Design-by-Analogy: Effects of Exploration-Based Approach on Analogical Retrievals and Design Outcomes

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This paper presents VISION (Visual Interaction tool for Seeking Inspiration based on Nonnegative Matrix Factorization), a computational design-by-analogy (DbA) tool that enables designers to visually explore a space of analogical inspiration for creative idea generation. While many currently available DbA tools use a query-based approach for retrieving analogies (i.e., input keywords or functions to return a set of relevant results), VISION allows designers to retrieve a collection of design analogies that are related to topics of interest and explore a space of potential inspiration, the way one would gather books of particular topics from multiple shelves at the library to find potential resources. Two cognitive engineering design studies were conducted to evaluate the efficacy of VISION during the conceptual design process. In the first study, conducted in a controlled-lab setting, VISION was evaluated based on its effect on the quantity, quality, novelty, and direct physical similarity ratings of design outcomes. In the second study, conducted in a graduate engineering design class, VISION was evaluated based on designers' abilities to retrieve analogies from different domains and analogies that are different from already existing design solutions. Studies show that VISION could provide an alternative to the query-based search that many DbA computational support systems use and open up new opportunities for designers to benefit from computationally supported analogies. [DOI: 10.1115/1.4053683]

Keywords: conceptual design, creativity and concept generation, data-driven design, design theory and methodology

1 Introduction

Design-by-Analogy (DbA) is a tool for innovation that has gained much attention in engineering design and the product development process. The method involves retrieving information or knowledge from one's memory or from an external repository of existing design solutions (source) and mapping that information to one's engineering design problem (target). This paper presents a new DbA tool called VISION that was developed in the authors' prior studies [1,2]. The tool automatically discovers a hierarchical clustering structure of patents, in which patents are classified into categories and their semantic themes are identified. The tool then uses web-based interactive data visualization to present analogies from the patents clustered by themes in a node-edge network. User interaction tools are provided for designers to retrieve analogies from the interactive data visualization. The paper begins with the discussion of usage of analogies in design, describes state-of-art computational supports for DbA, and explains how VISION may help designers to retrieve useful and unexpected analogies for use in solving their design problems. Next, VISION and its application during idea generation are described. The paper then presents two cognitive studies, a controlled-lab study and an in-class study, to measure the efficacy of VISION during the conceptual design process. Finally, conclusions are drawn from the results and directions for future work are discussed.

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2 Background

2.1 Cognitive Studies on Design-by-Analogy. Researchers in cognitive science and engineering design fields have worked to understand the roles and effects of analogies to provide guidance on how analogical retrieval can be enhanced [3–5]. For instance, Chou and Shu studied two roles of analogies—explanation and inspiration—in engineering design and discussed designers' familiarity with source analogies, quality of source analogies, and parallelism between source analogies and target design problems [6]. Casakin et al. studied how the distance of analogies (i.e., within-domain example or between-domain example) and the purposes of analogies (i.e., problem identification, analysis, explanation) influence team dynamics in the product design process. Davies et al. studied the implementation of visuospatial analogy for analogical transfer and problem solving [7]. Researchers have also investigated the impact of designers' goals on their choice of source analogies [8], and the relationship between different forms of analogies (textual, pictorial, or combined) and the creativity of the generated ideas [9]. Potential negative effects of analogies on ideation have been studied with design fixation [10–13], which occurs when a designer stubbornly clings to a single design when better ideas are available. Methods to mitigate the effect of design fixation have been studied by assisting designers to draw inspiration while they have an open goal or a task that has yet to be completed [14] or by assisting them to draw multiple ideas from multiple sources [15]. Other efforts include representing analogies in a vague and functional manner, as opposed to a precise and surface-level manner [16,17] and using examples that are formulated with a high level of abstraction, such as categorizing examples [18]. In a similar context, Koh found that when reviewing patents for idea generation, a better understanding of the patent design can increase fixation; designers are suggested to read patent claims instead of the full documents [19].

Analogies have been explored with the concept of surface-similarity and functional-similarity. Fu et al. used functional content of patents (verbs-only text) to create a functional representation of a patent structure and surface content of patents (nouns-only text) to create a surface representation of a patent structure [20]. The method of creating functional and surface representations of patent structures was developed with the idea that *verbs* tend to describe *functional* attributes of patents (i.e., verbs describe what something does) and *nouns* represent *surface* attributes of patents (i.e., nouns describe components, elements, and applications of a system, technology, and device). With functional similarities extracted from the functional content and surface content of patent datasets, designers could identify insights into different interrelatedness of patents. In the present authors' prior work, a number of structural sub-sets of patents was created using categories that engineers commonly use to discriminate among systems [2]. For example, the authors created structural subsets for the categories of Component, Behavior, Material, and Engineering principle and called these "conceptual lenses." Using these lenses, designers can change the way patents are structured and gain unique design insights from the different representations of patent dataset. For instance, designers can explore patents by their similar sub-functionalities using a Component-specific structural subset and patents by their similar descriptive quality using a Behavior-specific structural subset. Designers often have diverse objectives and lenses through which they look when searching for inspiration or external information. By allowing for the various lenses to influence the way patents are structured, designers could explore patents in a tailored and efficient manner and recognize different analogical relationships among patents. More detail about the conceptual lenses is provided in Sec. 3.

2.2 Computational Supports. Since designers often identify analogies by themselves or by a serendipitous encounter, DbA researchers have tried to systemize the analogical retrieval process by developing computational support systems that use the U.S. patent database as a source of analogies. For instance, Murphy created a function-based vector representation of patents to allow designers to retrieve patents that are functionally relevant to their design problems [21]. Liu et al. used a semi-supervised learning algorithm that automatically extracts functional information from patents and labels them using the functional basis for patent retrieval purposes [22]. Sarica et al. constructed TechNet, a large semantic network of technology related terms by mining the complete U.S. patent data from 1976 for technology search and retrieval [23]. Koch et al. created a query-based visual analytic system called PatViz that allows users for patent search using iterative refinement of query search results of complex patent data and user-generated graph views [24]. The reviewed methods use algorithms to extract analogies from the vast database that is more likely to be familiar to an engineering designer. The designer can then retrieve patents that are relevant to a given design problem to understand the nonobvious analogies that can be used for design concept generation.

2.3 Exploration-Based Approach. Although computational supports have been developed to access the wealth of knowledge contained within the patent database, many of the tools have focused on a query-based approach, in which a designer inputs a keyword or query function and is returned a set of stimuli determined by algorithms. The traditional query-driven search allows designers to retrieve a list of candidates within which designers can look for relevant headlines. However, the retrieved results largely depend on designers' abilities to use the right queries; some queries may rule out patent results that provide useful analogical inspiration to designers. If little guidance is provided, novice designers may use trial-and-error techniques to find relevant results, which leads to a longer cyclic process of designing products [25]. The present authors, in prior studies [1,2], approached the analogical retrieval process from a more designer-controlled position, allowing designers to explore for relevant yet unexpected sources of analogies. With an exploration-based approach, designers might be able to strategically expose themselves to source analogies of a particular topic and visually interact with the design repository to uncover useful and unexpected analogies. It is conjectured that this type of interaction allows designers to retrieve analogies more intuitively and thoroughly. A similar approach has been taken by Luo et al. with a data-driven rapid ideation tool called InnoGPS, which integrates an interactive data visualization for domain exploration and patent information retrieval [26]. The tool presented in this study also uses an interactive data visualization to enable designers to explore patent repositories. However, the important difference between InnoGPS and the tool presented here is that InnoGPS structures a patent network based on patents' technological domains, while this work uses data mining to structure a network based on patents' semantic topics. More discussion about the usage of data mining and interactive data visualization for developing VISION is provided in Sec 3.

3 VISION Overview

VISION (Visual Interaction tool for *S*eeking Inspiration based on Nonnegative Matrix Factorization) is an exploration-based DbA tool that uses data mining to construct structural forms of patent data and interactive data visualization to view, explore, and understand analogies present within the patent structures. The components required to support VISION are shown in Fig. 1 and detailed later. A complete detailed description of VISION is provided in Ref. [1].

3.1 Patent Database. The patent database stores the original patent text. The patent database supplies the patent text to the word-by-document matrix and provides a URL for the access of patent text from the interactive data visualization. In the researchers' prior work [1], two performance aspects of VISION—clustering quality of topic modeling result and frame rate of interactive data visualization—were analyzed, and their implications on the usability of VISION were discussed. The study suggests that scaling up of the number of patents improves the topic modeling quality but increasing the database size lowers the frame rate of the interactive visualization tool to the point that it could diminish designers' ability to retrieve and recall information. Due to VISION's data scale limitation, the repository only contains 500 mechanical design-related patents that are randomly selected from the United States Patent and Trademark Office database. While the size will be sufficient for the cognitive studies presented, a larger repository will be ultimately required to provide designers more opportunities to discover useful analogies.

3.2 Word-by-Document Matrices. Abstract, Claims, and Description sections of the 500 patent documents are parsed to capture the patents' design features. Only the words in these sections were converted into a word-by-document matrix, where columns represent individual patent documents, rows represent words in the entire corpus, and the elements inside the matrix represent the frequency of each word occurring in each patent document. Note that the word-by-document matrix needs to be recreated each time a new patent document is added.

3.3 Conceptual Lenses. VISION uses "conceptual lenses," such as Function, Component, Behavior, and Engineering principle to allow designers to switch perspectives while searching for analogies. Switching lenses affects semantic topics of patent data identified from the topic modeling and the way patent network is displayed in the interactive data visualization.

