An Empirical Study of the Effectiveness of Selected Cognitive Aids on Multiple Design Tasks

Noe Vargas Hernandez, Linda C. Schmidt, Gul Okudan Kremer and Chun-Yu Lin

Abstract The objective of this work is to study the concept generation effectiveness of three cognitive design aids: TRIZ—an ideation method, Sketching—a representation format, and use of the Smartpen—a journaling technology. The hypothesis is that TRIZ, Sketching and Smartpen, each improve the effectiveness of the concept generation process. The participating subjects belong to Penn State's Introduction to Work Design (IE 327) course. The course focuses on concepts of work design and measurement applied to manufacturing and service industries with a focus on improving worker performance, health and safety analyses. In the paper, we report on two sequentially completed design case studies, which allowed us to study the same group of subjects under two conditions. The first case study involved redesigns of a wire-cutter and a screw driver to improve work productivity. The second case consisted of analyzing an ultrasound operation for which students suggested improvements to the workplace and a redesign of the ultrasound transducer taking into account ergonomics and human factors principles. Our results indicate that indeed the tested design aids improved the ideation effectiveness; Smartpen has done the best in terms of increasing quantity of ideas generated, and TRIZ was the best in enhancing novelty.

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Introduction

Creativity in engineering design contexts is an important element of innovation. Accordingly, practitioners in industry [1] and academicians are striving to develop tools and methods to improve creativity [2–4]; and appropriately, researchers have been investigating the impact of these tools and methods. In this paper, we investigate the impact on ideation effectiveness of three design tools and methods: sketching, sketching with Smartpen and TRIZ. Although dissimilar (sketching is a representation method, Smartpen is a technology tool, and TRIZ is an ideation method), these three design aids provide a cross-cutting view of creativity in engineering design, particularly in design—related courses. Since these design aids contribute to the creativity process, the authors refer to them as cognitive aids in the context of this paper.

Sketching has been recognized as a tool to improve ideation. McCormick [5] summarizes the importance of sketching as follows: "Sketching is the tool for innovation, and is so vital to the engineering process that it should be taught and used as an essential part of engineering education and professional practice." Shah et al. [6] also showed that sketching has advantages for collaborative design. Despite this fact, however, prior work on the impact of sketching on ideation is limited in many ways. For example, Bilda et al. [7] conducted a think-aloud experiment with experienced architects to see if sketching is necessary in conceptual design. Two separate design processes were employed: one with sketching and the other prohibiting sketching and using a blindfold. The data was analyzed on the design outcome, cognitive activity and idea links. They report no significant difference between sketching and not sketching during conceptual design. However, they included only three subjects in the study, and hence, the result is not widely generalizable. In addition, while designing across different domains may have commonalities, transference of the results to engineering design domain may not be expected.

The Smartpen technology (www.livescribe.com) brings potentially additional cognitive benefits to sketching while designing: a Smartpen is a writing device that creates a visual recording of everything written or drawn with the pen tip via an infrared camera. The Smartpen can simultaneously create an audio recording. The device is designed to be used with special paper (provided in notebooks) so that the visual and audio records can be uploaded to a website in digital form for storage and playback via Livescribe software. Livescribe software also allows the sharing of the files by way of "pencasts" through email, Google Docs, facebook and similar sites. The simultaneous recording of the audio is useful in two ways: (1) it links what the user is hearing to what he is writing or sketching; and (2) the digitized pencasts can be transmitted to others through email or networking sites.

TRIZ is a systematic approach to the generation of innovative designs to seemingly intractable problems. It was first developed in Russia by Genrich Altshuller [8] in the early sixties and seventies and has been used for many years in

Europe and Asia. It is based on the analysis of thousands of patents. These original analyses articulated numerous solution patterns from diverse disciplines. The patterns and the tools are continually being updated by researchers worldwide.

TRIZ provides steps that allow design teams to avoid the "psychological inertia" that tends to draw them to common, comfortable solutions when better, non-traditional ones may exist. Despite the anecdotal evidence that TRIZ helps designers to be more creative, no comprehensive study showing its effectiveness has been done. For example, Ogot and Okudan [9] discussed the suitability of TRIZ for its introduction within the engineering curricula; Shirwaiker and Okudan [10] reviewed the design for manufacturing, manufacturing processes, and systems related TRIZ applications; and Shirwaiker and Okudan [11] proposed an ideation approach, which combines TRIZ and Axiomatic Design; and Okudan Kremer et al. [12] showed its effectiveness when used with mathematical programming. However, none of these studies address TRIZ effectiveness as an ideation tool relative to other ideation tools or cognitive aids.

Given the highlighted need for understanding effectiveness of sketching, sketching with Smartpen technology and TRIZ, we have undertaken empirical experimentations; here, we report our findings from one of our designed experiments. We assert that the ideation effectiveness comparisons of sketching and sketching with Smartpen with TRIZ are especially important in that while sketching can be considered more natural, intuitive for most engineers, TRIZ may not be. Below, we first review the recent works with a similar focus before we discuss our experimental design and results.

