Mitigating Fixation in Creative Process by Using Patent Data Tool as Stimuli

Master Thesis

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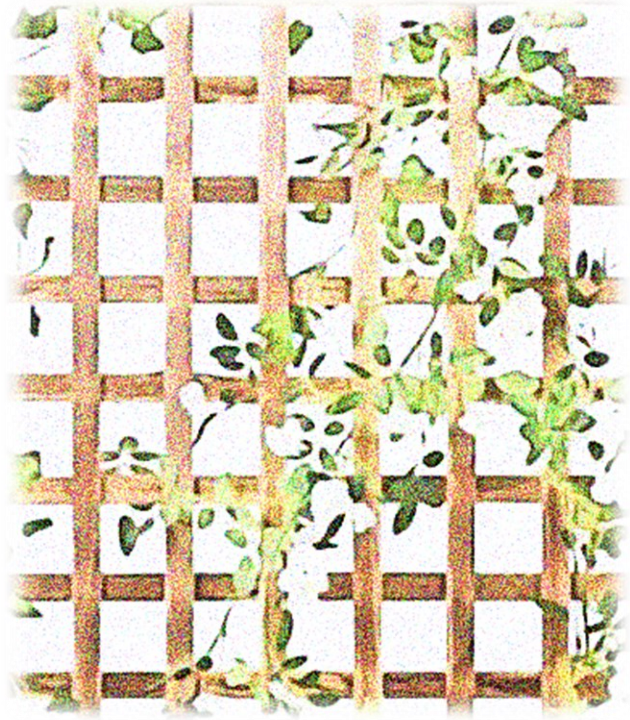
Design tool and process are not to limit

designer's imagination in a stiff way.

Instead, I hope they are like garden trellis,

which can better support creativity.

Ranzhi



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Abstract

In the early conceptual stage of design, novice designers and professionals experience different levels of fixation. Design tools and workflows can support designers to explore creative opportunities. Patent data tool for engineering design purposes is one example, using the design-by-analogy method to facilitate divergent ideation. This work will examine how designers can use the patent stimuli to explore both design problems and solutions and in what way.

The study applied a within-subject experiment with 6 participants. Each participant did brainstorming tasks with patent data tool and baseline tool. After the experiment, they gave feedbacks on the patent data tool. The concurrent think-aloud protocol, screen recording and idea sketches were used for explorative data analysis.

From the participants' self-report, they all gave positive feedbacks on the tool's value for acquiring new knowledge for divergent ideation. External raters clustered all the ideas by categories, following function-behavior-structure theory model. The overall fixation rate in the patent data condition did not bypass the baseline condition. From qualitative analysis on the ideation process, the patent data tool effectively eliminated *knowledge-based fixation* in the query stage. Its textual stimuli helped to release *conceptual fixation* if they were not exposed to solution visuals. The patent stimuli inspired participants with solution directly but did not provide problems consistently. The limitations of patent data tools are discussed. It points out the possibilities of using supplementary tools to better support exploration on problems, using analogies and thinking at an abstract level and overcoming *conceptual fixation*.

Lastly, future studies are needed to look into a combination of new tools to work with the patent data tool. Designers begin with understanding problem and user contexts from common sense knowledge tool. Afterwards, the patent data and biological-inspired tool can facilitate designers to ideate desired functions and related product behaviors. Ultimately, text to generative image tool can help conceptualize structural design. Future studies are needed to evaluate the effect of this new method.

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Chapter 1 Introduction

Creativity is one of the most important human cognitive capabilities, distinguishing human thinking from linear machine processing. Designers are expected to be creative and find "out of the box" solutions. To generate creative ideas, designers see how to reframe the problems, and how to search for solutions as a co-evolution process (Dorst & Cross, 2001). However, both design students and professionals experience different levels of fixation in the early conceptual stage, which prevents them from being productive (Jansson & Smith, 1991). They need inspiration from design tools and workflows to explore creative opportunities (Crilly & Cardoso, 2017).

Patent database records large numbers of innovation solutions. Companies register their latest intellectual property in the patent database as a business strategy. They can also dig innovation insights from other companies' registered patents (Rivera, 2000). Patent visualization tools, such as PatentsView (http://patentsview.org), give users a quick overview by applying data mining and text mining technology and presenting patents in clear-structured infographics. Because of the low efficiency of manually searching patent documents, researchers have built patent data analysis and visualization tools, such as TechNet (http://www.tech-net.org) and InnoGPS system (http://www.InnoGPS.com) to facilitate human interpretation of patent data. These knowledge-based visualization platforms automatically analyze millions of patent data based on sematic, document, and field levels. They can perform as design stimuli for designers to explore both the problem definition phase and solution phase (Luo et al., 2021).

Researchers propose a new computer-aided ideation process using combination and analogy methods to explore new engineering solutions with these patent tools. But, less is known about how these patent tools influence the design process and design fixation during different stages. This research will examine how designers can use these patent stimuli and iteratively work on both design problems and solutions.

Chapter 2 Literature Review

In this chapter, readers can understand the findings from previous research on design fixation, creative process, and patent data-driven tool. The first section gives you a general idea of the fixation research, its research framework, and design-by-analogy approach to minimize the negative fixation influence. The subsequent section focuses on the creative process as a cognitive process and several strategies to maximize creative outcomes. The last section introduces patent data-driven knowledge base, using TechNet as a representative of its kind and further explain the use of near-distance, far-distance inspiration.

2.1 Design Fixation

2.1.1 Definition and Categories

Jansson & Smith (1991) and Youmans & Arciszewski (2014) describe fixation as a negative factor that prevents designers from being creative. Crilly & Cardoso (2017) give a neutral definition of fixation, which allows a broader exploration and fair judgement on the fixation issue. According to them, design fixation refers to a cognitive condition with an unconscious bias from previous experiences, knowledge, or assumptions when a person can only explore a constrained creative space for a design work.

Youmans & Arciszewski (2014) conclude different types of fixation from a designer's awareness perspective. Firstly, it is an unconscious adherence to the existing design solutions (Jansson & Smith, 1991). It is difficult for most designers to be aware of this mental fixation and overcome it. Even if researchers warn designers not to copy from previous functions or failed examples in fixation experiment, designers do not succeed in overcoming the fixation effect. Secondly, designers can also be conscious and suffer from undesired fixation caused by their experience or knowledge. A designer's knowledge and experience help create an efficient and feasible way to solve problems. As a result, they stick to this certain path and no longer seek creativity. Similar to the first scenario, even if designers are aware of their fixation, they find that they can do little to overcome it. Thirdly, people also intend to resist novel, unproven ideas that can bring risks. This is a reasonable attempt to save cooperation investment and get rid of short-term uncertainties. Furthermore, a designer can also favor nostalgia and classic design instead of breaking the norm (Youmans & Arciszewski, 2014).

Jansson & Smith(1991) and Youmans & Arciszewski (2014) further propose another classification based on the thinking process between the conceptual and configuration mentality domains, which is strongly related with designers' knowledge and experience. A designer process his abstract ideas, connections, or models in the concept mentality space. In configuration mentality space, a designer thinks about tangible objects such as drawings, graphs, and shapes. The *conceptual fixation* means that a designer only thinks of a limited number of tangible forms in configuration mentality space. The *knowledge-based fixation* means that a designer fixes on a form of abstract knowledge or pattern and fails to consider other alternatives. If a designer can shift smoothly between abstract and conceptual domain in a creative thinking process, fixation can be avoided.

Combining these two approaches, a design fixation framework is formulated(Figure 1). The designer will possibly face more than one type of fixation mentioned above at the same time. Even years of working experience cannot reduce the effect of fixation (Zhang et al., 2018). One example of *knowledge-based fixation* and unconscious adherence is that designers can copy abstract functions from existing examples without intention or awareness (Jannson & Smith, 1991; Youmans & Arciszewski, 2014). Another example is that designers find it difficult to invent an alternative use of a product for a different purpose, which is a *knowledge-based fixation* but with conscious adherence (Kicinger et al., 2005; Youmans & Arciszewski, 2014).

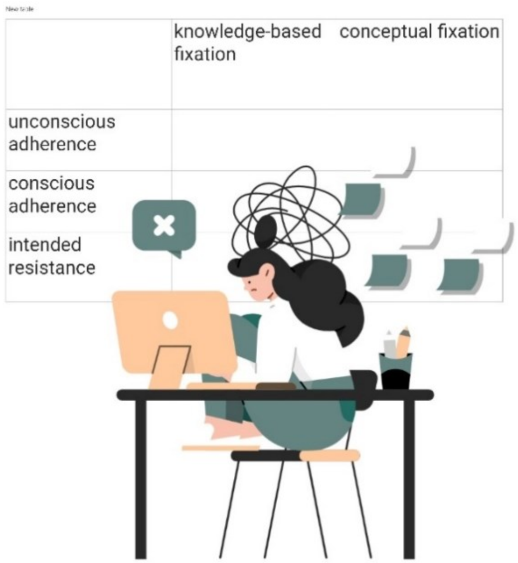


Figure 1 Classifications of different design fixation (Youmans & Arciszewski, 2014)

Researchers interpret the fixation phenomenon from broad perspectives and give different classifications of fixation. It is also valuable to examine fixation in design iterations, to be explained in the next section. This report focuses on how individual designer can fix between the knowledge and conceptual level of thinking and how designers are aware of their fixation.