To develop a conceptual lens, each word in the word-by-document matrix is classified as belonging to a conceptual

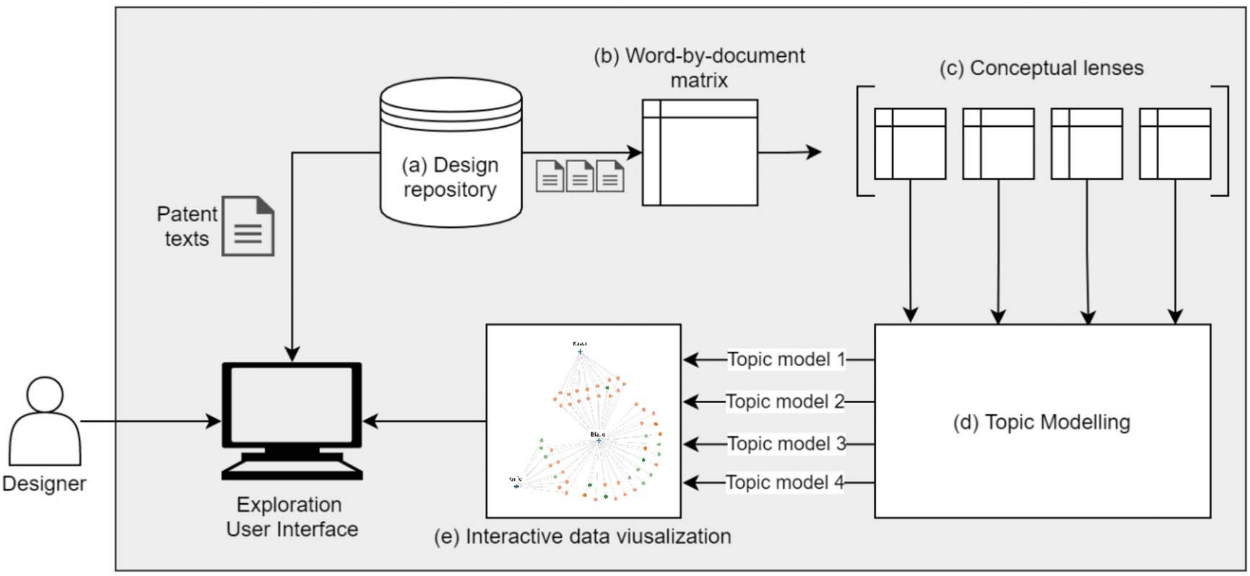


Fig. 1 VISION architecture

lens or not. Each word may belong to one or more conceptual lenses, for example "control" may be associated to function ("to control"), component ("a control"), or engineering principle ("control surface"). In this step, four lists of words characterizing each of the conceptual lenses are created. For instance, wordlists for Component and Behavior are manually compiled [2], a wordlist for Engineering Principle is created with words extracted from a glossary of engineering [1], and a wordlist for Function is created with verbs in the patent documents using a part-of-speech (POS) tagger [20]. The wordlists are then used to refine the original word-by-document matrix to contain only the rows of words listed in each wordlist, resulting in four *conceptual lens specific word-by-document matrices.* For instance, the Function conceptual lens-specific matrix contains only function-words (usually verbs) and the Component conceptual lens-specific matrix contains only component-words. Also, only single words were used to create the matrix. For instance, if a patent document contains "razor blade," the word will be counted twice as a "razor" and a "blade" if the corresponding Conceptual lens wordlist contains "razor" and "blade."

After the matrices were created, inverse entropy weighing was conducted on the matrices to give a more accurate weighting of the word occurrences based on their inferred importance. Note that the conceptual lens specific word-by-document matrices need to be recreated each time the word-by-document matrix or the list of words characterizing the conceptual lens are updated.

3.4 Topic Modeling. Nonnegative Matrix Factorization is a topic modeling method used in the data mining field [27–29]. It takes in a word-by-document matrix and factorizes it into a word-by-topic matrix and a topic-by-document matrix from which documents are clustered by similar topics, and five words that are the most relevant to the topics are identified. In this work, the topic modeling method was used to take in a *conceptual lens specific word-by-document matrix* as an input and outputs a *conceptual lens specific topic modeling of patents*, in which each patent document has a topic (a set of five words) that best discriminates each patent for each conceptual lens. For instance, a patent "Paper shredding roller assembly" may contain a topic, "blade, knife, handle, lock, wall" for the "Component" conceptual lens. These patent-topic combinations are used to form a network that can be displayed and explored.

3.5 Interactive Data Visualization. The interactive data visualization is used for designers to view, explore, and understand the structural form of patent data resulting from the topic modeling. For each conceptual lens, a network of patents is created in node-edge style using topics of patents derived from the topic modeling. In the visualization space, each patent node (circular) is drawn and connected to five labeling nodes (blue cross) that characterize the patent's topic. Figure 2 shows a step-by-step illustration of how three example patents of different topics are transformed into a node-edge network.

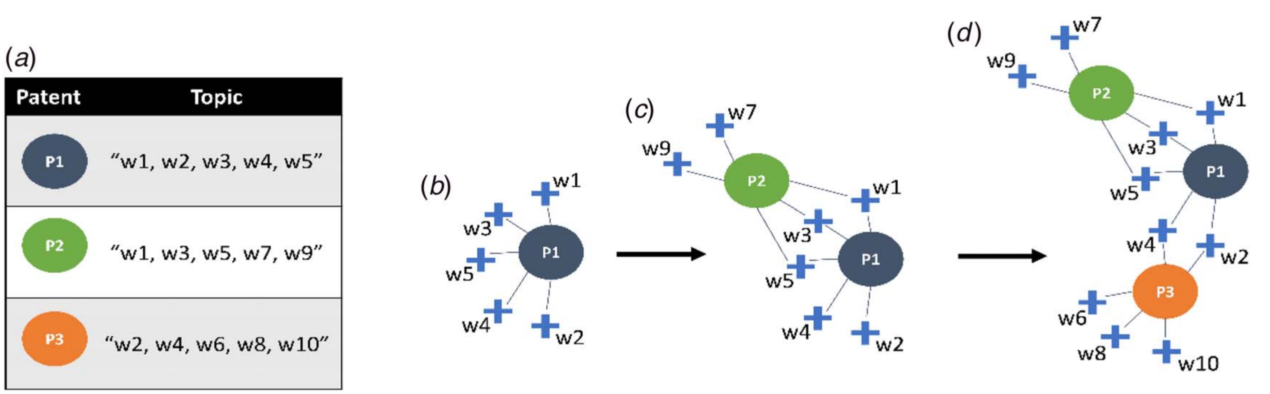


Fig. 2 Illustration of patent network development: (*a*) table of three example patents and their topics, (*b*) one-patent network, (*c*) two-patents network, and (*d*) three-patents network

The interactive data visualization provides various user interaction tools for retrieving analogies. Designers may use filtering of patents based on their topic words to view only patents of specific topics. It allows designers to reduce the size of the patent network to efficiently retrieve patents that they use to solve problems at hand. Designers may switch the lens between Function, Component, Behavior, and Engineering Principle to change the way that the patent network is structured. Hovering over a node will display the title of the patent associated with the node. VISION includes a search box, which allows designers to locate a patent node in the visualization space by patent's title. While VISION is meant to facilitate exploration, query-based searching is enabled for added convenience. Clicking on the node will open the patent document in a separate window.

3.6 Application of VISION. This section provides an application of VISION to solve a design problem to crack macadamia nuts. A designer first chooses a conceptual lens (Function, Component, Behavior, or Engineering principle) to view the patent network in order to focus on patents of specific analogies characterized by the conceptual lens. Next, the designer filters the patent network with keywords derived from the design problem's customer needs and functional requirements [30]. For instance, words like "Blade," "Razor," and "Knife" can be selected from the Component conceptual lens to view only patents that have a cutting mechanism (see Fig. 3). After the filtering reduces the size of the patent network displayed, designers can hover over nodes to display their titles to look for potential analogies and analogous domains. For instance, using the three keywords from the Component conceptual lens, designers can view patents like "Paper shredding roller assembly," "Chopping machine," "Hair trimming device," "Device for mincing food," and more to retrieve analogies of cutting from various domains.

4 Controlled Study Evaluation

The study described in this section investigates the effects of VISION (exploration-based approach) and Google Patent (query-based approach) for retrieving analogies on design outcomes. The controlled study serves to validate VISION as an exploration-based DbA tool for supporting innovative idea generation.

4.1 Methodology

4.1.1 Participants. The study was conducted at Georgia Institute of Technology with 26 students enrolled at the institute. The students were compensated with a monetary value of $25 for participating in 1-h study. There were 25 mechanical engineering students and one aerospace engineering student who participated. The aerospace engineering student was a graduate level student with over five years of experience in engineering design industry. There were 21 graduate level participants and five undergraduate level participants. Seventeen participants were male and nine participants were female. All participants took at least one design class at the institute and had average of 2.51 years of experience in design-related course projects and industry jobs.

