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# INVESTIGATING EFFECTS OF STIMULI ON IDEATION OUTCOMES

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## Abstract

This research investigates the effects of using stimuli, such as patents, on ideation outcomes, through the research questions: (a) What is the effect of stimuli on ideation outcomes? and (b) What is the effect of stimuli distance on ideation outcomes? An experiment to address these questions entails an ideation exercise involving 105 participants generating 226 concepts without or with patents and other resources. Significant findings are: (a) more concepts are generated with patents than without patents, (b) more concepts are generated with patents identified by participants on their own than using pre-chosen patents, (c) more concepts are generated using both patents and other resources than other degrees of stimulation, (d) concepts developed using both patents and other resources have higher novelty and quality than concepts generated without any stimuli, and (e) no significant correlations are observed between the proximity of stimuli to problem domains with novelty and quality of concepts. These results have practical implications on using stimuli to improve ideation outcomes for designers, design teams, and organisations, and motivate investigation into the stimuli used.

**Keywords**: Conceptual design, Creativity, Design engineering, Patents, Analogical design

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# 1 INTRODUCTION

Design creativity is the ability of an agent to develop outcomes that are both novel and useful, to address a design opportunity (Sarkar and Chakrabarti, 2011). Conceptual design – an early design phase in which solution principles are developed – is important for several reasons: a successful final solution is likely to originate by exploring a variety of solution principles rather than focusing on details (Pahl et al., 2007), allows greater scope for creativity because it is easier to make changes that are less expensive but have greater impacts than the downstream phases (French, 1988), etc. Several methodical aids to foster creativity during concept generation have been proposed. One among these is to provide stimuli to identify analogies from them for generating concepts and is considered one of the potent and useful methods (Chakrabarti et al., 2005; Chan et al., 2011). On one hand, stimuli can benefit concept generation to help develop multiple, creative solutions, enhance novelty, inhibit fixation, etc. (Chan et al., 2011; Goel, 1997; Linsey et al., 2010; Qian and Gero, 1996), but, on the other hand, they can also cause bias and fixation (Jansson and Smith, 1991). Therefore, stimuli need to be methodically chosen before using them.

Patents have been explored as sources of stimuli for engineering design. Patent documents contain technical descriptions of products or processes which are both novel and functional, from various domains. In engineering design, patent databases have been used for the study of current technologies, forecast of future technologies, generation of new solutions, representation and modelling of technologies, etc. (Fantoni *et al.*, 2013; Fu *et al.*, 2014; Murphy *et al.*, 2014). Although descriptions in patents are detailed and precise, inventors tend to hide more than disclose information in these descriptions (Fantoni et al., 2013). Consequently, these descriptions are not amenable to explain the working of products and processes. Therefore, questions relating to whether or not patents can be used as stimuli, and what patents can or cannot be used to improve concept generation persist.

The broad objectives of this research are: (a) to validate the efficacy of using patents, identified in different scenarios, as stimuli for concept generation, and (b) through this validation to identify avenues for developing methods and tools for searching and identifying relevant patents from several millions of patents in patent database for effective inspiration. The research in this paper examines the effects of using patents – sourced from technology fields located at different distances from the domain of a design problem – as stimuli for ideation on attributes of ideation outcomes.

# 2 LITERATURE REVIEW AND RESEARCH QUESTIONS

In this section, relevant literature is reviewed and detailed research questions are posed.

## 2.1 Analogical Design

Analogies are defined as similarities between seemingly unrelated objects in one or more aspects. Analogical design is the transfer of analogical information from objects in the source domain to objects in the target domain, to solve problems in the target domain (Goel, 1997; Hey et al., 2008; Qian and Gero, 1996). Researchers have explored various aspects of analogical design. However, to fit the scope of this research, only those that use patents as stimuli for ideation are reviewed here.

Chan *et al*. (2011) investigated empirically the effects of analogical distance (near vs. far), analogical commonness (more- vs. less-common), and the modality of stimuli representation (text vs. image) on various ideation metrics (extent of transfer of features from stimuli, breadth of search, quantity, quality, and novelty of outcomes), using patent stimuli from the US patent database. Chan *et al*. found that far-field analogies help develop concepts of higher novelty, higher variability in quality, greater solution transfer but fewer concepts than near-field analogies.