2.1.2 Fixation Research Framework

Fixation is an interesting domain to researchers because of the unknowns in the cognitive process related to creativity, inspiration, and information processing (Crilly & Cardoso, 2017). Previous fixation studies are sufficient in quantities and share some common grounds. Alipour et al. (2018) propose a design fixation research framework (Figure 2). Design problems, inspiration sources, designer, and design process can be variables which influence the design outcome. Besides, the distance between inspiration source and design problem, the designer's goal for source selection, and the similarity between source and design outcome can be different elements that influence the experiment outcomes. Most fixation researches focus on the early ideation phase and evaluate ideation outcomes (Crilly & Cardoso, 2017). From this framework, design iteration process and a technological stimuli using patent data will be introduced in the later sections.

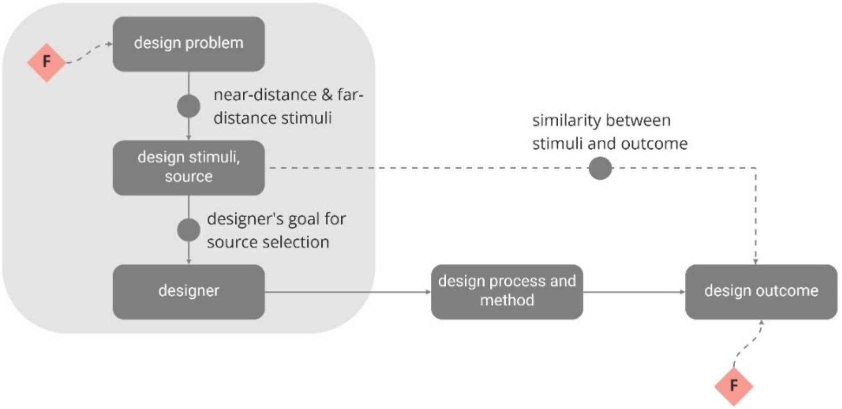


Figure 2 Variables in design fixation study (Alipour et al., 2018)

2.2 Overcoming Fixation in Creative Ideation Process

2.2.1 Design Iteration

Why researchers investigate fixation is to better achieve human creative capacity. A creative process will be an ongoing exploration, a co-evolution of problem and solution space (Dorst & Cross, 2001). In the idea-generating process, designers must diverge and generate as many ideas as possible. In analyzing a co-evolution process, we cannot simplify it as a routine work.

To generate creative ideas, designers explore how to reframe the problems and search for novel solutions as a co-evolution process (Figure 3). Dorst & Cross (2001) argue that there might not be a clear distinction between problem definition and solution-seeking. Moreover, during this process, creativity does not only come from breakthrough ideas which seem "strange and uncomfortable" at first sight. Instead, the thinking process of reconfiguring these strange ideas' value is more important.

Crilly & Firth's fixation case studies (2019) aligned with this perspective and confirmed that "new, useful, and surprising" design is not merely a breakthrough but "an ongoing process that connects many interacting moves." If so, fixation and de-fixation can also come along the process. We cannot simply judge one moment as productive breakthrough or negative one. For example, the designer can also be fixated on a previous breakthrough idea(Crilly & Firth, 2019). Fixation related to design iterations (Figure 3) is also interesting for future research.

Zhang et al. (2018) define three basic types of design iterations as efficacious, inadequate, and ineffective when designers move between fixation and iteration. The study uses urban architecture planning as an example to illustrate the fixation on the architecture ideation process. An experiment with high school students found that over half of students iterated efficaciously in the first task but were more fixated when moving towards the end. They also suggest using computational analysis to facilitate design process research quantitatively. It is assumed that similar experiences will also happen to industrial engineer students.

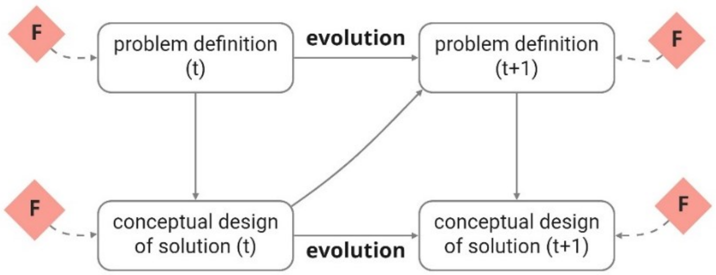


Figure 3 Fixations In the problem solution co-evolution process

2.2.2 Approaches to Minimize Fixation

The literature review by Moreno et al. (2016) provides a systematic overview of internal, and external methods to overcome individual fixation (Figure 4). Internal methods rely on designer's intuition, knowledge and experience without external stimuli, such as reframing problem. Reframing the problem has been discussed before.

External method means tool, material, or method that independent from designer's cognition to assist ideation. Csikszentmihalyi (1997) points out that there is no way for a designer to be creative alone through one's intelligence and cognitive process without an external system. Designers have to know the project domain, have access to the latest information, and finally be recognized by experts in that field. Different design domains are different in logic, components, and regulations. For example, design for a mass-production car and design for garment requires knowledge in two design domains. On the other side, the knowledge in that domain shall also fit designers' understanding. Otherwise, creative young people are unwilling to learn new knowledge in that domain.

Regular external methods include using analogy with open-ended design brief, ideation software, keyword tree graph, and visual stimuli like sketching, authentic images. These approaches are applied in the patent database analysis tool to be mentioned in the next session.

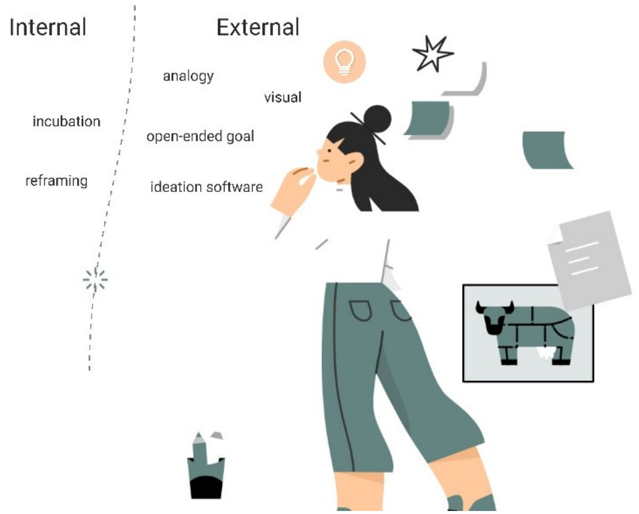


Figure 4 Internal and external methods to minimize fixation

2.2.3 *Using External Methods in a Fixated Way?*

According to Cardoso et al. (2012), looking for external inspiration is a frequent practice for designers. Because designers are trained to be sensitive to these inspirations, they can be triggered to novel solutions when looking for inspiration and interacting with them. Designers prefer to use images as design stimuli rather than text information because images are authentic, memorable, and available from broad sources. However, the way of using pictures or text as design stimuli should be carefully considered. It is suggested to be exposed to designers on an abstract level to avoid fixation (Cardoso et al., 2012).

Gonçalves et al. (2016) found that both novices and experienced designers shared common grounds for choosing inspiration materials. They all prefer to use existing solutions which are similar to their problems (near distance stimuli). They choose inspirations from the Internet, competitor ideas, personal knowledge, and design experience. For novice designers, the information related to personal knowledge and design experience is less than that of experienced designers. Afterwards, researchers found that either novices or experienced seldom use abstract information in a distant domain. Far distance inspiration is suggested by literature but are overlooked by designers. Most designers like to search for inspirations that can efficiently apply to solve design problems. Both novices and professionals tend to think visually to solve problems. As primary inspiration sources, novices are sensitive to inspiring images of shape, color, and functionality. Professionals are more interested in collecting pictures of functionality.

Although above researches recognized importance of external tool, Gonçalves (2017) further addressed that participants either rejected to use new tool or get fixated by it. In the experiment, a search tool using carefully chosen images and short texts was given to facilitate participants ideation. The stimuli includes both near-distance and far-distance inspiration. Existing product images or texts related with project brief can also be revealed from some stimuli. Interestingly, a few students did not want to use new stimuli at all and perceive the stimuli as a hinders to creativity. Some tried the tool only when they felt exhausted from old ideas. Furthermore, participants even reported that they were forced to use external stimuli passively. Accordingly, they just input random irrational stimuli to take advantage of opportunities. However, the participants who saw the value of stimuli showed fixation in their design outcomes. The stimuli they got from the search tool showed detailed product appearance which limit their own exploration.