4.1.2 Conditions. Eleven participants were assigned to "VISION" condition and 15 participants were assigned to "Google Patent" condition. Participants were randomly assigned to either the VISION or the Google Patent group, and those who were scheduled in the same time slot were assigned to the same group. The study was discontinued during the COVID-19 outbreak, which resulted in the different number of participants assigned to the test groups. There was no control condition as the focus of the study was to analyze the effects of VISION on design outcomes in comparison to Google Patent, the status quo query-based tool for retrieving patents. Google Patent was chosen as the reference query-based method in this work, as it is the most widely used tool for searching patents. The independent variable was the tool used for searching and retrieving electronic patent documents during the conceptual design process. The descriptions of the two conditions are:

(1) "VISION" condition—Participants in this condition used VISION (exploration-based tool) during the ideation process to search for and retrieve patents for DbA practice. VISION included a visual representation of a patent

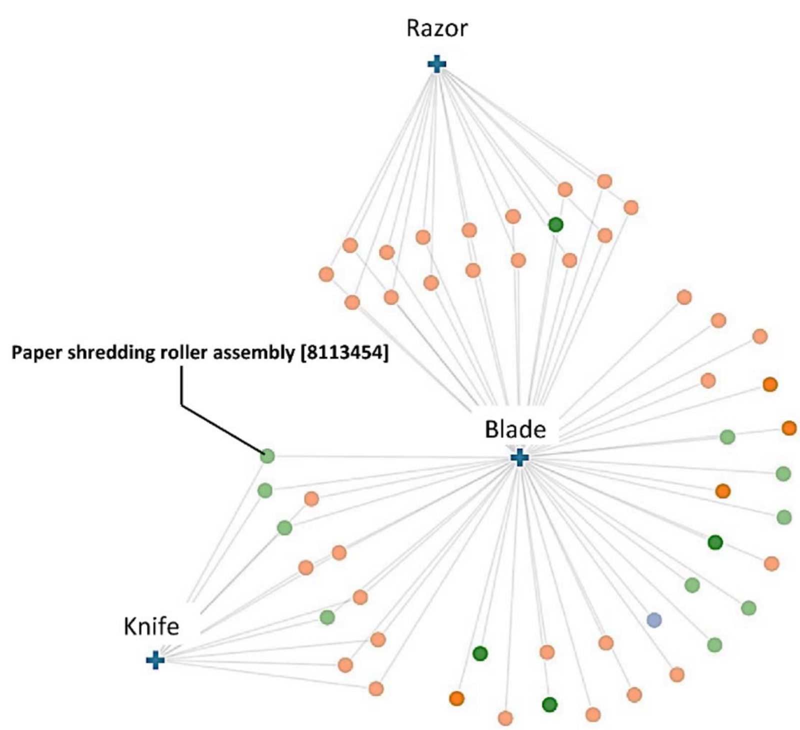


Fig. 3 Patents (round nodes) having cutting mechanism (blue cross nodes)

network with user interaction support. The patent network consisted of 500 patents that the researcher randomly selected from mechanical design related Cooperative Patent Classification subsections in the USPTO.

(2) "Google Patent" condition—Participants in this condition used Google Patent (query-based tool) during the ideation process to search for and retrieve patents for DbA practice. Google Patents is a search engine created by Google that includes over 120 million patents from over 100 patent offices around the world. In this study, the patent search was limited to patents registered in the USPTO.

4.1.3 Design Problem. Participants were given a design problem during the ideation process to evaluate the effects of VISION on design outcomes. The problem asked participants to design a device that collects energy from human motion for use in developing and impoverished rural communities [20,31,32]. The problem was chosen because its appropriately challenging yet conceptually simple so that participants can immediately start generating design concepts. Also, the design problem was meaningful in the sense that it is an ongoing design challenge in engineering design fields and encourages participants to engage in the ideation. The textual description of the design problem was as follows:

Design a device to collect energy from human motion for use in developing and impoverished rural communities in places like India and many African countries. Your goal is to build a low-cost, easy to manufacture device targeted at individuals and small households to provide energy to be stored in a rechargeable battery with approximately 80% efficiency. The energy is intended to be used by small, low power draw electrical devices, such as a radio or lighting device, hopefully leading to an increase in the quality of life of the communities by increasing productivity, connection to the outside world, etc. The target energy production is 1 kWh per day, roughly enough to power eight 25 W compact fluorescent light bulbs for 5 h each per day, or enough to power a CB radio for the entire day. For reference, an average adult human can output about 200 W with full body physical activity for short periods of time, with a significant reduction for sustained power output.

4.1.4 Experimental Procedure. The study was run with 26 participants in 13 different sessions, in which one participant or a group of two to three participants were present. Participants in groups were assigned to the same condition but worked on the ideation individually. There were two ideation phases in the study. In Phase 1, participants in all conditions were given the human motion energy generation design problem and worked for 15 min to generate ideas without using any ideation tools. They were asked to generate as many ideas as possible and use a black pen to sketch or write design ideas on provided ideation sheets. The purpose of Phase 1 was to allow participants to work on the design problem for some time, allowing them to understand the design problem and generate ideas before design tools are introduced to them. The ideation results in Phase 1 were used to confirm if all participants had equal ideation abilities. After the first ideation phase, participants in VISION and Google Patent conditions were given 10 min. tutorials on design-by-analogy (DbA) and how to use the tool of their respective condition to retrieve patents for DbA. They were provided laptop computers during the tutorial to practice using the tool. They were also provided computer mice to enable a fluent usage of the tool. To help them engage in the retrieval practice, they were given a task to search patents that can be used for designing a peanut shelling device (a device that can be used to break peanut shells) [30]. After participants expressed that they were confident using the tool they were proceeded to the second ideation phase. In Phase 2, participants used VISION or Google Patent on provided laptop computers to retrieve patents and generate ideas for the same human motion energy generation design problem. They worked for 15 min to generate as many ideas as possible and used pencils to sketch or write design ideas on the provided ideation sheets. In Phase 2, participants were given 15 min to generate ideas which are the same amount of time given in Phase 1 because it was assumed that they had already explored a number of ideas in Phase 1 which can help them generate additional ideas for the same design problem. In addition, if any design ideas were inspired by patents, they were asked to write and circle the patents' names next to the generated design ideas. During Phase 2, computer screens were video recorded with the participants' consent. The recorded videos were used to trace their activities during the patent retrieval process. The study ended with 10-min surveys to gather participants' demographic information and understand their user experiences with VISION and Google Patent during the second ideation phase.

4.1.5 Design Metrics. Design ideas were expressed on provided ideation sheets in the form of pictorial sketches, text descriptions, or a combination of both. The design ideas were analyzed with a range of design metrics to understand the effects of VISION (exploration-based tool) and Google Patent (query-based tool) on participants' design outcomes. The design metrics used were as follows: (1) quantity, (2) quality, and (3) novelty. For consistency, these metrics are the same as those used in one of the authors' prior design-by-analogy studies [31,32]. For quantity of ideas, only the design ideas generated in the second ideation phase were analyzed; the justification is provided in the next section. For quality and novelty of ideas, design ideas generated in the first and second ideation phases were analyzed. For design ideas generated in the first ideation phase, only those that use human motion as the primary input to generate electricity were used in the results. For design ideas generated in the second ideation phase, only those that (1) use human motion as the primary input to generate electricity and (2) are inspired by retrieved patents were used in the results. Although all ideas generated in Phase 2 were equally important as they could be developed into good ideas that are not fully based on patents, only the ideas that are based on patents were used for the analysis to examine the direct effects of VISION and Google Patent on design outcomes. Also, the patent references provided by participants and videos of screens captured were cross-checked to confirm if ideas were inspired by patents or not.

4.1.5.1 Quantity. Quantity is often used as an objective measure to assess the effectiveness of ideation. Prior studies in design have implemented the quantity of ideas as a measure of effectiveness, as more ideas can result in a greater chance of producing high quality, novel ideas [30,33–35]. Because the researchers were primarily interested in the effects of the tools on ideation, only the ideas generated in the second ideation phase that meet the two requirements stated above were analyzed. Also, because participants had 15 min to generate ideas in the first ideation phase, while they had 15 min to explore patents and generate ideas in the second ideation phase, the quantities of ideas generated in the first ideation phase and second ideation phase were not compared with each other.

4.1.5.2 Quality. Quality was evaluated to determine how well the design ideas met the customer needs or specifications defined in the design problem. It was measured using holistic ratings on a set of subdimensions of quality [31]. The subdimensions are listed as the following:

1. Cost
2. Feasibility of material/cost/manufacturing
3. Feasibility of energy input/output ratio
4. Number of people required to operate device at a given moment
5. Estimated energy output
6. Portability
7. Time to setup and build, assuming all parts already available at hand

Design ideas were scored on each of the subdimensions on a five-point Likert scale ranging from 0 (unacceptable) to 4 (excellent) by a mechanical engineering doctoral candidate focusing on engineering design research methods. For ease and consistency of scoring, one common idea, which uses human pedaling motion to generate rotational energy and transforms the rotational energy into electrical energy using a dynamo-type generator, was analyzed first. Other ideas were then analyzed based on the quality subdimension scores that were already given to the human pedaling idea. To check the interrater reliability of the scores, 25% of the design ideas were coded by a second mechanical engineering doctoral candidate focusing on engineering design methods. The 25% of the design ideas were randomly selected by the first rater using MATLAB's random number generator. The first rater was aware of the experimental procedure, study hypothesis, and conditions of the generated ideas while the second rater was blind to the information. The design ideas were rated in two trials. In the first trial, the first rater scored all design ideas and the second rater scored 25% of the design ideas using the 5-point Likert scale. After the first trial, the two raters resolved any disagreements from the first trial through discussion and re-scored the design ideas in the second trial. The scoring results from the second trial were used to compute the quality of design ideas. The interrater reliability test was performed using Gwet's first-order agreement coefficient (AC1) [36]. The calculated coefficient values are shown in Table 1. Gwet's AC1 was used over Cohen's Kappa because the quality data had a skewed distribution, and it provides a more stable interrater reliability coefficient for skewed data [37]. However, throughout the study, Cohen's Kappa was used for computing interrater reliability coefficients for non-skewed data. The agreements for all quality subdimensions were above moderate ($r_j > 0.4$) except for the *Time to setup* which was in the range of fair agreement. *Time to setup* was dropped from the subdimensions of quality, and the scores were calculated without it.