Fu *et al*. (2013a) developed a computational technique to quantify the similarities of functional and surface contents with the intent to automatically identify patents at different analogical distances, to be potentially used as stimuli for engineering design ideation. The tool generated Bayesian networks of patents based on functional and surface similarities (function and surface features correspond to verbs and nouns, respectively). In addition, several sub-clusters were also manually created within the networks based on similarity of functional and surface contents.

Fu *et al*. (2013b) conducted a design experiment to study the effect of analogical distance on the performance of concept generation using 45 patents from the US patent database as stimuli. The patents are structured into "near" and "far" based on latent semantic analysis and a Bayesian-based algorithm. Fu et al. found that far analogies helped generate concepts of lower novelty and quality than concepts generated using near analogies and no analogies.

Murphy *et al*. (2014) developed a methodology to systematically search and identify functional analogies from the US patent database. The methodology broadly comprises the following steps: (a) process patents to identify a vocabulary of functions, (b) define a set of functions in patents comprising 8 primary, 74 secondary and 1618 correspondent functions, (c) index patents using the functional set to create a vector representation of the patent database, (d) develop tools for query and estimate relevance of patents to query, and (e) retrieve and display patents relevant to query. The methodology is tested by applying it to two cases to identify functionally similar analogies.

Fu *et al*. (2014) proposed a methodology to support designers to search and identify functional analogies extracted from the US patent database, and tested its effectiveness in terms of novelty and quantity of solutions. The methodology is intended to systematically search and identify functional analogies, and subsequently, to use these to develop innovative concepts. The experiment involved a control group which did not use any analogies, and three experimental groups which used analogies for supporting various levels of functions. Between the different groups the following were observed: no significant difference in the quantity of solutions and the experimental group with all functions supported developed solutions of higher novelty than the control group.

### 2.2 Summary and Research Question

Many researchers used patents as stimuli to improve ideation. While there exists clear evidence that the use of patents is beneficial, but the studies are based on small samples of stimuli. These small samples may not be representative of the possible space of stimuli that could be used to improve ideation. Moreover, the findings in literature have not been consistent across studies for various reasons, including the lack of a common frame of reference with which to compare. Due to these inconsistent findings, it would be hard to predict the effects of using patents as stimuli and thus, create blockades in using patents. Therefore, the research pursued here seeks to validate the efficacy of using patents as stimuli for concept generation, through the specific research question: What is the effect of using patents as stimuli on novelty and quality of concepts?

## 3 RESEARCH METHODOLOGY

In this section the research approach, including the design exercise and data analysis, is described.

### 3.1 Design Exercise

Data from an ideation exercise of the course 30.007 Engineering Design and Project Engineering at the Singapore University of Technology & Design (SUTD) is used for this research. This course is intended for students in the Engineering Product Development Pillar (https://epd.sutd.edu.sg/) for holistic understanding and competency in engineering design. This ideation exercise is a part of a design project which runs throughout the course. The objective in this project for each team is to conceive, design and develop a spherical rolling robot for system requirements of their choosing, and fabricate and demonstrate a working prototype. This objective is deliberately kept open-ended to provide design teams the flexibility to develop concepts and a working prototype for an innovative application of their own choice. Here, a concept is defined as an overall solution, which can comprise multiple sub-functions and sub-systems. 105 participant designers are divided into 21 teams comprising 4-6 members in each team. These designers have undertaken several design courses and structured design projects prior to this project. The overall approach followed by the participants is illustrated in Figure 1. Concept generation is an individual activity and data from this phase is used in this research.

To explore the effects of patents as stimuli, the research team prepared two sets of patents for the participants to read and identify stimuli. The most cited US patent from each of the 121 3-digit patent technology classes, defined by the International Patent Classification (IPC) system, is provided. The forward citation count of a patent is highly correlated to its realised value or importance (Trajtenberg, 1990; Hall et al., 2005). These 121 patents comprise the first set (Most Cited category). In addition, a random patent – identified using a random number generator – is also provided from each of the 121 3-digit IPC patent technology classes. These 121 random patents constitute the second set (Random category). The patents from the Most Cited and Random categories provide the basic coverage of patents from all the technology classes in the total technology space. These patents are located at various distances from the field of spherical rolling robots.