2.2.4 Design-by-Analogy Philosophy

Previous subsection mentioned that designers prefer to use near-distance stimuli and images instead of texts. These stimuli can easily lead designers fixated on existing solutions. Stimuli should be abstract, and keep a distance from original domain. Design-by-analogy or analogical design is one of the powerful external methods. It has been investigated as an effective method in minimizing fixation, and producing novel outcomes(Moreno et al., 2016). It is the transferring of the knowledge in one context to another, which applies to a broad range of design tasks. It requires designers to creatively abstract the concepts, patterns, and prototypes from one original context into another situation (Goel, 1997). A rich pool of possibly connected ideas is needed to apply design-by-analogy method and overcome design fixation (Smith et al., 2011). For example, inspired by using shower pipe in Europe, Jim Crocker borrowed its structure to the corrective optics for Hubble Space Telescope (The University of Chicago library, n.d.).

Some well-examined mechanisms can be the rich ideation pool for analogical thinking, which usually exists in the patent database, or biology domain (Smith et al., 2011). According to Helms & Goel (2014), analogical inspirations help define and redefine the problem early in the design stage. Functional elements in one biological context can be successfully used in engineering design problems. One creative idea that can be successfully registered as a patent must be strictly tested to prove effectiveness. More about the patent database will be explained in the following section. However, less is known about the effect of using patent database as an analogical inspiration.

Unlike the problem-solution co-evolution model by Dorst & Cross (2001), Helms & Goel (2014) propose the co-evolution of problems using biological inspiration in Figure 5. In this context, existing biological knowledge is seen as an analogy. When a designer wants to solve a problem, he can find an existing biological solution to another problem. Then the designer can use the biological knowledge as an analogy to extend and expand the problem he is working on. If designers want to use design-by-analogy, they need to ask four fundamental questions "why, what, how and when" (Goel, 1997). Why do they want to use the knowledge in another domain to solve their problem; What knowledge do they plan to use; How do they modify the knowledge to fit their design task; When can they use it.

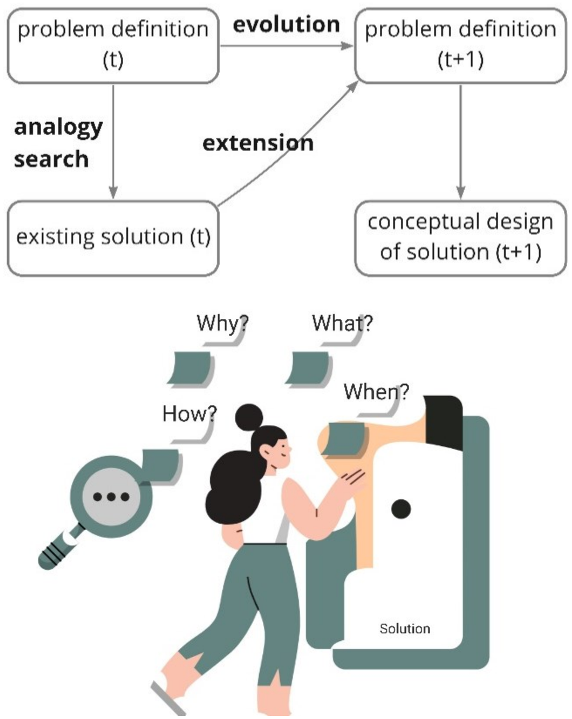


Figure 5 Problem and solution co-evolution in design-by-analogy process (Helms & Goel, 2014)

2.3 Patent Data Tool as Design Stimuli

This section will give a general overview of the patent database and TechNet as one of its representatives especially invented for creative purposes.

2.3.1 Patent Data Tool and Analysis Tools

A patent document is an official authorization from a government agency that only the inventor of novel equipment or design has the right to use or produce for a certain period of years (Griliches, 1998). The patent system allows inventors to have a market monopoly for their inventions and technical innovation. The system also serves as an open channel to reveal the latest innovation.

Bonino et al. (2010) listed various patent data sources and diversified usages. National patent offices are usually the main providers of the patent database. Commercial companies integrate this background information into their applications and list additional information, such as mutual citations and abstracts. Patent search, analysis and monitoring are three main user tasks. For patent operational purposes, users use patent database to write a new application, defend existing patent right, or to verify a new product launch. Users can also use for a broader explorative purpose, such as understanding technological map, identify new business opportunities. Expert users can steer the complexity of manually searching, analyzing patent information. But, for non-expert users, the low efficiency of manually searching and analysis are for unmanageable for occasional use. Automatic patent data analysis and visualization tools are needed by applying data mining and text mining technology and presenting patents into clear-structured infographics.

Because registered patent documents are in a standardized format authorized by government agencies, the numbers of patents reliably count the latest technology trends and level of innovation. There is a strong link between R&D works and innovation. The number of patents can indicate successful R&D activities which accumulate innovation. Reversely, patent documents can also show R&D activities, technological and economic structures, and development trends (Baumann et al., 2021). According to them, semantics technology is important for a patent knowledge base by providing users with optimized search and analysis results. For R&D purposes, patent data can be background information source that extracts new inventions through TRIZ method, one type of design-by-analogy. As a result, the problem and solutions can be presented as a search result on an abstract level to inspire new interpretations. For example, Patent Analyzer and Invention Machine are two tools supported by TRIZ tool for users to explore other engineering design solutions. Invention Machine moves one step further, presenting design problems to users. Nevertheless, two tools are not free and available online for public.

On the other side, investigating the technology trend from patent data alone will not be a success. The insights merely from the patent database following "uncertainty and ambiguity" features of new technology will limit researcher's understanding. The success of technology is also the co-evolution of technology with other factors, such as social, economic, and political factors (Li et al., 2019). For example, people's awareness and acceptance of technology solutions are critical to reducing "uncertainty and ambiguity" for good implementation. Designers shall play an important role in connecting technology and users, which means using the technology in the appropriate place with an innovative solution. The patent databases shall also facilitate designers to know the emerging technologies and existing solutions in ideation process.

2.3.2 TechNet Platform as an Example

TechNet(http://www.tech-net.org) is an open platform of its kind to facilitate human interpretation of patent data. These knowledge-based visualization platforms automatically analyze millions of patent data based on sematic, document, and field levels (Luo et al., 2021). Regular open patent database includes full descriptions of the invention and design illustrations. It is time-consuming for designers to read through and understand. Instead, TechNet extracts short key word and terms as design stimuli. Although it replace a systematic view of the whole patent document and original context, researchers believe it is more suitable for ideation use than traditional search. TechNet contains over 4 million terms of technical vocabulary pre-extracted from U.S. patent database since 1976. These terms describe features, compositions, constructures, and mechanisms related to engineering designs (Luo et al., 2021).

According to Luo et al.(2021), TechNet is built on the philosophy of design-by-analogy, which is computer-aided ideation process using combination and analogy methods to explore new engineering solutions. As Steve Jobs pointed out that “Creativity is just connecting things”. Analogy is the thinking process of linking existing solutions, usually as design stimuli, to creatively solve a problem in the target domain. The stimuli source and targeted problem are generally in two different categorizations, from which most people have not yet connected these concepts. From current studies, near-distance stimuli are easier to be interpreted, and possibly produce feasible solutions. Stimuli from far-distance have higher possibility of generating novel, and potentially cutting-edge solutions. These design stimuli are for designers to explore both the problem definition and solution phases. The challenge is to make sense of knowledge from irrelevant domains. Besides, designers are less likely to be fixated when reading this simplified, abstract stimuli instead of reading original documents (Luo et al., 2021). If designers have reviewed patent documents before ideation, it led to different levels of design fixation, which also linked with design distraction (Koh & De Lessio, 2018).

Tree graph search is one of the main functions of TechNet to fulfill design-by-analogy. It only provides users with a list of relevant keywords at an abstract level, which can potentially prevent *knowledge-based fixation*. It does not show product images or details, which prevents users from *conceptual fixation*. TechNet is chosen for this research because of its accessibility and intuitive interface. The website is open for all users without the required user registration procedure. Also, the interface design of TechNet presents tree graph search in a simplified way, which can avoid information overload or distraction. It is assumed as an easy-to-learn stimuli for designers.

2.3.3 Tree Graph Search Interface and Functions

One of the main interfaces of TechNet is the tree graph search in Figure 6. Once the user inputs a word, the website will extract closely related technical words from the patent database in the tree graph. If one user clicks on one term in the branch, more new branches will appear. User can continuously input new words coming up to their minds to do an iterative search. They can also double click on one keyword in search results to show more branches in this direction. The tree graph will be flowing accordingly when users drag and move one keyword for a better view.