Literature Review

Stavridou and Furnham [13] state that during any creativity experiment, a researcher can focus on four major aspects: (1) the creative process, (2) the creative subject, (3) the creative outcome, and (4) the creative environment, where the task is performed by the subject following a process that is either predetermined (i.e., following a formal method) or not in order (i.e., freestyle creativity) to generate an outcome. The research questions could involve an intervention to the subject (e.g., designer) or to the process (e.g., ideation methods) or to improvements in the outcome. Most recent studies in this domain, however, focused either on studying the process and the individual's designing (process-oriented studies), or the outcomes of the process (outcome-oriented studies).

Process-oriented studies of design creativity usually have been done through protocol studies. Such a study consists of a non-unique decomposition of the process and evaluation of each step using different metrics. In the 90s, there was an increase in the number of protocol studies of design constructed as studies of design activity. Protocol studies suggest that creativity is related to the discovery process and it can be measured in this stage. For example, Dorst and Cross [14] used protocol studies to identify creative aspects in the design related to formulation of the design problem. Protocol analyses are labor-intensive; however, they provide the best way to explain the influence of the experimental technique, context and cognitive aspects of creativity within the process framework in an explicit way.

The outcome–oriented approach hypothesizes that any intervention influencing the subject or the process will be reflected in the output [15]. If the outcome is creative, then it will be assumed that the intervention had a positive effect. Table 1 below summarizes a sample of most recent output-oriented studies. As can be viewed in the table, in these studies data collection was done either in individual [16] or team level [17, 18] and using tasks that are decidedly easy to understand in a short amount of time. Duration of the idea generation in class ranged between 20 min and 1 h; in some cases, in class idea generation was complemented with incubation periods outside of the class [3].

Most studies (see Table 1) included metrics with specific definitions in order to more objectively analyze the data. Direct quantity measures dominate the studies, as is to be expected in any experimental undertaking. Quantity metrics are usually objective to implement and provide data that is analysis ready. Quantity of ideas is particularly important in creativity studies as it is a measure of fluency in creativity terms. Variations of quantity metrics have been used as well (e.g., number of unique ideas, number of analogous ideas, etc.). For evaluation of design quality, criteria-based judgment has been used [19, 20].

Novelty is also among the most frequently used metric in these studies. Novelty is a measure of how unusual an idea is as compared to other ideas. It relates to expanding the solution space, and is calculated by collecting and categorizing all ideas generated per design function, and counting the number of instances of a particular one given the whole idea set [15]. Novelty measurement is important in understanding how unique the generated ideas are.

An important observation relevant to the sample studies is that one single intervention has been tested per treatment group and personal qualities of the subjects have been assumed to be equivalent (e.g., personality, creativity levels, gender, etc.); one exception to this is that of White et al. [21] where the authors used the self-assessment of creativity on Gough's descriptors.

In an effort to understand how different cognitive aids might impact subjects differently, this study analyzes the novelty and quantity of generated ideas by student teams across two design case studies where subjects were given the benefit of two different cognitive aids across the cases.

Selection of the cognitive aids deserves explanation: we opted to experiment with cognitive aids that might be perceived as (1) more intuitive versus not, (2) requiring additional training versus not, (3) has potential to prompt distant analogies versus not. For example, while sketching might be perceived to be more natural to an engineering student, TRIZ may not be; the training amount to grasp TRIZ will be longer than that of sketching for many individuals; finally, TRIZ has the potential to retrieve design principles that are not immediately thought of by the designer.

Table 1 A sample of outcome-oriented studies

Authors (year)	Subjects	Task	Duration	Design representations	Outcome measures
Yang [18]	Three courses approx 24 ME students each, subjects work in teams of 2–5	Pop a helium balloon suspended over a water pond	10 weeks	Paper based logbooks	Final grade; team ranking in competition
Okudan et al. [3]	121 engineering students, and 27 non-engineering students working in 4 person teams	Design of an affordable biomass cooker for rural communities	30-min in class idea generation period, followed by a 5 day incubation	Sketch and written explanation	Novelty; variety; quantity; number of unique ideas per experimental group
White et al. [21]	8 senior level design teams (5 or 6 per team) and 7 freshmen level teams (2 per team); pre-and post- test: self-assessment of creativity on Gough's descriptors	Design task differed by team	For each ideation method 30–60 min of training on methods; 60–90 min for idea generation	No information given	Quantity
Linsey et al. [19]	60 ME seniors in design methods course participants; extra credit	Quick peanut shelling	40-min idea generation period	Gallery View and rotational view of text only, sketches only, and text with sketches	Quantity; quality (rated by two judges); novelty; variety—measured per person
Vargas Hernandez et al. [17]	350 engineering undergrads, 14 groups of 25, 256 undergrad students from intro to psychology	Engineering: transport ping pong ball; psychology: tools for alien race	In class ideation sessions 20 min each, one week incubation	Sketches with labels, except for flexible representation (sketch vs. text vs. free J)	Quantity, quality, novelty, variety