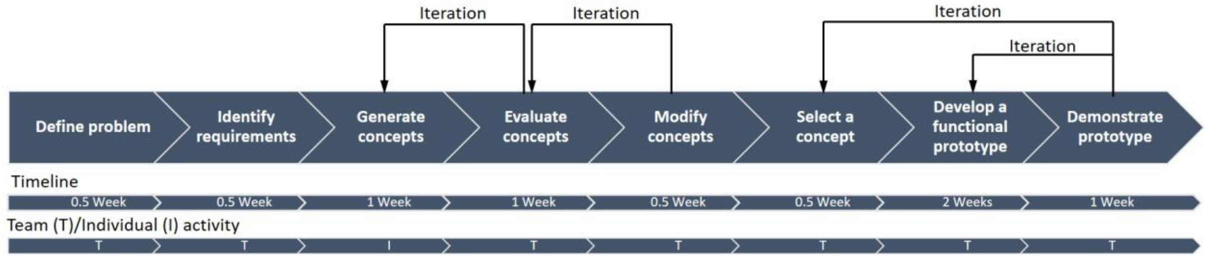



*Figure 1: Design and development stage-gate process with timeline delineating team and individual activities*

Figure 2 is a network representation of the technology space (Alstott et al., 2016). This network comprises all the 121 patent technology classes, represented as nodes, excluding several undefined patent classes, in the IPC system. More than 4 million US patents issued between 1976-2010 can be located within the different classes of the technology space based on their classification. The size of each node is proportional to the number of patents in that node. Each node is positioned based on its knowledge proximity to other nodes. Knowledge proximity between different technology fields (operationalised by patent classes here) can be calculated using various metrics with the information of patent citations or classifications such as Jaccard index, cosine similarity, co-occurrence, etc. (Alstott et al., 2016; Yan and Luo, 2016). For the network in Figure 2, knowledge proximity is calculated using Jaccard index, recommended by Yan and Luo (2016) as a superior choice, because the network based on Jaccard index is most correlated with the maps based on other knowledge proximity measures and thus, the most representative of the alternative measures. Jaccard index is the ratio of the shared references of patents in a pair of classes over the total number of unique references of patents in both these classes. The index is higher when patents in both classes share more references, indicating higher knowledge proximity between the technology fields they represent.

If design process in two fields requires distant or distinct scientific and design knowledge, i.e., low knowledge proximity, designers in one field may find it difficult to understand or design using knowledge and technologies from the other field (Luo, 2015). Prior patent data analysis has statistically shown that inventors are more likely to succeed in filing patents in proximate fields in the space (Alstott et al., 2016; Triulzi *et al.*, 2016). The thickness of links connecting a pair of technology classes, i.e., nodes, is proportional to the knowledge proximity between them. Though almost all the nodes are connected in the technology space network, only the strongest 120 links that connect all the 121 nodes are shown, i.e., a maximal spanning tree (Yan and Luo, 2017). Figure 2 also shows the two technology classes in which most patents related to spherical rolling robots are identified: A63 (Sports and amusements) and B62 (Land vehicles). These are considered the home or design problem domains for spherical rolling robots. The patents in the Most Cited and Random categories in the 121 technology classes are located at different knowledge distance from the home domains.

For each team comprising 4-6 members: (a) 1-2 participants are provided no stimuli (control condition), (b) 1-2 participants are provided with the most cited patent documents from each of the 121 technology classes of the technology network (forward citation group; experimental condition), and (c) the remaining participants are provided with 121 randomly chosen patents, one from each of the 121 technology classes of the technology network (random group; experimental condition). The participants in the experimental groups are provided with the title, abstract and images of these 242 patent documents. If the participants find these contents relevant and inspirational to their design problem, they are expected to read the sections on technical description of the patents in more detail for specific design concept stimulation. In addition to the given 242 patents, all the participants are also allowed to use other resources (such as the internet, books, databases, etc.).