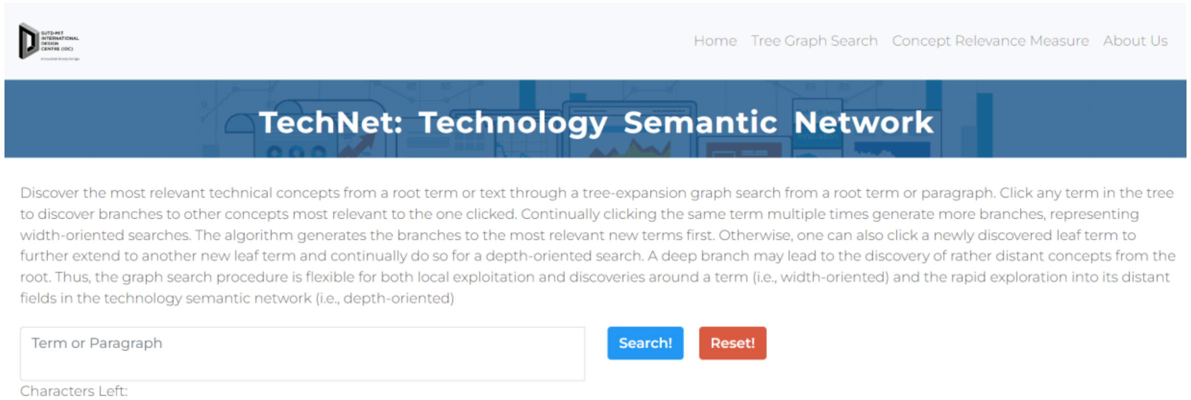


Figure 6 Interface of patent data tool (SUTD Data-Driven Innovation Lab, 2020)

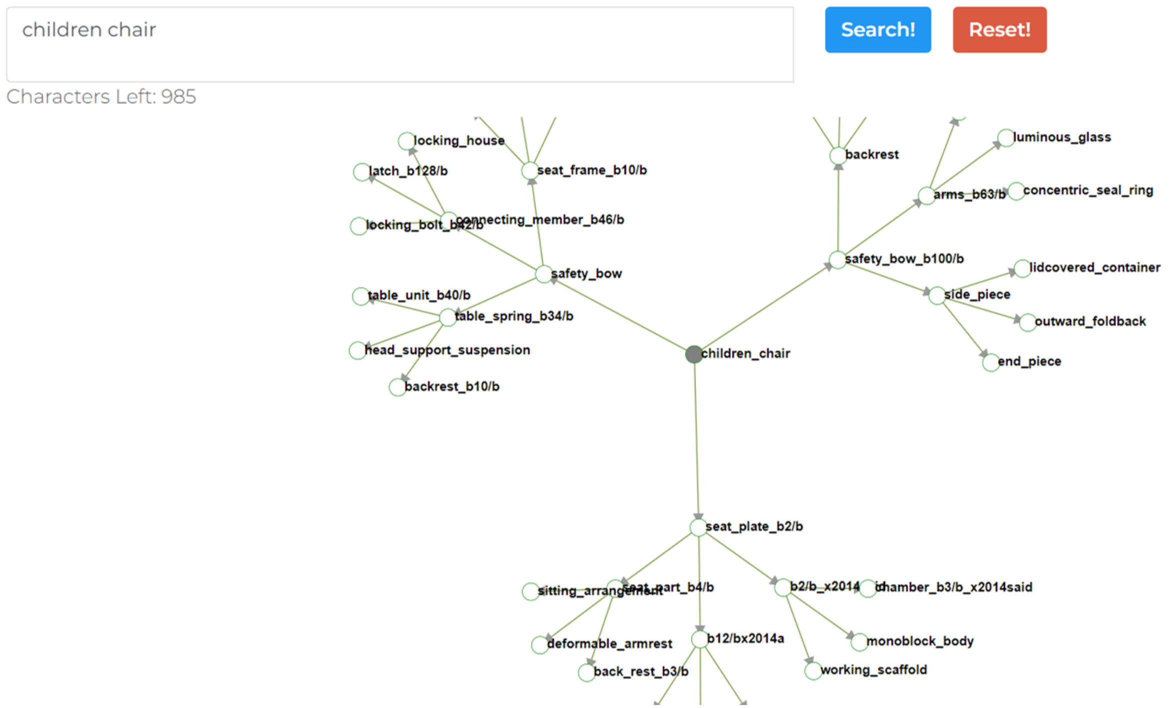


Figure 7 Search "chair" in patent data tool (SUTD Data-Driven Innovation Lab, 2020)

The author uses chair design as an example to explore the tree graph as a brainstorming tool (Figure 7). Once the search keyword is "children chair", some interesting results appear in the graph, such as "safety bow", "luminous_glass", "lid covered_container", "collapsible golf bag cart" etc. These four keywords guild divergent design directions from patent documents, which give designers imagination space (Table 1). These keywords and visual examples can also be found from baseline search engine.

From one pilot experiment and the author's observation, the tree graph search interface has limitations that hinder users from using it as creative inspiration. It can always show an error screen or ask the user to wait a long while when the user inputs some compound words. Using chair design as an example, the keyword "chair kid, chair children, chair wheel, music chair" can lead to the error screen in Figure 8. However, when users input similar word combinations such as "Children chair, sofa chair, wheelchair, push chair, comfortable chair", the website works well. The author tries some keywords randomly, as examples in Table 2. One possible explanation is the complexity of thematic analysis, which limits the system to link some compound search words with patent documents. This example suggests that frequently used words can most possibly display search results. As a result of this limitation, users should try different search words iteratively. This chair design example is also included in the training materials for experiment participants to learn the basic usage of the website.

TechNet also provides functions which measure far distance or near distance statistically or to show near-distance concepts with measures. The author chooses the tree graph search interface in the follow-up experiment because it is the most intuitive and easiest for first-time users to learn as brainstorming tool.

Table 1 Examples of interesting search results as stimuli in patent data tool as design stimuli

Examples of interesting search results	Author's interpretation on design direction
safety bow	safety functionality and bow shape
luminous_glass	Decorative functionality with a certain material
lid covered_ container	Storage functionality with a lid cover structure
collapsible golf bag cart	Storage, portable functionality with folding structure

Table 2 Trying out different search words in patent data tool

	Examples of search words that work	Examples of search words that do not work
including chair in key word	children chair, sofa chair, wheelchair, push chair, chair bed, comfortable chair, ...	chair kid, chair children, chair wheel, music chair, car chair, pull chair, ...
Not including chair in key word	Alarm, Clock, Pillow, Car seat, ...	Car children, Riding pony, ...

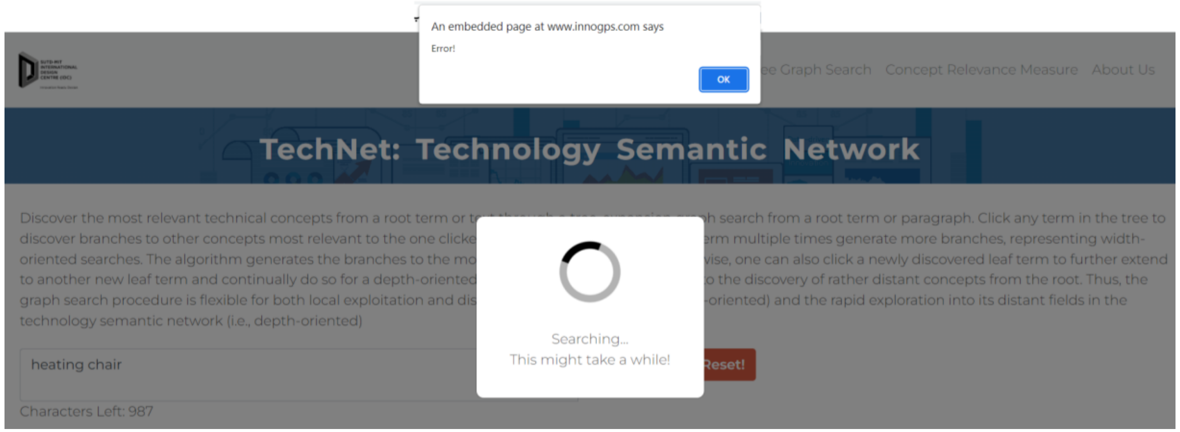


Figure 8 Error screen in patent data tool (SUTD Data-Driven Innovation Lab, 2020)

2.3.4 Near-distance and Far-Distance Patent Inspirations

From a university assignment with engineering design students, Song et al.(2017) identified students' ideation outcomes inspired from different distance level of patent documents. Guided by design-by-analogy method, all patent documents are categorized into three types: target domain, near-distance, and far-distance. Students were given unlimited access to using patent titles, abstracts, and images in the documents. Stimuli from target domains are most likely to be applied by participants. Students formed new design concept from a combine of patents from multiple distances, a mix with either target domain, near-distance or far-distance patents. Using near-distance stimuli contributes to most idea generation, developing more novel ideas. This refers to three scenarios, using near-distance stimuli individually, combined with far-distance stimuli, and all three types of stimuli. Ideas inspired from the far-distance, combines of the target domain and far-distance, had a better functional and structural quality (Song et al., 2017).