(continued)

Table 1 (continued)

Authors (year)	Subjects	Task	Duration	Design representations	Outcome measures
Lopez et al. [16]	17 Undergraduate ME students and 1 graduate student	Quick peanut shelling	40-min idea generation period, followed by subject rating of ideas and surveys	No information given	Quantity of : ideas, analogous (and non) ideas, and emergent features; semantic distance; similarity rating
Chan et al. [20]	153 senior engineering students (95 % ME) three factor- two levels each factorial experiment	Low-cost, portable device to harvest energy from human motion	30-min idea generation period examples were provided at specific time intervals	Sketches	Degree of solution transfer; quantity; breadth of search; Novelty; quality rated by two students on 6 performance dimensions
Cardosa and Badke Schaub [28]	60 industrial design engineering students, fourth year master students.	Device to retrieve a book from an out-of-reach shelf	1 h idea generation period	Sketch and written explanation	Quantities: ideas, key example attributes, solution categories; originality; ease of use and manufacture; book damage

Indeed, intuitiveness of sketching for many designers is clear in its widely used description: sketching is a designer's conversation with themselves. Further, researchers in engineering, architecture, art, education, and psychology used protocol analyses to ascertain cognitive aspects of sketching in design; the reader is referred to analysis of work on that topic by Purcell and Gero [22]. More recently, Cardella et al. [23] conducted a protocol study on engineering students, where the results reinforced that sketching supports communication and that sketching is a large part of the problem scoping stage. This study also correlated the representation activities (like sketching) to higher quality solutions. This finding is consistent with various other researchers whose work either showed that sketching aids designers/engineers work [24, 25] or there is a link between sketching and design thinking [7, 26].

We have used Smartpen-based sketching in our experimentation, along with regular (i.e., paper and pencil-based) sketching, which provides audio support as the designer reviews and progresses their design through sketching.

TRIZ has been recognized as a concept generation process that can develop clever solutions to problems by using the condensed knowledge of thousands of past inventors. The power of TRIZ, therefore, is its inherent ability to bring solutions from diverse and seemingly unrelated fields to bear on a particular design problem, yielding breakthrough solutions. Overall, TRIZ invites the designer to use a ready pool of knowledge for inspiration, retrievable through a systematic procedure. This systematic procedure affords the designer the benefit of a set of design principles that have worked before; in many cases these design principles can be considered to act as analogies that may not be native to the designer.

In the next section we explain the experimental set-up

Methods

The experiment included students (N = 79) from an Introduction to Work Design (IE 327) course, where all the students are junior-level industrial engineering majors. The course focuses on concepts of work design and measurement applied to manufacturing and service industries to improve worker performance through health and safety analyses. Throughout the semester students participate in eight lab sessions where they experiment with certain products or work settings that are to be redesigned. Two case studies were selected from these eight lab sessions that were conducted four weeks apart. The first took place during the 4th week, and the second during the 8th week of the semester.

Case Study 1 The first case study involved redesigning a wire-cutter and a screwdriver in order to reduce the Cumulative Trauma Disorder (CTD) related injuries in an assembly plant. The lab session started with observing a video clip and then performing a CTD Risk Analysis on assembler's right hand. Then, in order to estimate how much force is required to do the job, students were asked to cut several wires, and then squeeze the grip dynamometer equally hard. After this hands-on experience, students were asked to redesign the wire-cutter and the screwdriver to reduce the CTD risk and make the assembly possible with less force.

Case Study 2 The second case study focused on sonography, a diagnostic medical procedure that uses high frequency sound waves (ultrasound) to produce dynamic visual images of organs, tissues, or blood flow inside the body. The process involves placing the ultrasound transducer against the patient's skin near the body area to be imaged. Musculoskeletal disorders (MSDs) are common amongst sonographers. Students are provided with a set of survey results indicating anatomical sites of discomfort, percentage of sonographers affected, and types of activities leading to discomfort and pain, and are then asked to design a better ultrasound sonography process addressing both the physical, musculoskeletal issues stemming from using the physical device itself.

The course (IE 327) lab has six sections from which four were used in the experiment (for three treatments and one control group). Each of these four sections contains five groups of three or four people. Three different cognitive aids for concept generation were tested: TRIZ, sketching, and sketching using a Smartpen. The cognitive aids were randomly assigned to each section. In addition, one of the sections was used as the control group and no specific cognitive aid was assigned to the students. The lab instructor explained the case study and presented the information to each section. The lab instructor trained each section in their respective cognitive aid (i.e., treatment). The students were given a full week to come up with their redesigns. There were no constraints on the time allowed to come up with the ideas or the number of ideas. The overall case grade took into consideration all the aspects of the case study, including the tool redesign as well as the workstation, process, etc. It also took into consideration the report format, and grammar. Note that even though all the students agreed on participating in the study and signed the consent form, there were some groups that did not follow the method assigned to them; hence, relevant data points were excluded from the analysis.