The participants are instructed to generate functional and novel concepts, but not maximise the number of concepts generated. The participants are asked to sketch concepts with annotations and briefly explain how they work. In addition, the participants must also document the following: patents used, other resources accessed, and how stimuli are transformed into concepts. The participants are given a week to generate concepts. A consent form for approval is collected from all the participants. A pre- and a postideation survey is conducted to collect information relating to age, gender, academic background, nationality, and other demographic data of the participants, to understand their experience of using patents a priori and posteriori to this exercise, the effects of their usage, and other related factors.

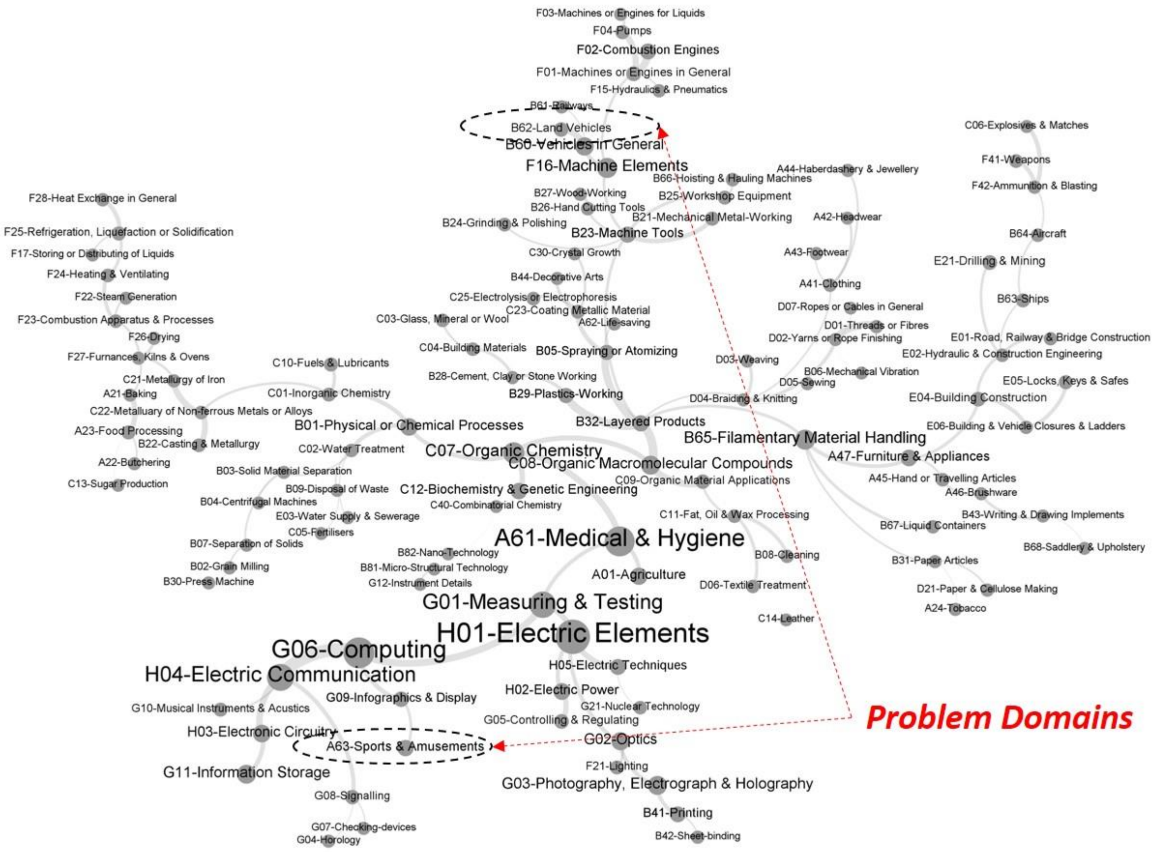



*Figure 2: Technology space network comprising 121 IPC technology classes*

## 3.2 Data Analysis

In literature, various metrics have been proposed to assess the performance of ideation, in terms of the attributes of the design outcomes of ideation, such as quantity, quality, novelty, variety, usefulness, feasibility, similarity, etc. (McAdams and Wood, 2002; Shah et al., 2003; Sarkar and Chakrabarti, 2011). In this research, we use novelty and quality to assess the effect of using patents. From the documentation, the stimuli used to generate concepts are identified and, novelty and quality of generated concepts assessed using the sketches and annotations of concepts as described henceforth.