Table 1 Inter-rater reliability coefficients of quality subdimensions

Quality subdimensions	Inter-rater reliability coefficient (r_j)
Cost	0.451
Feasibility	0.822
Energy ratio	0.594
No. People	0.990
Energy output	0.717
Portability	0.824
Time to setup	0.392

An overall quality score Q for each design concept was computed using Eq. (1):

$$Q = \frac{\sum_{j=1}^{n} q_j \times r_j}{Q_{max}} \quad (1)$$

where q_j is the quality score for quality subdimension j, r_j is the interrater reliability coefficient for quality subdimension j, and Q_{max} is the maximum possible quality score that a design concept can receive. Participants were not aware of the quality criteria, and all subdimensions were assumed equally important, as designers may have diverse objectives when solving the same design problem. Instead, the subdimensions were weighted by the interrater reliability coefficient to reduce the measurement error. The similar practice for analyzing the quality of ideas was done in one of the authors' previous design-by-analogy studies [31,32]. The overall quality score ranged from 0 (low quality) to 1 (high quality). Participants' mean quality scores were used in the results.

4.1.5.3 Novelty. Novelty was evaluated to determine whether the generated design ideas were unusual within a space of possible solutions. The novelty measures how rare an idea is compared to other ideas generated in the study and does not reflect on the usefulness of the idea. The space of possible solutions was determined by functionally decomposing all design ideas into potential subfunctions [31]. The list of subfunctions that were used in this study is shown in Fig. 4.

A total of 107 design ideas generated in Phase 1 and Phase 2 of the study were first decomposed into subfunctions. For example, the human pedaling idea, which was used as an example in the previous section, was decomposed into three subfunctions: namely, "Import/accept human interaction," "Transform human energy to mechanical energy," and "Transform mechanical energy to electrical energy." All design ideas were coded into subfunctions by a mechanical engineering doctoral candidate and 25% of the design concepts were coded by a second mechanical engineering doctoral candidate to see whether they agree that a design concept provides a solution to a given subfunction. The same 25% of design ideas used for scoring quality were given to the second rater. Again, the first rater was aware of the experimental procedure, study hypothesis, and conditions of the generated ideas while the second rater was blind to the information. The design ideas were rated in two trials. In the first trial, the first rater coded all design ideas and the second rater coded 25% of the design ideas. In the second trial, the two raters coded the design ideas again after resolving disagreements from the first trial through discussion. The agreement between the two coders was excellent ($\kappa = 0.899$). It was found that only five subfunctions occurred often enough within the

List of subfunctions

1.	Import/accept human interaction	7.	Import alternative energy source	13.	Store mechanical energy	19.	Store electrical energy
2.	Transform human energy to mechanical energy	8.	Transform alternative energy source into mechanical energy	14.	Transform mechanical energy to alternative energy	20.	Supply electrical energy
3.	Transform human energy to alternative energy	9.	Transform alternative energy source to alternative energy	15.	Transform alternative energy to electrical energy	21.	Transmit electrical energy
4.	Import other material	10.	Transform collected energy to mechanical energy	16.	Actuate/deactuate energy	22.	Convert electrical to light or EM
5.	Contain/store other material	11.	Transmit mechanical energy	17.	Transform mechanical energy to electrical energy		
6.	Transfer other material Turn it into a figure	12.	Transform mechanical energy	18.	Condition electrical energy		

Fig. 4 List of subfunctions for a human motion energy generation device

solution space to represent the design concepts. Thus, only the five subfunctions (highlighted in Fig. 4) were used in the results.

Each subfunction was then decomposed into *what*, *how,* and *compound* components. The *What* component specifies the type of input and output flow that is being acted upon; the *how* component specifies the device's function or method that acts upon the flow; and the *compound* component combines *what* and *how* into a *compound* statement. For the subfunction "Import/accept human interaction" of the human pedaling idea, *what* would be "foot," *how* would be "pedals," and *compound* would be "foot with pedals." For each subfunction, the decomposed solution components were used to form a solution space for that subfunction. Two mechanical engineering doctoral candidates both coded 25% of the data to assess whether they agreed on the type of solutions provided to *what* and *how* components of a subfunction, given that they had agreed a solution was provided to the subfunction. The agreements, averaged over all subfunctions, were excellent for *what* component ($\kappa = .893$) and *how* component ($\kappa = .802$).

After the solution space was acquired, a rarity score of a design idea's solution token within *j*th component of *i*th subfunction was calculated by

$$R = \frac{T - C}{T} \tag{2}$$

where T is the total number of all solutions tokens for the *j*th component for the *i*th subfunction in the solution space, and C is the number of the solution tokens for the same component type for the same subfunction in the solution space. This metric allowed a solution component to be considered rare if the number of that solution token does not appear often within the solution space.

An overall novelty score of each design concept was calculated using Eq. (3):

$$N = \frac{1}{i} \times \sum_{i} \frac{\sum_j w_j \times R}{1} \tag{3}$$

where R is a rarity score of a design concept's *j*th component of the *i*th subfunction. The rarity score of the design idea's *i*th subfunction was the weighted average of rarity scores of the *j* components where w_j is the weight of the *j*th component. The weights of *what, how,* and *compound* components were given 0.5, 0.3, and 0.2, respectively. The weights were selected to reflect the order of difficulty in achieving the rarity [31]. The novelty score of each design idea was computed as the average of the rarity score of the design idea's *i* components. Finally, participants' mean novelty scores were used in the results.

4.1.6 Direct Similarity. Design fixation occurs when a designer becomes focused on a provided example early in the design process, even if better designs are available [10,11]. In particular, Jansson and Smith showed that introducing examples can lead designers to generate solutions that mimic the examples, to the point of violating the design problem objectives [10]. To measure the degree to which participants generated ideas that mimic the retrieved patents, *Direct physical similarity* was measured. *Direct physical similarity* is a metric of design fixation that measures the degree to which participants directly copy an example design when generating ideas [11]. Other types of similarity include *Reproductive similarity,* which occurs when participants generate ideas using parts of an example design, and *Analogical similarity,* which occurs when participants generate ideas using design principles from an example design without directly copying the actual physical form of the example design.

One independent coder, a mechanical engineering doctoral candidate focusing on engineering design research methods, analyzed participants' design concepts based on *Direct physical similarities* to their respective patents. The coder was provided the patent documents and definitions of the *Direct physical similarity*, *Reproductive similarity*, and *Analogical similarity*. A score of 1 (a design concept directly copied the patent design) or 0 (a design concept did not copy the patent design) was given to each design concept. The coder was blind to the study hypotheses and the condition of each participant (VISION or Google Patent). To check the interrater reliability of the analysis, a second independent coder, a doctoral candidate focusing on engineering design research methods, coded the same data, following the same procedure that was given to the first coder. The second coder was also blind to the study hypotheses and condition of each participant. The reliability of the two coders rating reached a moderate level of agreement ($\kappa_\omega = .669$). Disagreements were observed among ideas that use the same means to collect energy (i.e., backpacks, shoes) but have different parts of the larger system (i.e., spring, strap, sensor) to generate electricity.

4.1.7 Number of Keywords Searched and Patents Accessed. Computer screens were video recorded during Phase 2 of the experiment to trace how participants used the given tools to explore or search for patents. An undergraduate researcher watched the videos and manually counted the number of keywords searched and the number of patents accessed during the patent exploration. These metrics were used to understand participants' activities during the ideation process, which could not be determined based on the design outcomes. The number of patents accessed was counted whenever a participant opened an electronic patent document. The number of keywords searched was measured differently for the two conditions. For participants in the Google Patent condition, only individual words typed in the search box were counted. For participants in the VISION condition, individual words typed

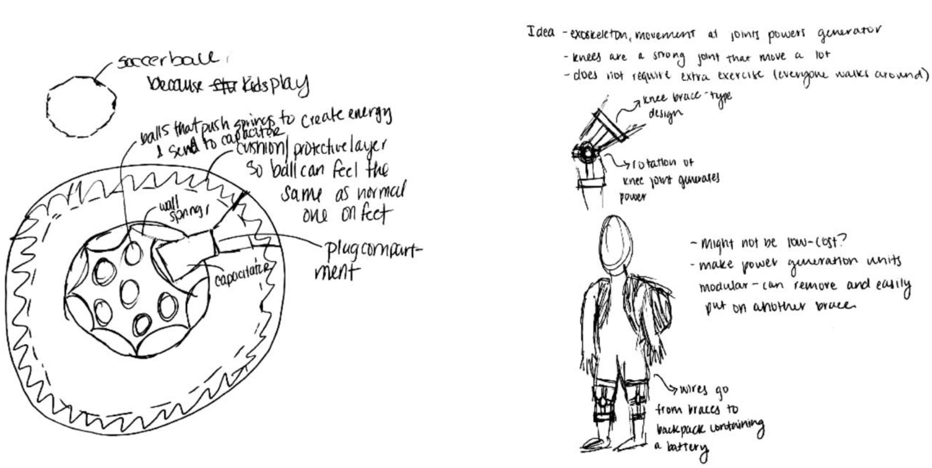


Fig. 5 Examples of generated ideas

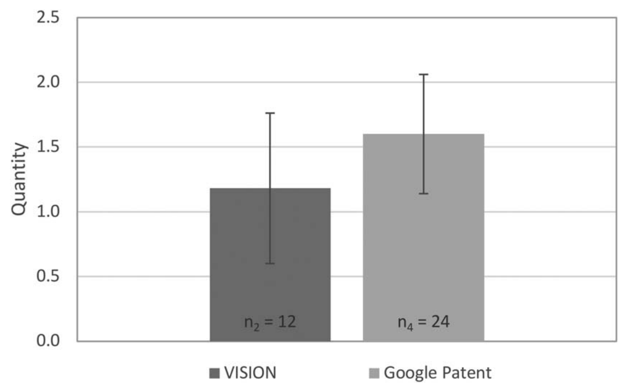


Fig. 6 Quantity of ideas generated per participant in Phase 2 with ± one standard error bars

in the search box and keyword labels activated in the filtering box (see Ref. [1] for the detail of VISION's filtering box) were counted. An interrater reliability test was performed by having a second coder, another undergraduate researcher, analyze the 25% of the video data. The percentage of agreement about whether a keyword was searched or not was 89.6%, and the percentage of agreement about whether a patent was accessed or not was 94.3%. The percentage of agreement was calculated as the number of times that the two raters agree on ratings (keywords searched or patents accessed) divided by the total number of observations rated. These agreement levels allow the manual counting to be considered unbiased and robust. The word clouds of keywords captured in VISION and Google Patent conditions are shown in Fig. 12.