Results

Upon return of the student work, lab reports were graded for correctness of the technical content by the lab instructor; Table 2 below displays these results for each treatment group.

Submitted designs from each group were tabulated describing each idea provided (Case 1 broken down into functions: screwdriver and wirecutter). The tabulated data were then used to calculate the quantity (total ideas generated by each team) and novelty (indicating how unique each provided idea is). Quantity and novelty data are shown in Tables 3 and 4. Sample designs are also provided in the Appendix.

Table 2 Ideation methods assigned to groups and grades

Section #	Group #	Gender	# Students per group	Method for CS#1	Used the method?	Case study #1 grade	Method for CS#2	Used the method?	Case study #2 grade
1	1	1F3M	4	Sketching	Y	85.5	TRIZ	Y	99
1	2	4M	4	Sketching	Y	68.5	TRIZ	Y	76
1	3	4M	4	Sketching	Y	80	TRIZ	Y	94
1	4	2F2M	4	Sketching	Y	88.5	TRIZ	Y	77.5
1	5	1F3M	4	Sketching	Y	89	TRIZ	Y	93
2	1	4M	4	Control	Y	74.5	Sketching	Y	93.5
2	2	1F2M	3	Control	Y	85	Sketching	Y	97
2	3	3M	3	Control	N	75.5	Sketching	Y	78.5
2	4	4M	4	Control	Y	85	Sketching	Y	87.5
2	5	4M	4	Control	Y	77.5	Sketching	Y	97.5
3	1	3F2M	5	TRIZ	Y	91	Smart pen	Y	90
3	2	1F3M	4	TRIZ	N	84	Smart pen	Y	83
3	3	1F3M	4	TRIZ	N	83	Smart pen	N	84.5
3	4	4M	4	TRIZ	Y	96.5	Smart pen	Y	92
3	5	4M	4	TRIZ	N	80	Smart pen	N	89.5
4	1	2F2M	4	Smart pen	Y	77.5	Control	Y	89
4	2	1F3M	4	Smart pen	Y	94	Control	Y	87.5
4	3	1F3M	4	Smart pen	Y	90	Control	Y	94
4	4	4M	4	Smart pen	Y	83.5	Control	Y	83.5
4	5	1F3M	4	Smart pen	Y	83.5	Control	Y	90.5

Table 3 Quantity results (quantity values for case study #1 covers both designs)

Section #	Case study #1	Quantity screwdriver	Quantity wirecutter	Case study #2	Quantity
1	Sketching	3.00	3.00	TRIZ	2.20
2	Control	1.50	3.50	Sketching	2.80
3	TRIZ	5.00	2.50	Smart pen	3.67
4	Smart pen	4.6	4.60	Control	2.60

Results, presented below in Tables 3 and 4, can be summarized as follows: we provide a rank order of cognitive aids as well the course section (in parentheses) in descending values of the performance metric of interest. For example, a quick review of Table 3 verifies that TRIZ intervention (undertaken by section

Table 4 Novelty results (as summation of ideas with different novelty points)

Section #	Case study #1	Novelty screwdriver	Novelty wirecutter	Case study #2	Novelty sonography
1	Sketching	0.82	1.70	TRIZ	0.95
2	Control	0.58	0.57	Sketching	0.99
3	TRIZ	1.80	2.0	Smart pen	1.02
4	Smart pen	1.25	1.27	Control	0.75

"Methods") resulted in the highest quantity (5). These rankings show that across all interventions and sections, TRIZ and Smartpen interventions and section "Methods" and section "Results" seem to be better in comparison to others.

The following rankings compare each section (i.e., treatment) for each of the case studies.

Quantity Value Result Ranking Comparison by Treatments:
Case Study #1—Screwdriver
TRIZ (sec3) > Smartpen (sec4) > Sketching (sec1) > Control (sec2)
Case Study #1—Wire-cutter
Smartpen (sec4) > Control (sec2) > Sketching (sec1) > TRIZ (sec3)
Case Study #2
Smartpen > (sec3) Sketching (sec2) > Control (sec4) > TRIZ (sec1)
Novelty Value Result Ranking Comparison by Treatments:
Case Study #1—Screwdriver
TRIZ (sec3) > Smartpen (sec4) > Sketching (sec1) > Control (sec2)
Case Study #1—Wire-cutter
TRIZ (sec3) > Smartpen (sec4) > Sketching (sec1) > Control (sec2)
Case Study #2
Smartpen (sec3) > Sketching (sec2) > TRIZ (sec1) > Control (sec4)

Although these rankings provide easy to understand comparisons, convergence on both the interventions as well as the course sections makes it difficult to draw conclusions. In other words, it is not clear if the success observed in high performance of quantity and novelty is a result of the interventions (TRIZ and Smartpen) or the characteristics of the students in course sections "Methods" and "Results". Our relevant research questions can be expressed more explicitly as follows:

1. For all three conditions, which section performed the best in terms of quantity?
2. For all three conditions, which section performed the best in terms of novelty?
3. For all three conditions, which treatment (ideation method) performed best in terms of quantity?
4. For all three conditions, which treatment performed the best in terms of novelty?