One of the authors, an expert with extensive knowledge of prior art in robotics and spherical robots, rated novelty of concepts on a 4-point scale (0-3), corresponding to no, low, medium and high novelty. Quality of a solution is a measure of the fulfilment of requirements. To assess quality, three abstraction levels, namely functional-, physical principle- and structural-levels are considered. Quality of concepts is assessed using: $Q = 0.5 \times f + 0.3 \times w + 0.2 \times s$ , where Q is the overall quality of a concept, f is a measure of the degree of fulfilment of the identified requirements by the functions in the concept, w is the degree of fulfilment of the identified functions by the working principles in the concept and s is the degree of fulfilment of the physical principles by the components and their relations in the concept. Higher abstraction levels are the basis for building the lower abstraction levels, and so, weighting factors of 0.5, 0.3 and 0.2 are used corresponding to the function-, working principle- and structure-levels, respectively. f, w and s are assessed by the first author using a 3-point scale (0-2), corresponding to no, partial and complete fulfilment. So, the overall quality of a concept will also vary between 0 and 2. An inter-rater reliability test is conducted using two raters (second and third authors) for 20 concepts. After two rounds of iterations involving analysing, settling and reconciling differences (reaching Cohen’s Kappa ratio of 0.86), the learning from these iterations is used to rate the quality of the remaining concepts. The overall quality is calculated using the f, w and s scores for each concept. The frequency distribution of the generated concepts over their quality scores has three distinct zones: $Q \leq 1.2$, $1.2 < Q < 1.7$, and $Q \geq 1.7$. These zones are categorized as low-, medium- and high-quality grades.

## 4 FINDINGS

A total of 226 distinct, system-level concepts are generated by 105 participants, each of who generated at least one system-level concept. Note that these concepts are at system-level and therefore, comprise many sub-functions and sub-systems. *138 concepts (~61%) are generated with patents as stimuli and 88 concepts (~39%) without patents* (see Figure 3). The groups "without patents" and "with patents" are treated as the control and experimental groups, respectively, to study the effects of using patents as stimuli.

As mentioned earlier, the participants are also allowed to access other resources, which can serve as stimuli, in addition to the given patents. Consequently, various degrees of stimulation are used to generate concepts, namely: (a) without any stimuli, (b) with other resources only, (c) with patents only, and (d) with patents and other resources. Note that the groups (a) and (b) constitute the concepts generated without patents, and the groups (c) and (d) constitute the concepts generated with patents. The distribution of concepts generated under various degrees of stimulation is shown in Figure 4. *More than a half of these concepts (115 concepts, ~51%) are generated with combined stimulation of patents and other resources. Other resources play a significant role in the concept generation, either individually (78 concepts, ~35%) or in combination with patents (115 concepts, ~51%).* Only a small portion (23 concepts, ~10%) of the concepts are generated using patents only and a smaller portion (10 concepts, ~4%) developed without any stimuli.

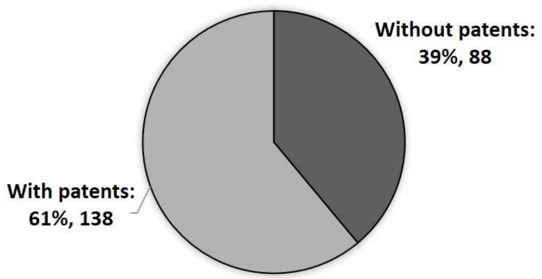



*Figure 3: Distribution of concepts generated with and without patents*

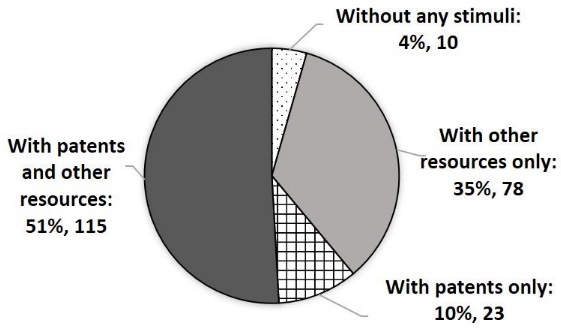



*Figure 4: Distribution of concepts generated using various degrees of stimulation*