The findings of using patent documents showed a difference from the data-driven patent analysis tool. Later case study research used the similar patent data driven platform to show that it can be used as design stimuli for open-ended design tasks or specific problems. Designers can find more feasible ideas by using these near-distance stimuli. In contrast, far-distance stimuli can lead to more novel but less feasible solutions. A search method was also suggested by locating the target domain and then exploring the search scope of the near-distance and far-distance keyword stimuli (Luo et al., 2021). Further research is needed to test the effectiveness of the data-driven patent analysis tool in the experiment setting.

Patent researchers also suggest using patent search for the creative task should be conducted in an iterative and exploratory process. Also, different design methods can facilitate this process (Bonino et al., 2009). Considering these state-of-art tools are new for design innovators, the value of this study can provide more understanding of how these tools can facilitate the iterative ideation process.

Chapter 3 Research Questions and Methods

In this chapter, research questions are formulated, followed by research methods and pilot experiments. The first section introduces research gaps and research questions. Afterwards, a systematic review of the previous experiment setup is given with the experiment plan. The subsequent introduces the pilot experiment, results, and modifications for the formal experiment plan. The last two sections describes the experiment procedure, and recruiting participants.

3.1 Research Questions

From the literature review, this project aims to research use these patent data tool as design stimuli to minimize fixation in the early conceptual process. The following research questions guide the whole research:

RQ1: *What are the current effects of using patent data as stimuli to explore creative space in both problem definition and conceptual design phase?*

RQ2: *How can designers collaborate with patent data stimuli effectively to explore problems and solutions?*

For the first research question, some sub-research questions are listed as following:

Sub RQ 1-1: How do designers interact with patent data tool as stimuli in the design process?

Sub RQ 1-2: How are the design outcomes by using patent data tool as stimuli?

Sub RQ 1-3: How do designers iterate on problems and solutions co-evolution with patent data tool?

Sub RQ 1-4: What challenges designers to use patent data tool as inspirational sources?

3.2 Experiment Plan

3.2.1 Within-Subject Setup

A controlled experiment was set to answer the research questions. The experiment uses within-subject design to test the effectiveness of using patent data tool as stimuli. Within-subject experiment fits the theoretical perspective and has advantages over between-subject design (Charness et al., 2012). It provides solid statistics with fewer participants required. Besides, it matches theoretical thinking. In the experiment, participants can be exposed to regular stimuli (a baseline tool having access to visuals and paragraphs from the internet) and patent data stimuli as comparison. Each participant will receive these two treatments to generate different dataset. They will reflect on their preferred tool (either baseline tool or patent data tool) and effective method after trying out both stimuli. This means that within-subject design aligns with the researcher's need to design an experiment scenario similar to real life.

However, when applying a within-subject experiment setup, a researcher needs to think about psychological consequences caused by different treatments in the experiment, which is defined as experimenter demand effect (Rosenthal, 1976; Charness et al., 2012). Experimenter demand effect happens because the participant wants to guess the research purpose and change their preferences and criteria in different treatments to align with researcher’s expectation. As a result, methods to minimize the experimenter demand effect and bias should also be considered.

When the experiment is to discover participant's preferences or willingness to use a product, within-subject design can cause the experimenter demand effect, and become less accurate than the between-subject design. But both methods show little difference when the experiment is to test participants' skills, such as remembering photos of faces (Deffenbacher et al., 1981; Charness et al., 2012). This brainstorming experiment with patent data will test both individual creative skills and ask their willingness to use a new tool. So the experiment setting should ensure that the demand effect influences participants’ judgement on the new tool at a minimum level.

Effective ways to reduce the biased result from within-subject design is recommended. One way is to change the order of the design tasks, and survey questions for participants. So that the participant perceives each scenario and survey questions are independent of previous ones. Participants are less likely to fill in the survey with the same behavioral tendency. Designing the experiment in a segmented timeframe with irrelevant tasks in the break can also help participants evaluate each treatment less influenced by previous scenarios. Also, evaluating a single product in one treatment will not overwhelm participants other than evaluating a mix of products in the same session (Charness et al., 2012). Besides, Mummolo & Peterson (2019) argue that the purpose of the experiment, and researcher’s expectations can be clearly revealed to all participants before they fill in the surveys, which will not add to experimenter demand effect. So that the research aim will be clearly stated to the participants in the recruitment and training session.

3.2.2 Experiment Procedures and Tasks

According to Kohn & Smith (2011), individual brainstorming can outperform small collaborative groups. Besides, during an individual brainstorming session, idea quantities can reach the highest in the first 5 minutes. Then the numbers drop significantly in each 5-minute quadrant. So each ideation session is set to be 20 minutes as the same with Kohn & Smith’s experiment (2011). Instructions are given for each participant following Osborn's guidelines (Osborn, 1957; Kohn & Smith, 2011) in five points: do not judge the ideas, go for quantity than quality, freewheel the mind, combine and improve the ideas, and focus on the brainstorming in Figure 9.

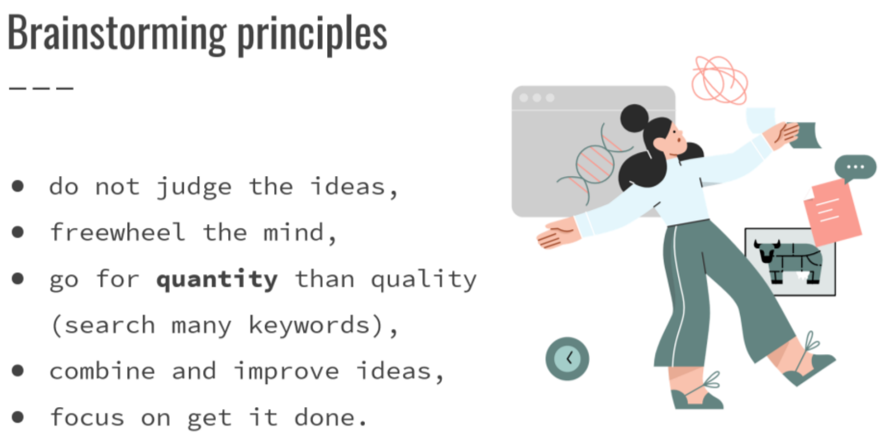


Figure 9 Introduction of brainstorming principles to participants (Osborn, 1957; Kohn & Smith, 2011)

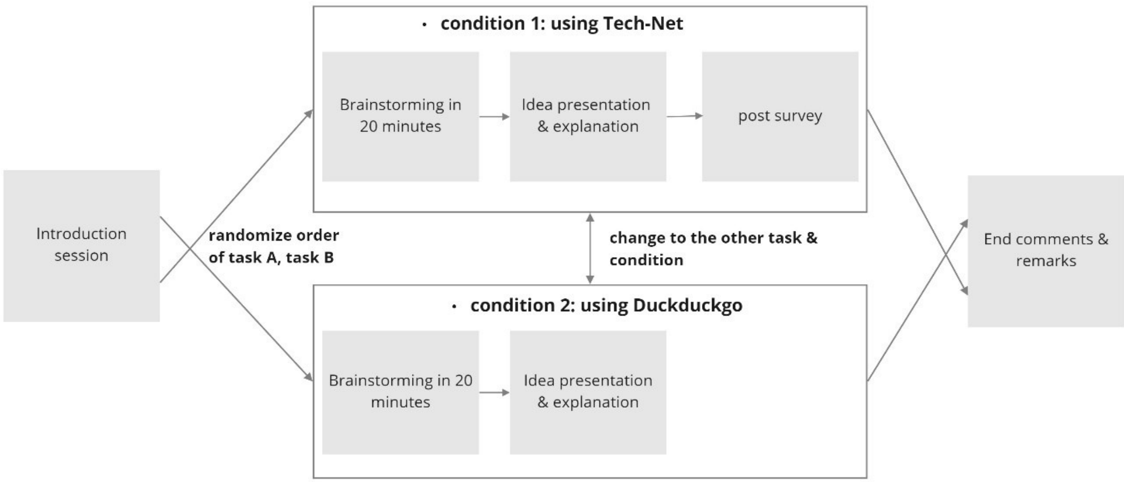


Figure 10 Experiment process

To reduce biased results, each participant will do two design tasks under two conditions (using patent data tool, using baseline tool) in randomized order and combination (Figure 10). In the baseline condition, a participant can use an online search tool Duckduckgo to search for textual or visual inspirations. In the patent data condition, the participant can only use Tech-Net tree graph webpage to search for their textual inspirations. When they cannot understand specific technical words from search result, they are permitted to use baseline tool Duckduckgo to understand this specific terms. They can not input other words that Tech-Net does not show.

The design task can be either open-ended or constrained. An open-ended task tells participants directly what objects to design without giving other limitations or boundaries. A constrained task means that participants need to design solutions that only fit some given requirements. The design tasks used by previous researches are compared for experiment setup (Table 3).

