia, PA, September 10–13.

Orloff, M. A. 2006. *Inventive Thinking Through TRIZ: A Practical Guide*. New York: Springer.

Ramde, D. 2009. *Energy-Efficient Traffic Lights Can't Melt Snow*. Associated Press. Accessed February 26, 2014. http://www.utsandiego.com/news/2009/Dec/15/energy-efficient-traffic-lights-cant-melt-snow/.

Rantanen, K., and E. Domb. 2002. *Simplified TRIZ: New Problem Solving Applications for Engineers & Manufacturing Professionals*. St. Lucie: Times Mirror, London.

Richland, L. E., and I. M. McDonough. 2010. “Learning by Analogy: Discriminating Between Potential Analogs.” *Contemporary Educational Psychology* 35 (1): 28–43. doi:10.1016/j.cedpsych.2009.09.001.

Sartori, J., U. Pal, and A. Chakrabarti. 2010. “A Methodology for Supporting “Transfer” in Biomimetic Design.” *AIEDAM* 24: 483–506.

Shah, J. J., S. M. Smith, and N. Vargas Hernandez. 2003. "Metrics for Measuring Ideation Effectiveness." *Design Studies* 24 (2): 111–134.

Sprenger, A. M., S. M. Atkins, D. J. Bolger, J. I. Harbison, J. M. Novick, J. S. Chrabaszcz, and M. R. Dougherty. 2013. "Training Working Memory: Limits of Transfer." *Intelligence* 41 (5): 638–663. doi:10.1016/j.intell.2013.07.013.

Torrance, E. P. 1998. *Torrance Tests of Creative Thinking: Norms*. Bensenville, IL: Scholastic Testing Service.

Trey, L., and S. Khan. 2008. "How Science Students Can Learn about Unobservable Phenomena Using Computer-Based Analogies." *Computers & Education* 51 (2): 519–529. doi:10.1016/j.compedu.2007.05.019.

Trickett, S. B., J. G. Trafton, and C. D. Schunn. 2009. "How Do Scientists Respond to Anomalies? Different Strategies Used in Basic and Applied Science." *Topics in Cognitive Science* 1: 711–729. doi:10.1111/j.1756-8765.2009.01036.x.

Tzuriel, D., and A. Shamir. 2010. "Mediation Strategies and Cognitive Modifiability in Young Children as a Function of Peer Mediation with Young Children Program and Training in Analogies Versus Math Tasks." *Journal of Cognitive Education and Psychology* 9 (1): 4872. doi:10.1891/1945-8959.9.1.48.

Vargas Hernandez, N., L. C. Schmidt, and G. E. Okudan. 2013. "Systematic Ideation Effectiveness Study of TRIZ." *Journal of Mechanical Design* 135 (10): 101009. doi:10.1115/1.4024976.

Vargas Hernandez, N., L. Schmidt, G. Okudan, and J. Linsey. 2010. "Systematic Ideation Curriculum Effectiveness Investigation & Deployment to Enhance Design Learning." Computers and Information in Engineering Conference, Montreal, Quebec, Canada, August 15–18.

Vattam, S. S., M. E. Helms, and A. K. Goel. 2010. "A Content Account of Creative Analogies in Biologically Inspired Design." *AIEDAM* 24: 467–481.

Visser, W. 2009. "Design: One, but in Different Forms." *Design Studies* 30: 187–223.

White, C. S., and E. J. Caropreso. 1989. "Training in Analogical Reasoning Processes: Effects on low Socioeconomic Status Preschool Children." *The Journal of Educational Research* 83 (2): 112–118.