With the flexibility to access other resources, for stimulation, the designers also identify patents on their own, in addition to the given patents. This constitutes the "Own" category in addition to the given "Most Cited" and "Random" categories. The participant designers also use multiple patents from more than one category as stimuli. The distribution of concepts generated using the various categories of patents is shown in Figure 5. *A majority of the concepts (87, ~63%) are generated using patents from the Own category, either individually (67 concepts, ~49%) or in combination with other categories of patents (20 concepts, ~15%).* Only a small portion of the concepts are generated with stimulation using the given patents from the Most Cited (27 concepts, ~20%) and Random categories (24 concepts, ~17%).

Figures 6 and 7 show the average novelty of concepts generated: (i) without and with patents, and (ii) using various degrees of stimulation, respectively. The vertical error bars show the standard errors. No significant difference (2-tail t-test: t=-1.03, p=0.31) is observed between the average novelty of concepts generated without and with patents (see Figure 6). However, *the average novelty of concepts generated using a combination of patents and other resources is significantly higher* (2-tail t-test: t=-2.12, p=0.04) *than those generated without any stimuli* (see Figure 7). The average novelty of concepts generated using: (a) other resources only and (b) patents only are also significantly higher than the average novelty of concepts generated without any stimuli (2-tail t-test: t=-2.08, p=0.04 and 1-tail t-test: t=-1.42; p=0.08, respectively). No significant differences in average novelty are observed between the other degrees of stimulation. In summary, *average novelty of concepts is higher when stimuli (patents, other resources or their combination) are used in comparison to no stimuli*.

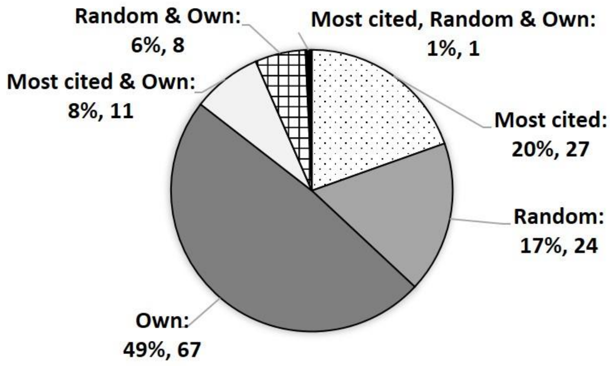



*Figure 5: Distribution of concepts developed using various (combinations of) patent categories*

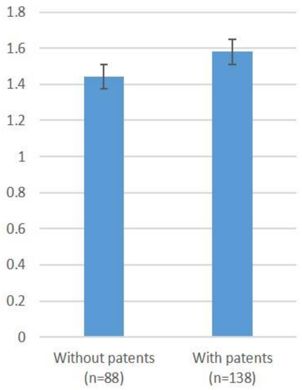



*Figure 6: Average novelty of concepts generated without and with patents*

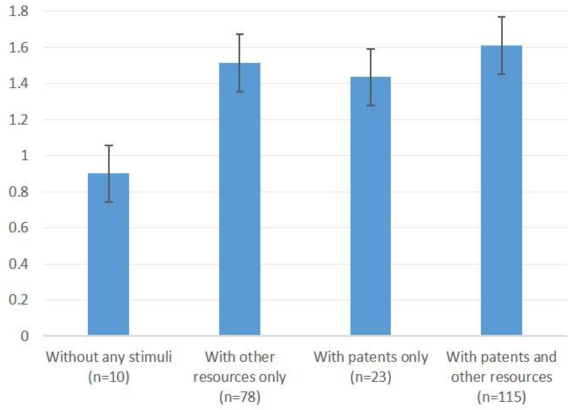
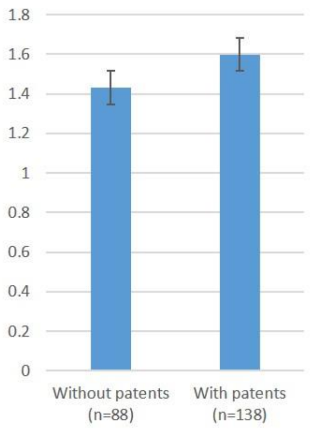