To select the best performing course section and cognitive aid from the results on the three different design problems we use the Borda count selection process [27]. In Table 5, the first three columns from left show the quantity and novelty values

Table 5 Borda Counts for sections and treatments

Section #	Quality borda count	Novelty borda count	Treatment	Quality borda count	Novelty borda count
1	1	0	Sketching	4	4
2	4	2	Control	3	0
3	6	9	TRIZ	3	7
4	6	4	Smart pen	8	7

for each section, and the rest of the columns to the right show the quantity and novelty values per treatment. The Borda count process helps select the best option out of a ranked ordered set of options by giving ascending weights (starting with n − 1 to 0) across cases. For example, for the screwdriver case study ranking of the treatments under the quantity metric, TRIZ (also sec3) gets a weight of 3, Smartpen gets 2, Sketching gets 1, and Control gets 0 as a weight (or a multiplier). Instances of the same treatment (e.g., TRIZ) are then summated across rankings with the appropriate weights.

A review of Table 5 shows that sections "Methods" and "Results" fared better compared the other two in terms of quantity, and TRIZ and Smartpen treatments were better in terms of novelty.

Borda counts, however, cannot explain if either section grouping or treatments are statistically significant in their effect on the performance measures (quantity and novelty). Accordingly, we proceeded with further statistical analysis of the data.

We have investigated the significance of these main effects using general linear models (GLM) where we have taken the course grade and the student count per team as co-variates. It was considered that the overall course grade might reflect students' ability, experience, and overall motivation in completing these design tasks, and we also wanted to ensure that our results were not confounded due to number of students in teams. Although most teams were 4 person teams, we had a few 3-person teams, and one 5-person team. Two GLMs, solved once for novelty and once for quality are shown below.

As it can be observed below, indeed, treatment is found to be a significant ($p = 0.048 < 0.05$) factor for its impact on novelty, and among the treatment options TRIZ seems to induce the highest values for novelty (see Fig. 1). A similar analysis was done for quantity (see Fig. 2); in this case, however, none of the main effects were significant. Among the treatment options, Smartpen seemed to produce the highest quantity in the generated ideas.

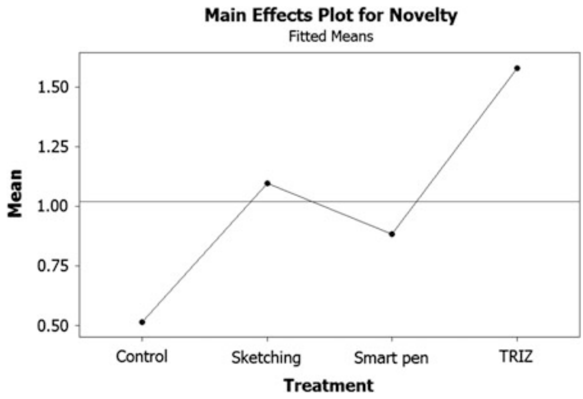

Fig. 1 Mean novelty values for treatment alternatives

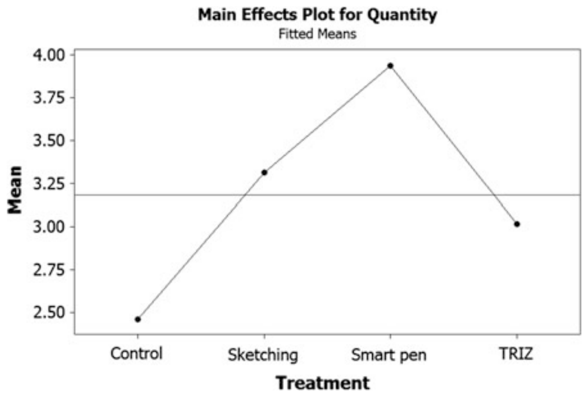

Fig. 2 Mean quantity values for treatment alternatives

General linear model: novelty versus treatment

Factor	Type	Levels	Values			
Treatment fixed 4 Control, Sketching, Smart pen, TRIZ						
Analysis of Variance for Novelty, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Section	1	1.2508	1.6380	1.6380	3.04	0.089
Student/team	1	0.0186	0.4126	0.4126	0.77	0.387
Course grade	1	0.0401	0.0696	0.0696	0.13	0.721
Treatment	3	4.6370	4.6370	1.5457	2.87	**0.048**
Error	43	23.1879	23.1879	0.5393		
Total	49	29.1344				

Based on these presented, we assert that indeed ideation treatments have been found to impact design creativity outcomes, more specifically for our case: quantity and novelty.