4.2 Results. Examples of ideas generated in the ideation study are presented in Fig. 5. One participant in the VISION condition and one participant in the Google Patent condition retrieved patents but generated ideas that do not use human motion for energy generation. Two participants in the VISION condition did not retrieve any patents for idea generation. These ideas were counted as zero in the quantity result, and they were not used in the quality and novelty results presented in the following sections.

4.2.1 Quantity. Participants in the VISION group generated 27 ideas (n_1) in Phase 1 and 12 ideas (n_2) in Phase 2. Participants in the Google Patent group generated 34 ideas (n_3) in Phase 1 and 24 ideas (n_4) in Phase 2. Only the ideas that met the criteria specified in Sec. 4.1.5 were counted. The participants in the VISION ($M = 2.45$, $SD = 1.04$) and Google Patent ($M = 2.27$, $SD = 1.39$) groups generated a similar number of ideas in Phase 1. A Mann-Whitney U test was run to determine that there is no significant difference $U(N_{VISION} = 11.0, N_{Google\ Patent} = 15.0) = 63.0$, $z = -1.07$, $p = .286$) between the quantity of ideas generated during the second ideation phase in the VISION condition ($Mdn = 1.00$) and the Google Patent condition ($Mdn = 1.00$) (see Fig. 6).

4.2.2 Quality. A mixed ANOVA was run to determine if there is any difference between the quality of ideas generated in the VISION condition and the Google Patent condition (see Fig. 7). The within-subjects factor was the presence of patent retrieval tool during the ideation (i.e., Phase 1 and Phase 2). The between-subjects factor was the type of the patent retrieval tool (i.e., VISION and Google Patent). There were no outliers in the data, as assessed by boxplots. Quality of ideas generated for each condition were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$). Homogeneity of variances was satisfied, as assessed by Levene's test ($p > 0.05$). The mixed ANOVA indicated that the introduction of the patent retrieval tool significantly decreased the quality of ideas $F(1, 20) = 18.3$, $p < 0.001$, $\eta_p^2 = .477$. The type of the tool did not have a significant main effect on the quality of ideas $F(1, 20) = 1.92$, $p = 0.181$, $\eta_p^2 = 0.088$. There was no significant interaction effect between the two factors $F(1, 20) = 0.101$, $p = 0.753$, $\eta_p^2 = 0.005$.

4.2.3 Novelty. A mixed ANOVA was run to determine if there is any difference between the novelty of ideas generated in the VISION condition and the Google Patent condition (see Fig. 8). The within-subjects factor was the presence of patent retrieval tool during the ideation (i.e., Phase 1 and Phase 2). The between-subjects factor was the type of the patent retrieval tool (i.e., VISION and Google Patent). There were no outliers in the data, as assessed by boxplots. Novelty of ideas generated for each condition were normally distributed, as assessed by Shapiro-Wilk's test ($p > 0.05$). Homogeneity of variances was satisfied, as assessed by Levene's test ($p > 0.05$). The mixed ANOVA indicated that the introduction of the patent retrieval tool significantly increased the novelty of ideas $F(1, 20) = 10.0$, $p = 0.005$, $\eta_p^2 = 0.333$. The type of the tool did not have a significant main effect on the novelty of ideas $F(1, 20) = 0.209$, $p = 0.652$, $\eta_p^2 = 0.010$. There was no significant interaction effect between the two factors $F(1, 20) = 0.217$, $p = 0.646$, $\eta_p^2 = 0.011$

4.2.4 Direct Physical Similarity. Direct physical similarities between ideas generated in the second ideation phase and their respective patents were examined using Fisher's exact test. Figure 9 shows the number of ideas in the VISION and the Google Patent conditions that were given direct physical similarity

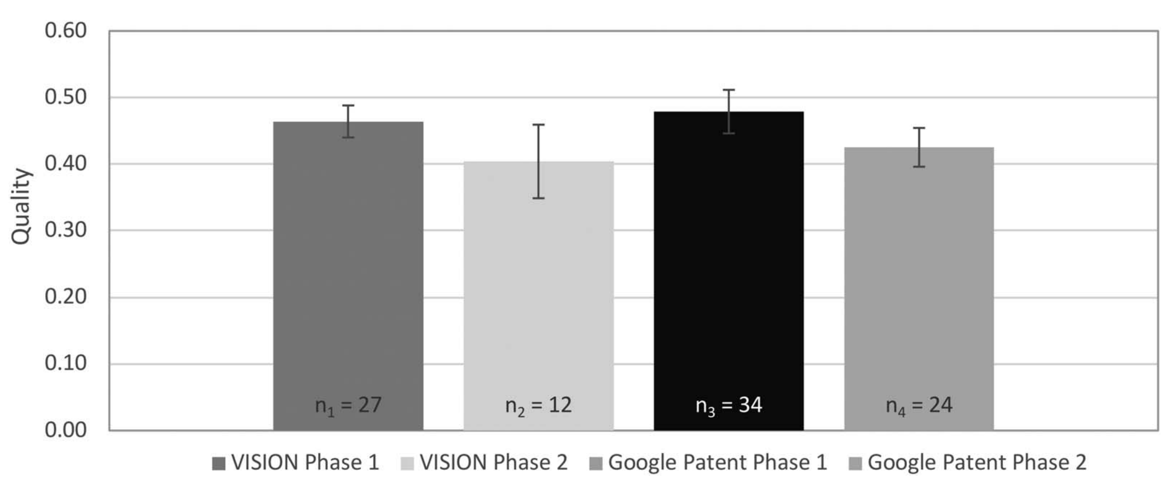


Fig. 7 Quality of ideas with ± one standard error bars

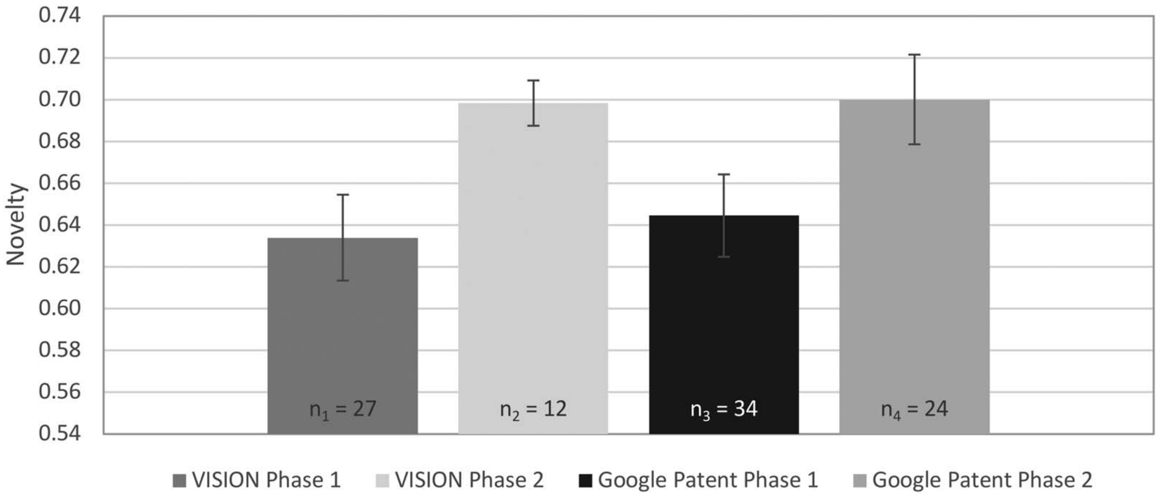


Fig. 8 Mean novelty of ideas with ± one standard error bars

scores of 0 (not similar) or 1 (similar). The test indicated that the participants in the Google Patent condition generated ideas that are directly similar to retrieved patents significantly more than did participants in the VISION condition ($p < 0.001$).

4.2.5 Number of Keywords Searched and Patents Accessed. Mann-Whitney *U* tests were run to determine if there were any differences in the number of keywords searched and number of patents accessed during the second ideation phase between the VISION condition and Google Patent condition (see Fig. 10). For the number of keywords searched, the test indicated that there is a significant difference $U(N_{VISION} = 11.0,\ N_{Google\ \ Patent} = 15.0) = 5.00,\ z = -4.03,\ p < 0.001)$ between the VISION condition ($Mdn = 18.0$) and the Google Patent condition ($Mdn = 7.00$). For the number of patents accessed, the test indicated that there is no significant difference $U(N_{VISION} = 11.0,\ N_{Google\ \ Patent} = 15.0) = 58.0,\ z = -1.30,\ p = 0.194)$ between the VISION condition ($Mdn = 4.00$) and the Google Patent condition ($Mdn = 5.00$). Although more keywords were searched using VISION than Google Patent, the number of patents accessed was similar, implying that Google Patent was more efficient than VISION in terms of retrieving patents that are relevant to the keywords used.