*Figure 7: Average novelty of concepts generated using various degrees of stimulation*

Figure 8 and Figure 9 show the average quality of concepts developed: (i) without and with patents, and (ii) with various degrees of stimulation, respectively. *The average quality of concepts generated with patents is significantly higher than the average quality of concepts generated without patents (2-tail t-test: t=-4.61, p<0.00001)* (see Figure 8). The differences between the average quality of concepts generated using the various degrees of stimulation are also significant (ANOVA: f-ratio=9.00, p<0.01) (see Figure 9). The average quality of concepts generated with patents and other resources is significantly higher than the average quality of concepts generated without any stimuli (2-tail t-test: t=-3.86, p=0.0002) and the concepts generated with other resources only (2-tail t-test: t=-3.89, p=0.0001). The average quality of concepts generated with patents only is significantly higher than the average quality of concepts generated without any stimuli (2-tail t-test: t=-3.13, p=0.0038). The average quality of concepts generated with other resources only is significantly higher than those generated without any stimuli (2-tail t-test: t=-2.34, p=0.02) and with patents only (2-tail t-test: t=1.95, p=0.05). No significant difference is observed in the average quality between concepts generated with patents and other resources and those developed with patents only. In brief, *using stimuli (patents, other resources or their combination) helps generate concepts of higher quality than concepts generated using no stimuli; using patents with other resources helps generate concepts of higher quality in comparison to concepts developed with other resources only*.

## 5 DISCUSSION

The following are the important findings in this research: (a) no significant difference in average novelty between concepts generated without and with patents, (b) concepts generated with patents have higher average quality than those generated without patents, and (c) concepts generated with stimuli (patents, other resources and their combination) have higher average novelty and average quality than those generated without any stimuli.



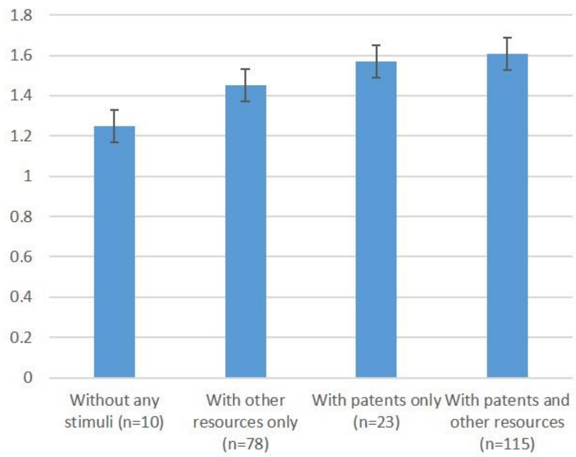




*Figure 8: Average quality of concepts generated without and with patents*

*Figure 9: Average quality of concepts generated using various degrees of stimulation*

## 5.1 Significance of findings

The average novelty of concepts generated with patents is not significantly different from the average novelty of concepts generated without patents. However, the patents used in this study helped identify and create certain attributes in concepts, which may not have been possible without the use of patents. Potentially, these attributes may have generated novelty, and this novelty is comparable to the novelty of concepts generated without patents. Therefore, by generating concepts, without patents and then with patents, can potentially widen and enhance novelty of the conceptual space. The average novelty of concepts generated with stimuli (patents, other resources or their combination) is higher than the average novelty of concepts generated without any stimuli. Therefore, it can be ascertained that stimuli helps identify and create attributes, which contribute to the novelty of concepts.

The average quality of concepts generated with patents is higher than the average quality of concepts generated without patents. It is likely that the patents helped create features and thereby, contributing to higher quality. This is also seen with the average quality of concepts generated using the various degrees of stimulation; concepts generated using both patents and other resources yield higher quality than concepts generated using either patents only or other resources only.