Bae et al. (2020) compared participants' creative performances when doing open-ended and constrained tasks. A computer-aided knowledge graph tool provides participants with a group of keywords, building connections to new concepts. It is found that participants in the open-ended task group reported that they used much less cognitive thinking and physical effort to finish the creative task when using the given mind mapping tool. Furthermore, participants with the this tool can generate highest numbers of diversified ideas in the open-ended task group. Considering using patent data tool is new for designers, the experiment design should not require too much cognitive effort from participants. We choose open-ended tasks to test how effective patent data tool can result in novel ideas, and how participants use design-by-analogy.

The topics of the design tasks also matter. Besides searching for new ideas on the Internet, designers use their personal knowledge and design experience as inspirations (Gonçalves et al., 2016). The baby crib design task from Gonçalves & Cash (2021) is tested with one participant in pilot test. However, the participant reported that it difficult for her to emphasize and define problems because she did not have relevant life experience. But, daily objects such as umbrella, lamp, toothbrush are common, affordable, and needed by the majority of participants (Kudrowitz & Wallace, 2013; Horn & Salvendy, 2009). Interestingly, Kudrowitz & Wallace’s experiment (2013) even recruits professional improvisational comedians as 25% of participants do design tasks. In the final setup, two design tasks are chosen based on toothbrush, raincoat, and umbrella as daily objects. Participants are asked to design two novel object. One is to make tooth clean while another is to protect users from rain and wind. The design tasks are printed and shown to participants during the experiment.

Design outputs are sketches, think-aloud protocols, video recordings of the sketch process, and screen recordings. The data recording process shows in Figure 11. Two video recording are used to record the ideation process data. One main camera records both the sketching process, and think-aloud protocol. Another camera records the whole scene of ideation process as backup data.

Both retrospective and concurrent protocols can be used to analyze participant's cognitive thinking. Gero & Tang (2001) find out that both protocols produce very close results to understand designers' cognitive process. According to Kuusela & Paul (2000), retrospective protocols have the advantage of not interrupting the design process, which can be used for analysis of design outcomes. In contrast, concurrent protocols tell the design process with in-depth information from a relatively small numbers of participants, which are better for analysis of design process.

Besides the brainstorming principles, design-by-analogy is also introduced to participants. It is present through a short Youtube video that one professor from the same industrial design faculty explaining design-by-analogy method. The experimenter also introduces chair design as an example, and tells search results from TechNet. So that participants can be aware of how they build connection of search result with their design task. The chair design example is shown in Figure 12.

Table 3 Examples of design task for ideation experiment

Participant group	Target users of design	Open-ended task	Constrained task
Students, professionals from design background or engineering background, Professional improvisational comedians	majority of people	Umbrella, toaster and toothbrush for ideation (Kudrowitz & Wallace, 2013) Toothbrush as an example to explore patent data (Dewulf & Childs, 2021)	cheap, disposable, spill-proof coffee cup (Jansson & Smith, 1991; Howard et al., 2013)
Students, professionals from design background or engineering background	Driver, car owner		car-mounted bicycle rack system easy to mount both bicycles, and racks (Jansson & Smith, 1991; Howard et al., 2013) whatever can prevent drivers from distraction during driving (Bae et al., 2020)

Parent and their baby	a baby crib which help the baby to sleep independent from parents (Gonçalves et al., 2016, Gonçalves, 2017, Gonçalves & Cash, 2021)	
Disabled people		a measuring device for visually disabled people (Jansson & Smith, 1991; Howard et al., 2013)
African farmers		a mechanical device to shell Peanuts for African farmers to be efficient, productive, and less costly (Linsey et al., 2010; 2011; Viswanathan and Linsey, 2013a; 2013b, Viswanathan, 2017)

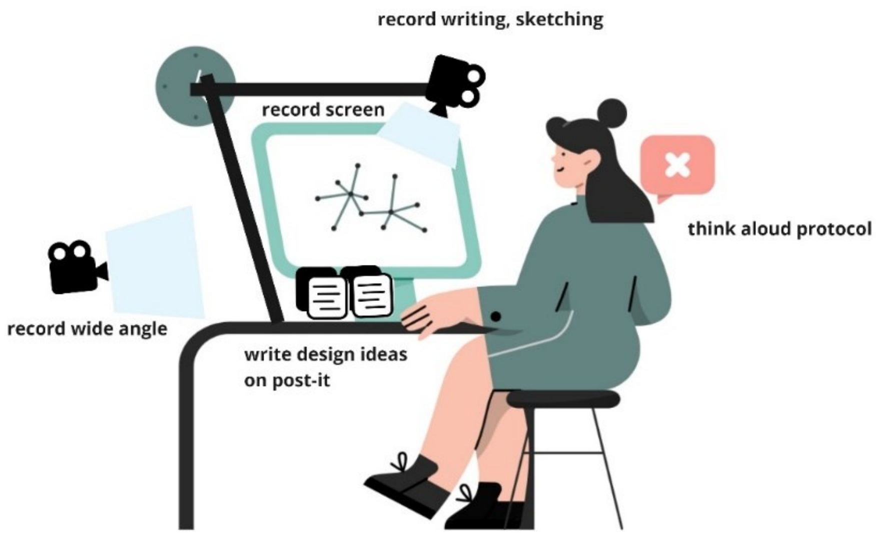


Figure 11 Recording data in the experiment

Figure 12 Children chair design using patent data tool, edited by author, retrieved from TechNet (SUTD Data-Driven Innovation Lab, 2020)

3.3 Pilot Experiments

One participant recruited from convenient sampling joined the first experiment. She did the baby crib design task with the patent data tool. Some issues found from the first pilot experiment are in Appendix 5. The participant reflected that she did not have life experience with babies. This remarks point out that the design tasks should be daily object familiar to most people. Besides, brainstorming is not her research domain or interest, which made the experiment in 20 minutes difficult for her. This addressed the importance of recruiting participants interested in doing brainstorming tasks and curious to learn new patent data tools. She also suggested having an introduction session for the design tasks and methods. Introducing too much theoretical background is not necessary. She also recommended to use scaling in the post-experiment survey for analysis process.

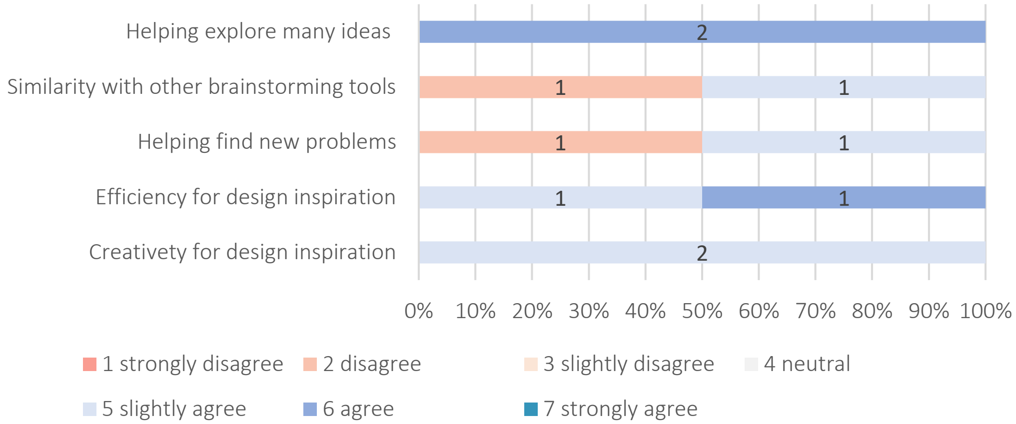


Figure 13 Participants' feedbacks about tool's effect in 2nd pilot experiment

In the second round of the pilot test, two researchers in the industrial design faculty were recruited from convenience sampling. Both were familiar with individual brainstorming and agreed with the importance of generating as many ideas as possible in the early ideation stage.

Both participants did the same design task, designing something to protect users from rain and wind in two randomized conditions. It is an open-ended task and designing for majority of people. The screen recording showed the keywords participants input into the website and their frequency of using the tool (Appendix 11). Speak aloud protocol and their self-reflection revealed how they applied the search result for their new ideas.

Both participants used google image search and translation to understand some specific terms from the website. It can be seen that both participants generated fewer idea in the second experiment. The main learnings (Appendix 6) from this pilot experiment was to use two different design tasks to measure the effect of the patent data tool.

From the post-experiment surveys, both agreed that the website is helpful for them to explore many ideas (Figure 13, Appendix 11). Both of them agreed that relevant keywords from the tree graph broadened their thoughts on the design topics. Two participants have opposite views on how this tool can help with problem reframing.

The positive feedbacks on divergent thinking showed that the experiment with patent data tool was validated for final experiment. One participant's feedback (Figure 14) showed why he agreed that the patent data tool is useful for searching for solution inspirations. "*Google search is the end … Tech-Net search is the starting point…Tech-Net can add the width of your ideation*." The engineering terms and knowledge from the patent data tool were valuable for the designer's ideation. From the surveys, two participants thought they did not need extra guidelines to use the website. Regarding improving the website for a better user experience, visual and interactive elements are mentioned by both of them. One mentioned she prefers to have more images to explain the search result. The other also mentioned that the website's visual elements could be improved.