4.3 Discussion. The design ideas generated using VISION (exploration-based approach) and Google Patent (query-based approach) did not significantly differ from each other in terms of quantity, quality, and novelty. However, it was found that the introduction of VISION and Google Patent resulted in design ideas that have significantly lower quality, but higher novelty scores compared to design ideas that were generated prior to the introduction of the tools. The diminished quality was not expected. One possible explanation is that searching patents and navigating the tool induced higher cognitive load, inhibiting them from considering various design specifications during ideation. In the case of the Google Patent condition, 15 out of 20 ideas generated using Google Patent were directly similar to patent designs. Most ideas were effective in generating electrical energy using human motion, but they violated the primary objective of designing a low-cost and easy-to-manufacture energy generation device. In the case of the VISION condition, two participants did not retrieve any patents for idea generation. Their design activities were traced using their video data, and it was found that they spent most of the design time on visiting different patent documents, implying that it could have been cognitively overwhelming to understand patent designs and find useful analogies during the ideation study. Perhaps, the participants could have easily given up on identifying analogies from the patents, hoping that visiting different patents would immediately give them any kind of analogical inspiration. In addition, one participant in the VISION condition retrieved a patent named "Inert gas generator for fire suppressing (US6634433B2)" and

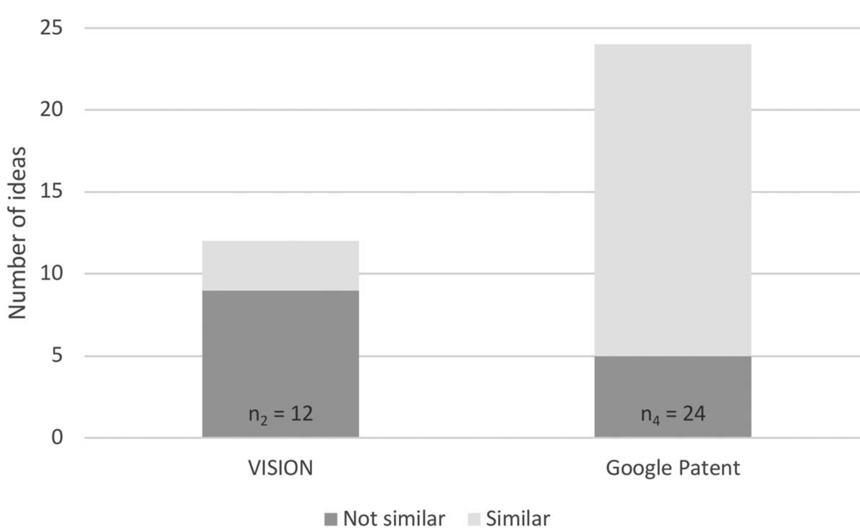


Fig. 9 Number of ideas that are directly similar to respective patents

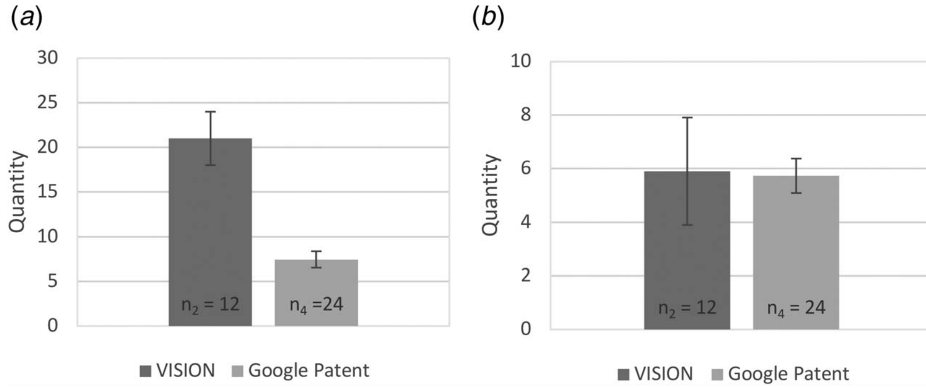


Fig. 10 Number of (*a*) keywords searched and (*b*) patents accessed with ± one standard error bars

generated an idea that only uses burning of biofuel—not human motion—for energy generation. The participant told the proctor after the study that he forgot about the design specifications as he was exploring various patents. The introduction of VISION and Google Patent during the ideation could have distracted the participants from generating ideas that meet the design specifications. The diminished quality can be also explained by the finding that participants in the Google Patent condition retrieved within-domain patents, while participants in the VISION condition retrieved between-domain patents to generate ideas. The

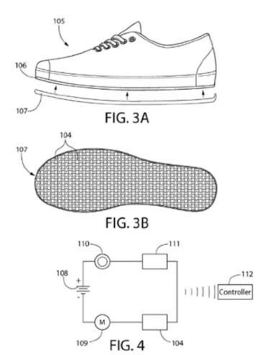
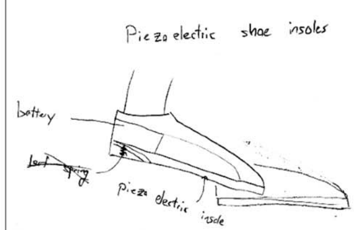
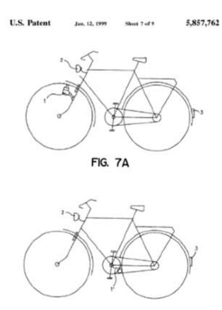
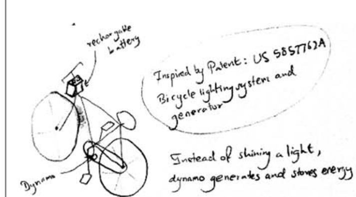
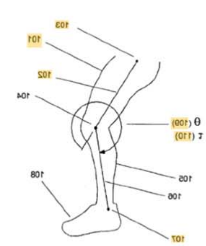
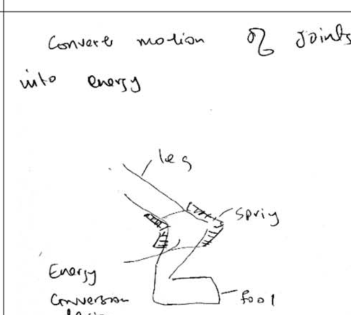
Patent name	Patent image	Generated idea
Energy-saving wearable piezoelectric transportation device (US20150272263A1)		
Bicycle lighting system and generator (US5857762A)		
Method for generating power across a joint of the body during a locomotion cycle (US7645246B2)		

Fig. 11 Design ideas that directly copied patent designs

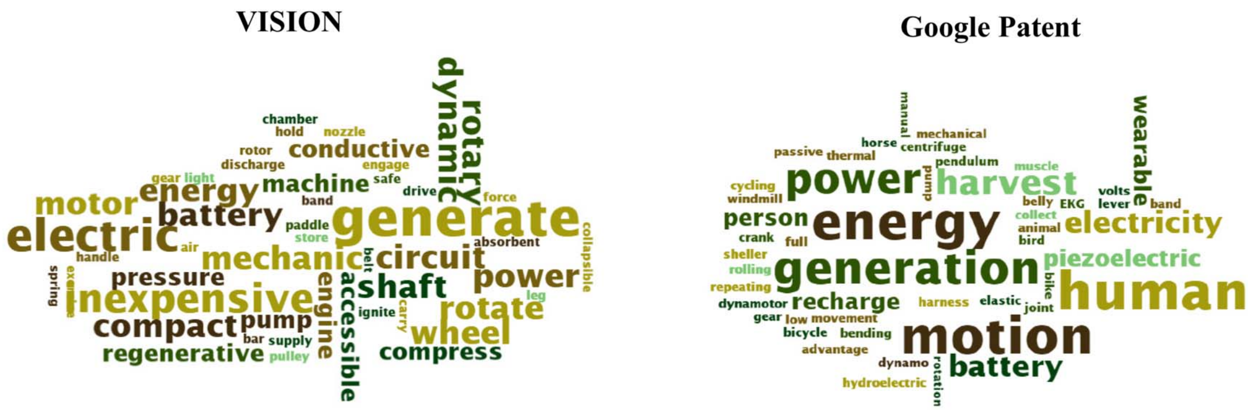


Fig. 12 Word clouds generated using keywords searched

within-domain patents were design concepts that specifically use human motion for generating electricity. Examples included concepts that use bicycle pedals, piezoelectric sensors, and resistance devices worn on human bodies. Although these patents may help designers to solve the design problem, they can act more as technological references than analogical sources. Contrastingly, the between-domain patents were design concepts that were from other technological domains, such as toys, furniture, exercise devices, and health devices. This finding could imply that the within-domain patents retrieved by Google Patent were "too near" for participants to identify useful analogies; the between-domain patents retrieved by VISION were "too far" to be relevant to the design problem [32]. Futures studies need to investigate programmatic methods to identify a "sweet spot" for distance where patents are far enough to provide useful analogies and near enough to be relevant to the design problem.

Participants in both conditions were able to use VISION or Google Patent to generate design ideas that are significantly more novel. Design ideas generated using the provided tools were more uncommon within the design solution space created in this study. It could be that the patents provided analogical inspiration to the participants, resulting in the generation of new and bold design ideas in the second ideation phase. Although ideas generated with VISION did not satisfactorily meet the design specifications, these ideas were unexpected compared to ideas generated in the first ideation phase.