General linear model: quantity versus treatment

Factor	Type	Levels	Values			
Treatment fixed 4 Control, Sketching, Smart pen, TRIZ						
Analysis of Variance for Quantity, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Section	1	14.695	2.727	2.727	1.32	0.257
Student/team	11.030	0.254	0.254	0.12	0.728	
Course grade	1	0.224	0.020	0.020	0.01	0.922
Treatment	3	13.212	13.212	4.404	2.13	0.110
Error	43	88.839	88.839	2.066		
Total	49	118.000				

Discussion

Various researchers study the impact on creativity in engineering design as measured by assessing the number and novelty of the output given to a specific design problem. Empirical studies are done most often using students and factorial designs that attempt to isolate the impact of a single treatment on the designing task results. When sufficient numbers of students are available a control group will be included in the experimental design. Having a control group allows the results of different treatment interventions on students with the underlying assumption that the student groups all have the same base-level experience, aptitude and motivation to perform the designing tasks. This is not automatically the case.

This work is different from the other creativity studies cited in that the reported results came from introducing the same interventions on each group of students in a series of treatments (e.g., section "Methods" used TRIZ to solve cases 1 and 2). The reported results for each intervention are from sections of the same students working in the same groups. Thus, the cumulative impact of personality and motivation are eliminated as sources of variation within each group and each ± ion and among treatment results for the same groups. There may still be differences between sections, although as the number of students per section increases, the differences will tend to diminish.

The Borda count was used as a simple indicator to select the treatments and sections that performed the best in terms of quantity and novelty of design results. The Borda count was able to identify the best (highest ranking) sections and treatments for each performance measure. The advantage of the Borda count is that it is simple to use, not requiring any statistical calculations. Naturally, then, no statistically significant conclusions can be drawn using the Borda count.

The results found by the Borda count were verified and supplemented by the GLM analysis. This analysis identified the treatment to be statistically significant in producing different results than the other factors. The GLM analysis showed that the section and group effects were not statistically significant in the presence of the interventions. Furthermore, it was shown that grades were not significant in describing the difference in results. Interestingly, the section effect was significant at a p-value of 10 % on novelty.

One final observation is that the results for the sketching and Smartpen groups were very similar on novelty but the Smartpen produced higher quantity (numbers of ideas) in the results than the other treatments. The authors hypothesize that this reflects a positive bias on the part of students toward playing with new technology.

Conclusion

The experiments reported here indicate that the use of TRIZ aids student groups in the design tasks by improving the quantity and novelty of the ideas generated in two case studies over the control groups. The use of sketching, with and without the Smartpen technology improved the number (quantity) of ideas generated. These conclusions are limited to the experimental scope; nevertheless, these are relevant to improve our understanding of key cognitive aids for creativity. The importance of accounting for variation in results due to subject personality and motivation factors is discussed.

Appendix A: Samples for Ideas Generated

(Fig. 3)
(Fig. 4)
(Fig. 5)
(Fig. 6)
(Fig. 7)