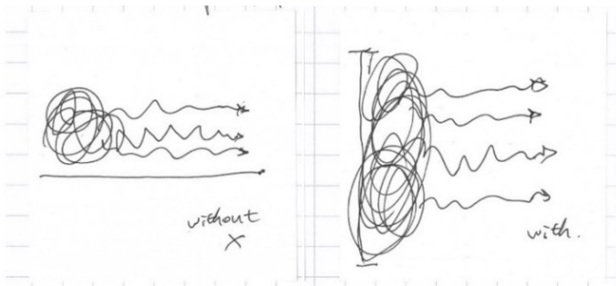


Figure 14 One participant's reflection on diverged ideas in baseline condition (left), patent data condition (right)

3.4 Data Analysis Plan

Some direct and indirect criteria, such as idea quantity, fixation rate, self-report are used to analysis experiment data. Quantity is an objective criteria often used as one extent of brainstorming outcomes. It is also named fluency or productivity. Many researchers agree that producing many ideas in brainstorming can contribute to enough good original ideas. Because of previous experiments, the more ideas generated, the higher level of creativity. So it is logical to evaluate one's creative level on the fluency in generating ideas (Kudrowitz & Wallace, 2013).

Moreno et al. (2016) give a systematic literature review of direct and indirect metrics on fixation. Most-used direct metrics are developed on Jansson and Smith's measurements proposed in 1991, which calculate the number of repeated functions, or ideas compared to the total number of ideas (Crilly & Cardoso, 2017). These objective statistics focus on the outcomes and directly prove the fixation severity. For example, in the fixation experiment, researchers usually show a solution example to participants in the fixation group and calculate how participants repeat or borrow from the given an example afterwards. In this experiment, no example was shown to participants. Function-behavior-structure model is to be explained to calculate fixation rate in next chapter.

Besides direct metrics, some indirect metrics can be self-assessment and analysis of the idea's free-move (Table 4). Indirect metrics can only imply the happening of fixation but not provide exact proof. It can collect participants' feelings, reflection, and analysis of idea moves qualitatively. Linkography method was not used because of it needs large workloads to define each idea move for all ideation sessions.

Table 4 Indirect fixation measurement (Moreno et al., 2016)

Type	Metric
Self-assessment	surveys ask about perception of fixation reduction, generation of unexpected ideas, and workflow improvement (Segers et al., 2005)
Degrees of freedom	Linkography and Shannon's analysis principle that the novel idea in the divergent stage do no show interconnected moves with other ideas while fixated ideas can interconnect with other ideas (Kan & Gero, 2008).

One of the strengths of using computer-aided stimuli is recording of the process that participants using the stimuli. This can also provide the quantitative data for observing participants. For example, the quantity and frequency of keyword search and their similarity with the outcomes can imply how participants use the tool. For example, Zhang et al.'s research (2018) records students' digital footprints in architecture CAD software. They define a fixating moment as when the student fails to change the artifacts' design elements that fit requirements better. So that the student was at a low level of creativity. When participants repeated design features of previous ideas, they encountered fixation.

Because of the explorative manner of data analysis, different analysis methods and theory models are explained in the next chapter.

3.5 Participants Recruitments and Trainings

After pilot experiment and positive feedbacks, formal experiment can be proceeded. The experiment data manage plan and human research ethics checklist (Appendix 3, 4) was approved by Human Research Ethics Team and data steward in the university. All the participants were recruited from convenient samplings. All of them were graduate students and PhD researchers from the industrial design faculty at TU Delft. Participants (except P1) used English in the think-aloud protocol. P1 used Mandarin in the think-aloud protocol, which was translated into English by machine. A poster of the experiment (Appendix 10) was sent to recruit participants. Once participants showed interest, the experiment procedure (Appendix 7), introduction slides (Appendix 8), and approved consent form (Appendix 2) were all sent to participants at least 2 days before the experiment. One participant (P1) did the whole experiment in one day. Other five participants did the two experiment in two continuous days.

The introduction was essential to familiarize participants with the patent data tool's interface, speak-aloud protocol, and brainstorming rules. The patent data tool and design-by-analogy method were explained during the brainstorming training session with example usage. Participants were told to create as many ideas as possible. The participants were also told to verbalize their thinking process. Before the formal experiment began, participants tried on the tool without time constraints and confirmed they knew how to use it. In the experiment, the design task (Table 5) including brainstorming tips and rules (Appendix 9) was printed and put in front of participants. Randomized conditions and design tasks were given to 6 participants (

Table 6). Pre-experiment survey results are in Appendix 12.

After each brainstorming, each participant has about 5 minutes simply recap the ideation process, and design solutions. This retrospective protocol was also transcribed with concurrent protocol (Appendix 17). In the retrospective protocols, some participants appeared to forget about their ideas, or the stimuli. In the analysis of ideations, concurrent protocol and concurrent screen recording was combined to analysis participants ongoing ideation process.

Table 5 Design tasks for daily object design

Task A: *Design a novel(unconventional) portable device that can keep user dry in strong wind and rain. Please think aloud!*

Task B: *Design a novel(unconventional) device that can keep users' teeth clean every day. Please think aloud!*

Table 6 Randomized tasks and conditions to reduce demand effect

Participant No.	1st Task	1st Condition	2nd Task	2nd Condition
1, 6	A	D	B	T
2	B	D	A	T
3, 5	B	T	A	D
4	A	T	B	D

Chapter 4 Experiment Results

This chapter presents the outcomes of the experiment and analysis in three subsections. Firstly, the total ideation results are counted, and participants self-reflected on the effect of the patent tool. Secondly, external raters categorized all the ideas following the function-behavior-structure model. By calculating fixation rate in different categorizations, it explains how participants fixated on each condition and at which abstract level. Finally, qualitative analysis of the ideation process is analyzed from the think-aloud protocol and screen record. Different ideation patterns with two different ideation tools and types of fixation are shown in this section.

4.1 Ideation Results and Self-Reflections

After experiments, participants' ideas were recorded according to definitions of an idea and made into a list of anonymous idea decks. The statistics of each participant's interaction with tools were calculated from think-aloud protocols and screen recordings. In the last subsection, participants self-reported the effect of using patent data tool to reduce fixation.

4.1.1 Numbers of Ideas Generated by Participants

The definition of a valid idea is given in this section. The basic definition of an idea is that one participant gives a solution or an operation to work out the design brief (Moreno et al. 2014). The think-aloud protocols need to align with screen recordings, sketches, and notes. These process materials show the idea, reasoning, visual form, and interaction with tools. If one participant dives into design details of one solution without adding new functions or changing the design problem, it count as the same idea. Analyzing design briefs or reframing problems without giving a solution will not be counted as an "idea". Sometimes, it is difficult to distinguish from think-aloud protocol that participants moved on to a new idea or kept modifying the previous one. Because they added new sketches and notes. Linsey et al. (2005) and Linsey et al.(2010) gave a more detailed instructions to solve these kinds of issues:

- One idea must provide one or more primary and secondary functions.
- One idea that solves more than one problem still counts as one idea.
- An emerging idea combines previous valid ideas and can be a new idea.
- One idea counts even if it includes unnecessary functions or is not performed correctly.
- The sketch and think-aloud protocol must describe an idea. It should not only imply something.
- One idea still counts as a new idea when it brings new problems not included in the brief. These ideas can potentially meet a higher level of consumer expectations. For example, some ideas address environmental problems, reduce waste, recycle, or satisfy a hidden customer need.

From their guidelines, ideas generated by the same participants with similar solutions should be counted as only one idea. But, some ideas did happen to provide similar primary functions with different secondary functions. These counted as different ideas, which would be put into the same idea category to be explained in the later section.

An overview of the idea quantities and search times in two tools are in Figure 15. The total number of ideas generated in the baseline condition bypassed that in the patent data condition. The total search times in the patent data condition were slightly higher than in the baseline condition. However, individual performance in the two conditions showed more significant differences. The numbers of each participant's ideas is shown in Figure 16. It can be seen that P4 generated most ideas in the baseline condition. P2 and P3 generated relatively more ideas next to P4. Interestingly, P2 and P3 had similar performances in both conditions. However, P4 generated much fewer ideas in the patent tool condition. Both P6 and P5 encountered more than 10 times of technical issues and error screens in the patent data condition (Figure 17). The patent tool can save search efforts among P1, P3 and P4. All the searching inputs and results in two conditions are in Appendix 14.

How participants interacted with each tool is shown in Figure 17. In the patent data condition, participants were allowed to use the baseline tool to interpret the technical terms they did not understand (Figure 18). However, not everyone needs the baseline to facilitate. P2 and P4 just ignored the technical terms that they did not know.

From the above statistics, it seems that using patent data tools in general was less effective compared with baseline tool. The later subsections will further examine fixation rate and fixation phenomenon to evaluate the tool's effect.