The design ideas generated using VISION and Google Patent were both novel in the current study's design solution space. However, it is important to note that 15 out of 20 ideas generated using Google Patent were directly similar to their respective patent designs. Although these ideas may have received high novelty scores in this study, the ideas are not original (see Fig. 11 for examples). To understand why the ideas generated using Google Patent were directly similar to their respective patent designs, keywords searched in the two conditions were analyzed by creating word clouds. The word clouds in Fig. 12 show the top 50 keywords searched using VISION and Google Patent, in which the size of the font corresponds to the frequency of the keywords searched. The word clouds demonstrate that participants in the VISION condition used various keywords during the patent exploration. One possible explanation for this is VISION's filtering box. VISION provided a filtering box that consisted of a list of labels that describe clustering topics of the patent network. The filtering function was originally intended to allow participants to scale down the patent network for rapid and effective patent exploration. All participants in the VISION condition used the filtering function to down-size the patent network. Also, they used the labels in the filtering box as suggested keywords, and therefore explored patents that are not specifically related to the human motion energy generation devices. In addition, VISION did not initially have patents within the domain of human motion energy generation, which drove the participants to seek analogies from different technological domains. In comparison, participants in the Google Patent condition searched fewer keywords than those in the VISION condition. The keywords that were frequently used were the words specified in the design problem statement (i.e., "human", "motion", "energy", "generation", and "power"). With that, participants in the Google Patent condition retrieved patents that are in the domain of human motion energy generation devices. This finding suggests that it can be difficult for novice designers to retrieve patents that are outside of the domain of the design problem, as they lack the experience to explore different analogical domains. It is consistent with Casakin's study with visual analogies which demonstrated that novice designers retrieved within-domain examples as much as between-domain examples, while expert designers retrieved significantly more between-domain examples [38]. Similarly, Dahl and Moreau's study demonstrated that students used a lower proportion of between-domain examples when they were exposed to within-domain examples [39]. The study also showed that the presence of one or two within-domain examples hindered the students' abilities to produce original ideas. The usage of within domain-examples is not always harmful to the ideation process, as expert designers can use within-domain examples and still be able to focus on deeper similarities; however, for novice designers, usage of within-domain examples can lead them to copy the source examples [40]. It is possible that the participants in Google Patent condition looked for within-domain examples and generated ideas that are directly similar to the retrieved patents because reusing the designs that have been tested and certified reduces the risks involved in the ideation process [41].

The findings presented in this study are important for a few reasons. First, the study validated that VISION allows designers to retrieve analogical inspiration from patent data. In this study, participants were able to interactively explore VISION's patent network using the provided functions, identify design analogies from the patent data, and generate design ideas that were novel compared to design ideas that were not generated with the tool. Furthermore, the design ideas generated with VISION were not worse than the ideas generated with Google Patent, which is the current most widely used method for searching patents for design-by-analogy practice. Though, it is important to raise the issue again that some participants were not able to generate ideas using patents retrieved by VISION. As with any new method, the tool needs to be improved such that it can be used for practical ideation methods. Factors that make finding analogies difficult using VISION need to be explored with further work. Second, VISION is an exploration-based design tool that helps designers retrieve patents that are analogically distant from the design problem domain. Participants who used VISION were able to use exploration features, such as searching nodes and filtering, to retrieve patents that are in various domains. It is important to note that the words used to create the patent network are determined by its topic modeling method, which differentiate it from other patent searching tools. In contrast, participants who used Google Patent used a limited number of keywords to search patents, and the most frequently used keywords were directly from the design problem statement. For the keyword searching method, retrieval of patents or analogical stimuli largely depends on designers' abilities to generate the keywords. For novice designers who lack skills to use different keywords, it would be cognitively difficult to retrieve far-field analogies and easy to be constrained to patents that have surface similarities [40,42]. Also, it was found in the study that the retrieval of patents whose domains are similar to that of the design problem resulted in the generation of ideas that directly copy the patent designs. The ideas copied from patents can be developed into good designs, but Google Patent is not the best method for generating novel ideas when only limited time is provided to ideate. A computational tool, such as VISION, that guides designers to find analogies in patents that are different from the design problem could be helpful in generating analogy inspired designs.

5 Engineering Design Class Evaluation

To further evaluate how designers use VISION during the patent retrieval process, the tool was introduced to a graduate level engineering design class for validation. The study allowed for analyzing the tool's effectiveness in a more realistic design setting in which participants had a longer time to become familiar with the process and use the tool to solve various design problems. The multiple case studies from the design projects allowed the data to be analyzed qualitatively, providing new insight into VISION's impact on the patent retrieval process, which was not sufficiently analyzed in the controlled lab study. In the following section, the method of multiple case study data collection is presented. The results of data analysis are discussed along with the limitations and learnings from the study.

5.1 Methodology. VISION was taught in a graduate level engineering design class as a part of a lecture. The class was a project-based course that focuses on learning and applying various methods for product innovation and design for open engineering systems. For semester-long course projects, teams of five to six students followed the engineering design process, which includes identifying customer needs, generating ideas, and testing prototypes to design or redesign products of their choosing. Students were encouraged to choose products or design problems that were mostly mechanical and contain 25–50 components for them to effectively apply engineering design methods. Examples of design projects chosen by teams included a macadamia nutcracker, smart toilet seat, lunar sample collection device, acoustic tower moving device, residential lifting device, and safety squat rack. The course was also offered in a distance-learning format; all in-class lectures were recorded and delivered online using a learning management system. The course deliverables were the same for the distance-learning students. They formed teams with on-campus students and completed the course projects. All teams submitted design reports as the final course deliverables.

The case studies began by delivering an 80-minute lecture by one of the researchers. The researcher spent the first half discussing design-by-analogy for creative idea generation and the second half teaching students how to use VISION for retrieving patents. During the tutorial session, the students had a chance to run the tool on their personal computers and ask general questions about the method. For distance-learning students, the recorded tutorial was provided online, along with the researcher's contact information to answer any questions they might have had. There were no distance-learning students who contacted the researcher for inquiries regarding VISION. After the lecture was delivered, both on-campus and distance-learning students were offered extra credit in compensation for their participation in the study, with the option to complete an alternate assignment for extra credit if they did not wish to participate. During the study, participants were asked to use VISION's exploration features to retrieve at least three patents and generate design ideas using each of the patents retrieved, in sketches or text, for their team's design problem. Participants then completed online surveys that ask about their demographics and impressions about VISION and their design experiences during the ideation activities. The students were given three weeks to participate in the study and submit lists of patents, analogies, and design ideas. The design task was assigned to individual participants, not teams, to observe the tool's impact on each individual's patent retrieval process. The students were encouraged to work on the assignment individually by asking them to describe the retrieval process (i.e., features used, words filtered, title of patents accessed, and analogies identified) in detail. Those who successfully turned in the assignment and completed the surveys were given extra credit toward their course grades.

5.2 Participants. Data was collected from 16 students from the design class. There were seven on-campus students and nine distance-learning students. Fourteen students were male and two students were female. They were all masters-level graduate students in mechanical engineering with average of 2.73 years of experience in design courses and design related jobs.

Participants' design data from the study were evaluated qualitatively based on the following two criteria: (1) ability to retrieve patents from different domains and (2) ability to retrieve patents that are in domains different from that of design problem. These criteria were chosen because the purpose of these case studies was to determine the utility of VISION in design practice for patent retrieval, rather than design ideation outcomes. Ability to retrieve patents in different domains was used to understand whether participants were searching patents and refining the search results or exploring different patents and variations of design concepts. Ability to retrieve patents that are in domains different from that of design problem was meant to assess whether they explored patents that are different from already existing design solutions. A mechanical engineering doctoral student with experience in design determined if a domain of the retrieved patent was similar to that of the design problem. For each criterion, an evaluation rubric was developed, as shown in Table 2. The rubric was used to evaluate the data and assign a score of Poor, Acceptable, or Excellent. Inter-rater agreement analysis was performed by two mechanical engineering doctoral students with experience in design. The two raters each coded 25% of the experimental data. The agreements were moderate for Ability to retrieve patents in different domains ($\kappa_w = .600$) and Ability to retrieve patents that are in domains different from

Table 2 Qualitative assessment rubric

Qualitative assessment criteria	Poor	Acceptable	Excellent
Ability to retrieve patents in different domains	Participants retrieved patents that are all in similar domains to one another	Participants retrieved one or two patents that are in different domains to one another	Participants retrieved patents that are all in different domains to one another
Ability to retrieve patents that are in domains different from that of design problem	Participants retrieved patents that are all in domains similar to that of design problem	Participants retrieved one or two patents that are in domains different from that of design problem	Participants retrieved patents that are all in domains different from that of design problem

that of design problem ($\kappa_w = .667$). The participants were not aware of the scoring methods and the purpose of the study.

5.3 Results and Discussion. In total, participants retrieved 47 patents and generated 47 ideas. The retrieved patents were evaluated using the two criteria shown in Table 2 to assess their ability to retrieve various patents for idea generation, which is an important objective of VISION. Regarding the first criteria *Ability to retrieve patents in different domains*, 11 participants scored *Excellent*, four participants scored *Acceptable*, and one participant scored *Poor*. For *Ability to retrieve patents that are in domains different from that of design problem*, 12 participants scored *Excellent* and four participants scored *Acceptabl*e; no one scored *Poor*. For each criterion, examples of retrieved patents and resultant design solutions are provided to understand the roles of VISION during the patent retrieval process.