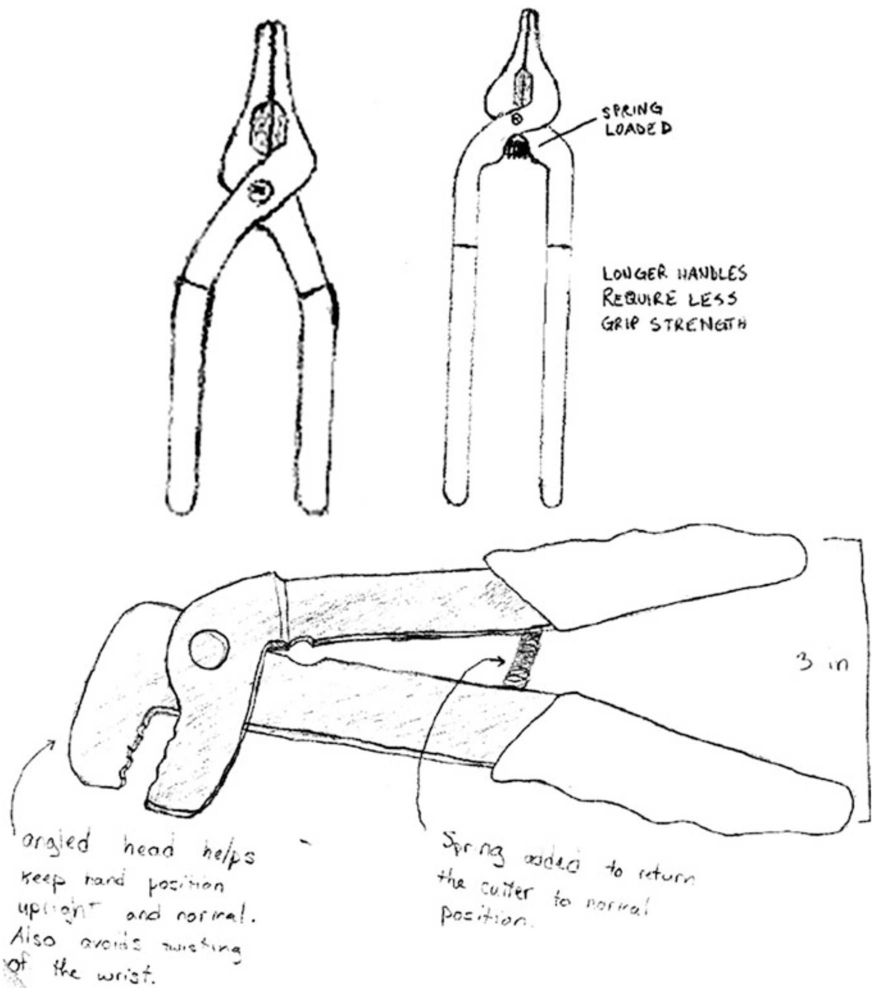

Fig. 3 Set 1 old pliers (*Less Torque*) new pliers (*More Torque*) and wire cutter redesign