Existing research that uses patents for stimulating concept generation, uses small samples of stimuli, which may not be representative of the space of the stimuli that can be used. The concept generation exercise in this research is designed to overcome this issue. From each of the 121 technology classes that span the technology space, 1 most cited patent and 1 random patent are chosen, totalling 121 patents each in the Most Cited and Random categories, which are given as stimuli for the concept generation of spherical rolling robots. In addition, some designers also identify patents on their own.

The broad objectives of this research are: (a) to validate the efficacy of using patents as stimuli to support ideation and (b) through this validation, to identify avenues for developing methods and tools to search and identify patents to be used as stimuli. The research pursued in this paper is a step towards these broad objectives, where 242 patents – 121 each in the Most Cited and Random categories – are identified from the Technology Space Map and given to the participant designers to be used as stimuli for generating alternative concepts for spherical rolling robots. In addition to the given patents, some participant designers identified many patents on their own and some others used other resources as stimuli for generating concepts. The influence of using patents from the Own category and Other Resources on the generated concepts is significant. Browsing through the given patents within a week to identify relevant stimuli from them may have been cumbersome. Therefore, a search-and-retrieve interface through which millions of patents could be searched using related keywords, relevant patents retrieved and ranked in the order of their appropriateness to the keywords, would be useful. These keywords could be linked to function, behaviour, structure or other attributes of products or processes in patents. Presumably, this interface could reduce the effort on designers' side to identify analogous stimuli for their design problem. Fu et al. (2013) and Murphy et al. (2014) have developed computational design tools to search and identify functionally-relevant analogies from the US patent database. The other resources comprise video-, image- and text-based descriptions of products and processes in patents, to supplement the contents in patents, and these also have a significant impact on concept generation. Therefore, patents can be linked to various media of how products and processes operate, as an addendum in methods and tools based on patents to foster ideation. There are multiple benefits of using stimuli of multiple modalities (Chan et al., 2011; Sarkar and Chakrabarti, 2008).

In this research, data of 226 concepts generated by 105 participants, ideating individually for 21 different problems, without or with patents and other resources as stimuli in uncontrolled conditions is used. This data spans a wide spectrum of variables. Unlike other laboratory-based controlled ideation experiments, the participants in this experiment require more domain knowledge to accomplish the tasks. From the alternative set of concepts generated by individuals within a team, one concept is chosen and modified, if necessary, then prototyped and its working demonstrated by each team. Arguably, the performance of a prototype depends on the set of alternative concepts generated earlier. The participants are graded based on their performance at the end of each phase of the development process. In addition, some of these projects are further pursued towards entrepreneurial and co-curricular activities. Therefore, the participants have adequate vested incentives to pursue this ideation exercise seriously. The validity of the findings must be considered in the context of these wide span of variables and the seriousness with which this exercise is pursued.

The path followed in this study represents a unique intersection between research and education, as the topical opportunity of spherical robots, and the related design brief of the course, come from a parallel multimillion-dollar research project at the university. This project will use data from this research.

### 5.2 Limitations

The findings from this study have to be positioned in the context of the following caveats. Firstly, for the most cited and random categories, abstracts, figures and technical descriptions of 121 patents, one from each technology class, are given. These descriptions are often lengthy and described in a tedious and non-obvious manner. Further, browsing through the 121 patents to assimilate the information, identify relevant stimuli from them and use these for generating concepts, all within a week, may have been cumbersome for the designers. Secondly, the patents given to the designers are not directly related to the design problem, and therefore, their relevance is questionable. Thirdly, this study involved student designers pursuing their undergraduate degree with some design experience. More experienced designers process information differently and accordingly, their concepts would be influenced. However, this research does not account the effect of experience.

## 6 SUMMARY AND CONCLUSIONS

The specific objective of this research was to examine the effects of using multiple patents that span the technology space as stimuli for ideation on attributes of ideation outcomes It was observed that: (a) the concepts generated with patents have higher quality, but not novelty, than concepts generated without any stimuli, and (b) concepts generated with various degrees of stimulation – patents, other resources and their combination – have higher novelty and quality, than concepts generated without any stimuli. Some new directions for developing methods and tools to facilitate searching and identification of relevant patents from the patent database to foster concept generation have also been determined in this research.

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