5.3.1 Ability to Retrieve Patents in Different Domains. First, most participants were able to retrieve patents that were all in different domains from one another. One participant who redesigned a macadamia nutcracker retrieved three patents with which to generate unique design ideas. For the first idea, the participant retrieved a patent "Cutter having changeable carrier (US7328513B1)," a hand cutting tool that has a lever on one end and fixed jaw on the other end. The participant identified an analogy *squeeze* and generated an idea that described a handheld device similar to a pair of scissors that have semispherical cup where a nut rests as blade is brought to bear on the nutshell. For the second idea, the participant retrieved a patent "Demolition tool (US8458838B2)," a multi-functional demolition tool used by firefighters for puncturing ceilings. The participant identified an analogy *plunge down* and generated an idea that described a box where nuts sit in the bottom of the box while blades plunge down hydraulically to crack nutshells. For the last idea, the participant retrieved a patent "Apparatus for cutting disposable containers (US3669673A)," a machine capable of shredding plastic bottles and metal cans into pieces. The participant identified an analogy *shred* and generated an idea that described a device similar to a paper shredder that cracks nutshells as nuts are fed into the device and pass between rotating cylinders that have shredder teeth. All these patents were from different technological domains that provide different functional analogies for cracking nutshells. These ideas are preliminary as there are possibilities of damaging nuts upon operation. However, the ideas can be developed into final solutions if designers explore ways to protect nuts during the shelling process. Other participants' results that demonstrate the breadth of patents retrieved are shown in Table 3.

5.3.2 Ability to Retrieve Patents That Are in Domains Different From That of Design Problem. Second, most participants were also able to retrieve patents whose domains were different from those of design problems. Again, this measures the degree to which the participants explored patents that are different from already existing design solutions. Between-domain analogies, or analogies found from a different domain, can be useful during creative ideation process [3,43]. One participant who designed a lunar sample collection device retrieved a patent, "Fixation of elemental mercury present in spent molecular sieve desiccant for disposal (US5173286A)" and identified an analogy that "a molecular sieve filters out mercury while [a] grabber may need to filter out lunar dust for dust resistance." The participant used the analogy to generate an idea that has "a grabber with two sieve-like halves at the end of a rod that come together to grab a lunar sample, contain it, and filter out any lunar dust. A tension rod is used to clamp the halves together." Interestingly, tongs designed by NASA designers use the same principle for picking up small individual rocks for space missions. This exemplifies the use of VISION to identify useful analogy from a retrieved patent.

Another participant, who designed a smart toilet seat, found a between-domain patent useful for gaining new perspective on the design problem that they worked on. The participant retrieved a patent "Statistical analysis and feedback system for sports employing a projectile (US5882269A)," which records a golfer's series of practice shots and then presents errors to the user via personal data assistance. The participant used this patent to come up with interesting features for a smart toilet seat. The following quote is provided by the participant:

"[the analogy] presents an interesting opposite intent to the project. So far, the focus has been to generate a sensor system to read biometrics that does not seem invasive and secondary act more as a hidden feature to the toilet—i.e., keep the toilet seat as analogous to current toilet seats. This current era is the culture of constant feedback to better oneself. What if a screen was linked to the toilet seat—via wiring or sending to an app—that benchmarked personal recorded biometrics against what someone of that age/weight/height should statistically have?"

Along with the submitted work, the participant provided feedback that the tool helped the team to discover patents outside of what the team had previously been considering. This exemplifies the effectiveness of VISION in enabling designers to explore for between-domain patents that give different insights into design problems. From the survey result, participants generally reported that VISION helped them to identify unexpected analogies. Other feedback included difficulties using VISION due to the limited number of patents available in VISION, a minor bug in the visual interactive system, and lack of functions for tracking patents that have been already accessed. This suggests that there is still work to be done to improve the usability of VISION for effective retrieval of patents

Table 3 Examples of retrieved patents

Design problem	Patent titles	Domains
Safety squat rack	Rope braking system (US9279476B2)	Cable fastener
	System and method for real-time recognition of driving patterns (US7444311B2)	Measuring traffic conditions
	Portable load lifting system (US7172221B1)	Exoskeleton
Lunar sample collection device	Food and treat dispenser (US6886739)	Pet food dispenser
	Fixation of elemental mercury present in spent molecular sieve desiccant for disposal (US5173286A)	Agglomeration
	Wrench with restrained adjustable jaw (US6116121A)	Spanners; wrench
Acoustic tower moving device	Rotatable crane apparatus for a rescue vehicle (US4515282A)	Cranes
	Remote controlled scaffold hoist (US5316265A)	Application of remote-control devices
	Magnetic Carrier (US6168221B1)	Magnetic holding means

6 Limitations

There are several limitations in the first and second studies that are important to acknowledge. In the first study, participants were given 15 min to generate ideas in the first ideation phase and 15 min to generate additional ideas using VISION or Google Patent in the second ideation phase. One limitation is that participants were asked to generate as many ideas as possible during the given 15 min, and it could be problematic to measure the quality of ideas that requires a certain level of detail. In fact, participants were able to generate ideas in the given 15 min. The limited number of ideas generated could affect the novelty scores in this work, as the novelty calculation is largely affected by the quantity and diversity of ideas generated in this work. To cope with this limitation, a space of possible solutions for a design problem can be pre-generated with a large data sample and used as a ground truth data to compute the novelty score. Taking the size of the possible solution space (i.e., number of ideas) into account in the novelty equation is another method to improve the accuracy of the calculation. In addition, the limited time to work on the design problem could have encouraged participants in the Google Patent condition to retrieve patents related to the design problem, which resulted in the copying of patent designs. Unfortunately, because participants were only able to generate one or two ideas in the second ideation phase, it was not possible to analyze if they were fixated on the patent design or if they were able to move away from the example to generate original ideas. During the second ideation phase, the time spent on using the tool and time taken to generate ideas was not reported in this work due the difficulty of objectively measuring the activity time with the videos of screen captures (i.e., a pause on the screen can be interpreted as thinking about methods to retrieve patents or pausing the search to generate ideas). If it were possible to measure the exploration or search time and ideation time, the data could be used together with other measurements made in this work to give an indication of VISION's ease of use. Although the survey was used to understand participants' overall experiences with VISION or Google Patent, post-interview sessions could have been utilized to understand why some participants generated ideas similar to patents and why some participants were not able to generate any ideas using retrieved patents. Multiple design problems could have been utilized in the study to more deeply assess the efficacy of VISION. Lastly, participants in the VISION group could access only 500 patents while those in the Google Patent group could access the entire patent dataset. Scaling up the size of patents in VISION is an important work that needs to be addressed in future studies.

In the second study, participants were given three weeks to use VISION to retrieve at least three ideas and generate a design solution for each of the retrieved patents. One limitation is that the study does not include a comparison of VISION with other tools, such as Google Patent, to analyze if participants could have retrieved similarly diverse patents using other tools. Also, participants were not asked to report the amount of time taken to retrieve patents using VISION and generate ideas which could have provided useful insights into the study. Lastly, although participants were instructed to work individually on the assignment, there is a possibility that some participants communicated with their team members to complete the assignment.

7 Future Studies

As with many new design methods, there still is work to be done to turn VISION into a marketable tool. In addition to scaling-up VISION to include much larger set of patents, providing variety of user interaction support tools can improve designers' abilities to retrieve useful and unexpected analogies. For example, having a mini map that is placed at a screen corner in the visualization space can aid designers to navigate themselves in the patent network. A memo pad for making notes on potential analogies and ability to bookmark patents can help designers to keep track of their exploration results. The exploration support tools can be developed by collaborating with human computer interaction practitioners to evaluate their usability in a design process. In addition, different method for visualizing the patent network can be explored. For example, the network can be visualized in Window's navigation pane style that shows lists of patents under different "topic" folders. The pane style visualization can be provided along with the patent network to give designers options to interact with whichever is more convenient or useful.

VISION provides Component-, Behavior-, Engineering principle-, and Function-based representations of a patent network. Future study can focus on structuring the patent network with different analogical properties to provide designers different lenses for retrieving analogies. In addition to the four lenses that are already provided in VISION, researchers studied if patents can be structured based on their physical forms—shapes, materials, and scales. Structuring the network based on physical forms is left unfinished in this work but it is an important work for creating a wider portfolio of lenses available in VISION. It was learned from prior experiments that structuring patents based on physical forms is a difficult process as most patent documents do not have words that describe patents' shapes, materials, and scales. A different method for analyzing similarities of patents is needed. This could be explored by using an image comparison tool to measure how two patent images are similar to each other and create a network of visually similar patents based on the comparison result.

Finally, one last interesting avenue for future work is using designs from nature [44] as VISION's additional source of inspiration. VISION currently focuses on finding analogies within human inventions archived in the electronic patent database. When the future work described in this section is achieved, researchers can improve the tool to incorporate designs in nature to help designers retrieve analogies from both nature and patent database.

8 Conclusion

This paper presents two cognitive engineering design studies to measure the efficacy of VISION developed in the authors' prior studies [1,2]. In the first study, conducted in a controlled-lab setting, VISION (exploration-based approach) was compared with Google Patent (query-based approach) based on their effects on design outcomes. The important finding is that VISION helped designers to retrieve patents that are different from already existing design solutions, resulting in novel design ideas. Google Patent also helped designers to generate novel design ideas, but the ideas were not original, as there were direct similarity between the generated ideas and retrieved patents. However, it is important to acknowledge that both VISION and Google Patent resulted in low quality ideas. Similarly, the second study, conducted in an engineering design class, demonstrates that designers were able to explore patents that are in various domains and patents that are different from already existing design solutions. Considering these empirical findings, VISION provides designers a new way to access the wealth of knowledge contained in the historical records of invention and technology. When deployed at a large-scale with improved exploration support, the tool will open up new opportunities for designers to benefit from computationally supported analogies.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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