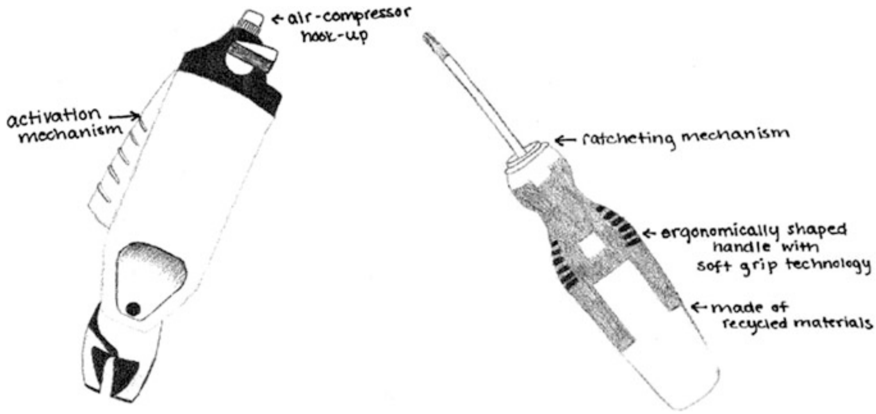

Fig. 4 Set 2 compressed activated pliers and ratcheting screwdriver

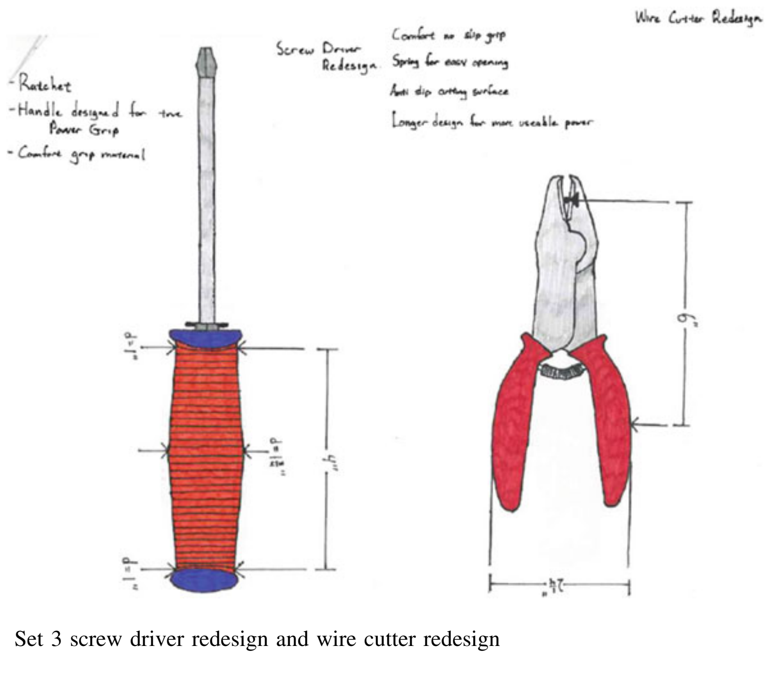

Fig. 5 Set 3 screw driver redesign and wire cutter redesign

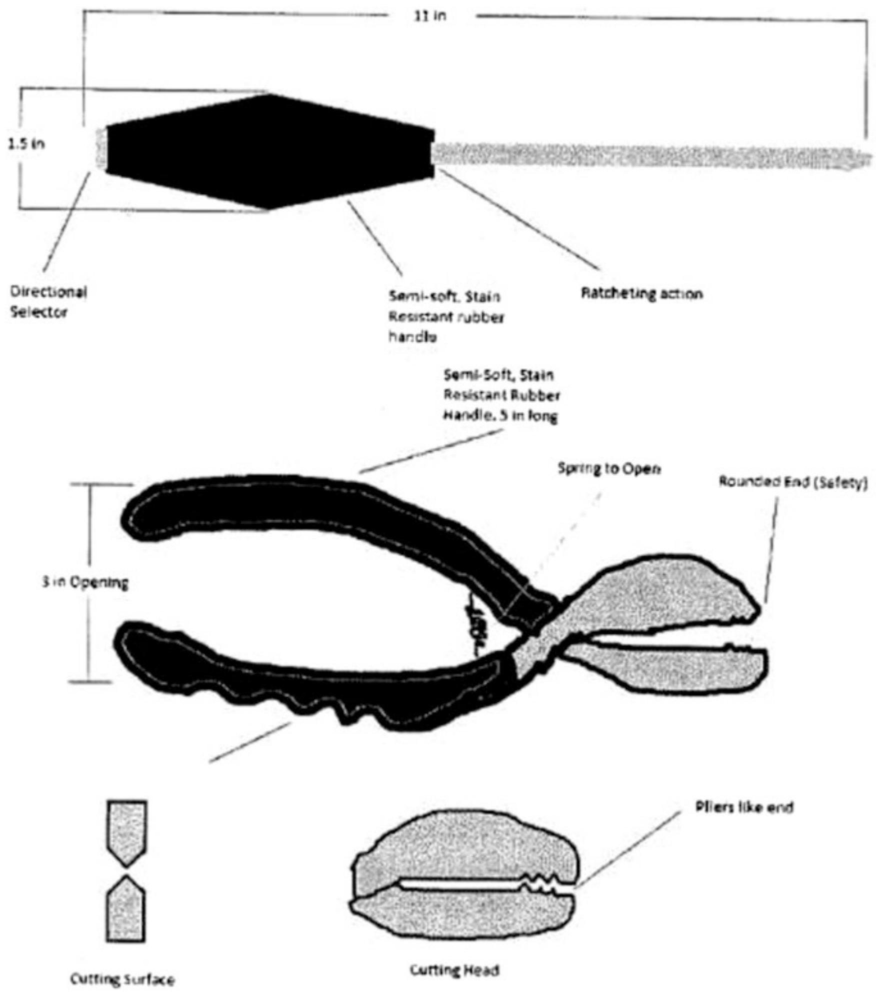

Fig. 6 Set 4 screwdriver redesign and wire cutter redesign

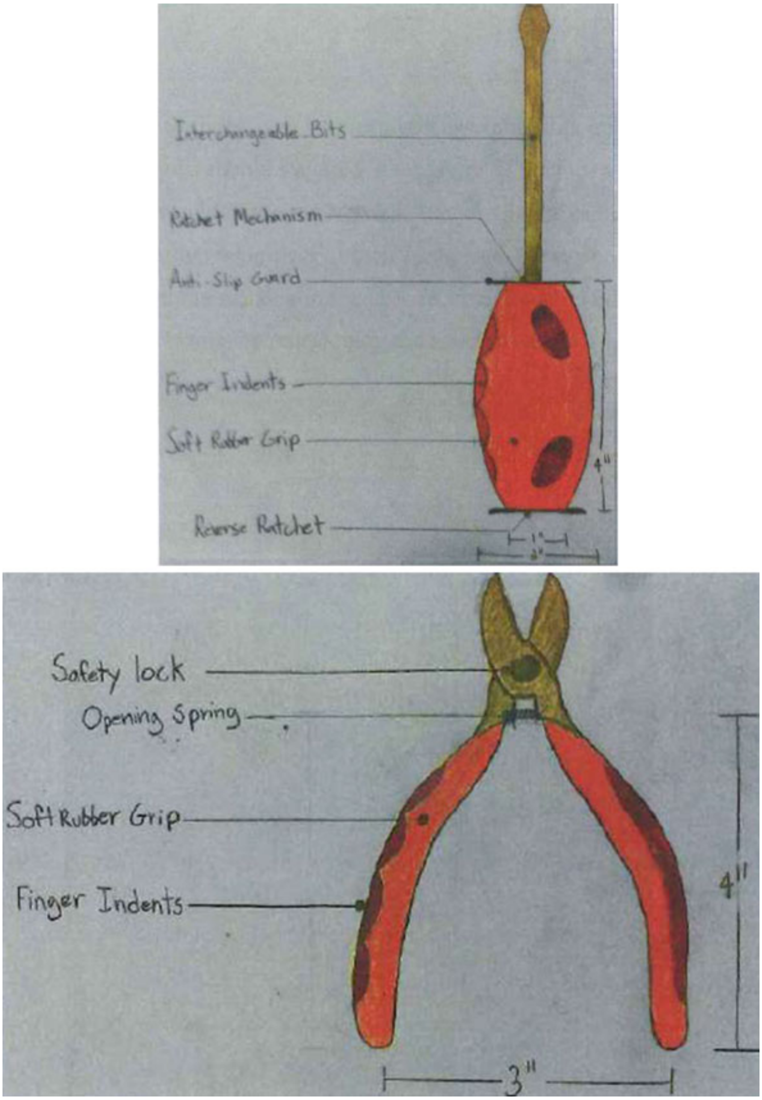

Fig. 7 Set 5 screw driver redesign wire cutter redesign

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