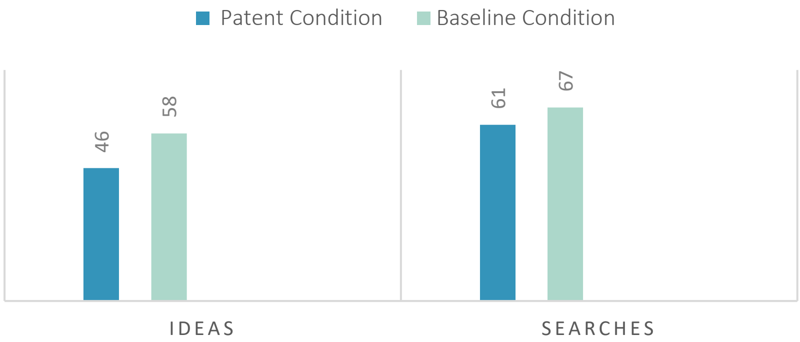


Figure 15 Total numbers of ideas and total numbers of searches in 2 conditions

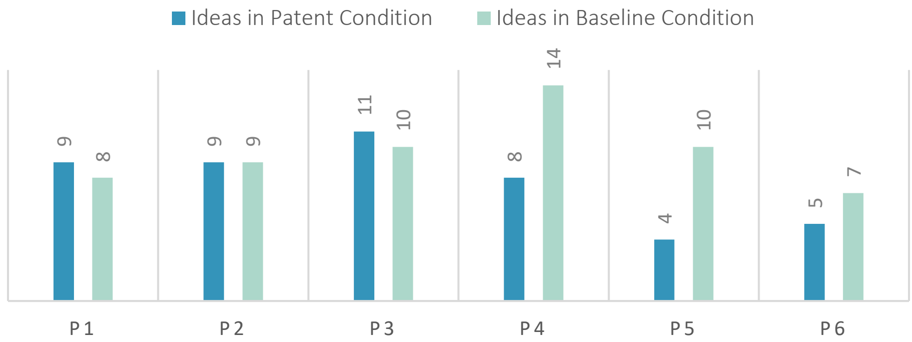


Figure 16 Numbers of ideas generated by participants in 2 conditions

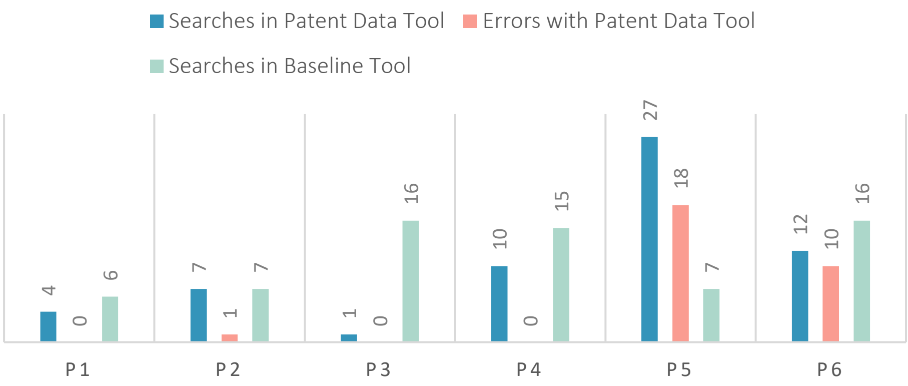


Figure 17 Searches in 2 conditions and errors in patent data tool

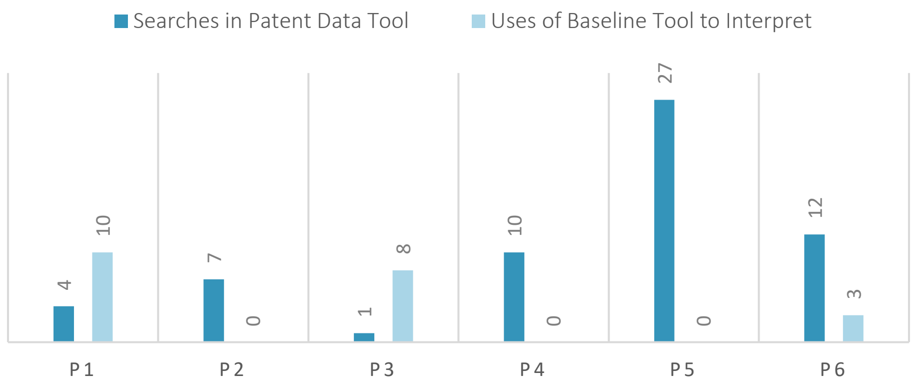


Figure 18 Using baseline tool to interpret technical terms in patent data condition

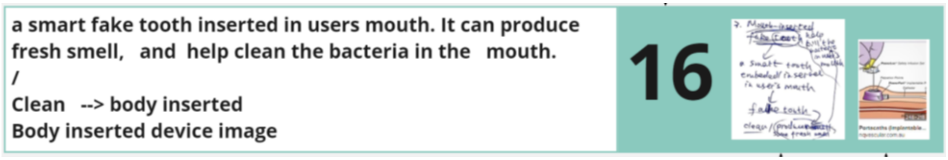
4.1.2 Making Idea Deck

To show the ideation results and design stimuli, the idea deck was made on Miro broad, including all 104 ideas (Appendix 15). The author reviewed think-aloud protocols, brainstorming videos and screen recordings to ensure that each solution, problem and inspirational source aligned with the participants' thinking process. Each deck included design solution, design problem, textual or visual stimuli and search keywords. Each idea is given a random number without revealing the participant number. Participants' original language was selected into a short, coherent sentence. Each idea information formed an independent idea card on Miro board. Two different colors were used to distinguish the two design tasks. The following deck example and explanations for Task B was in Figure 19.

Most participants generated these ideas within a 20-minute constrain without explaining why they chose one stimuli. One participant mentioned that some ideas made sense while some other ideas probably should be better defined.

1st area: solution

2nd area: problem
3rd area: query, & search result
4th area: query in the baseline tool



Blue color deck is for Design task B, red color deck is for Task A.

Left Side on the Deck:

1st section of paragraph gives the solution “a smart fake tooth…”.

2nd section tells the problem. “/ ” means that participant did not mention any specific problems for the solution.

3rd section a short sentence with “⍰” means participant was working in the patent data condition. He/she input “clean” in the search bar, used “body inserted” search result as design stimuli. If it did not show “⍰”, it means participant was in the baseline condition.

4th section “body inserted device” image on the last row means participant also searched “body inserted device” image on internet. If there was “NO” in this area, it means participant did not use any inspirational source. In some idea decks, “Probably” means author’s interpretation of their inspirational source. Because they did not mention in the think- aloud protocol. But, they looked through these sources before.

Right Side on the Deck:

“16” is a randomized number for the idea without revealing the participant number.

Scanning of participant’s sketch and note were shown. The image of the right side is the image inspiration participant searched in the baseline tool.

Figure 19 Idea No.16 (by P6 in the patent data condition) as an example of idea deck and explanations

4.1.3 Participants' Self-Reports and Reflections

Participants' gradings of the patent data tool are in Figure 20. Original data collected from Microsoft Forms are in Appendix 13. All participants agreed that the tool was useful in exploring different design directions to different extent. 4 out of 6 people chose the "agree" option, and 1 chose "strongly agree". Most (5 out of 6) said the tool differed from other familiar brainstorming tools, such as image search or designer's online communities. 4 people reported that the tool was slightly useful or useful in helping them define new problems. Most participants agree that the tool would make their brainstorming process more efficient and creative at different levels.

Participants also reported the patent data tool's effect to overcome fixation and their consciousness of fixation (Figure 21). For this question, all the participants could choose more than one answer. 4 out of 6 participants agreed that the patent data tool could help them overcome *knowledge-based fixation*. 4 participants also pointed out that if they knew the inspirations were from patent dataset, they felt less uncertainties in new product development. When asked about awareness of design fixation, the opinions were divided. 4 agreed they felt conscious about fixation and the tool helped them finding new ideas and being less stuck. 2 said they feel aware of copying others solutions by using the tool. 2 said that it could help them find more tangible design concepts. More analysis are needed in the next section to examine *knowledge-based fixation*, their awareness of fixation, and intended resistance to new ideas.

For the need for external design methods, half participants (3 out of 6) agreed with this opinion (Figure 22). 2 participants (33%) said probably needed but not certain. Only 1 participant mentioned that there would be no necessity for such a new method.

Participants were also asked to fill in the benefits and challenges of using this tool. No standard answers were provided for participants. At the same time, when participants were filling in the survey questions, their think-aloud reflections were also recorded. All the participants agreed that the search results in the tree graph were useful for brainstorming (Table 7). It provided keywords that they did not expect and helped them think outside the box. Some of the quotes are selected below. P1 mentioned that these keywords represented the knowledge relevant to design tasks. P2 mentioned the unexpected keywords helped her with a design direction. Both P1 and P5 mentioned that the inside-layer keywords were more useful and relevant to their search intention than outside-layer keywords.

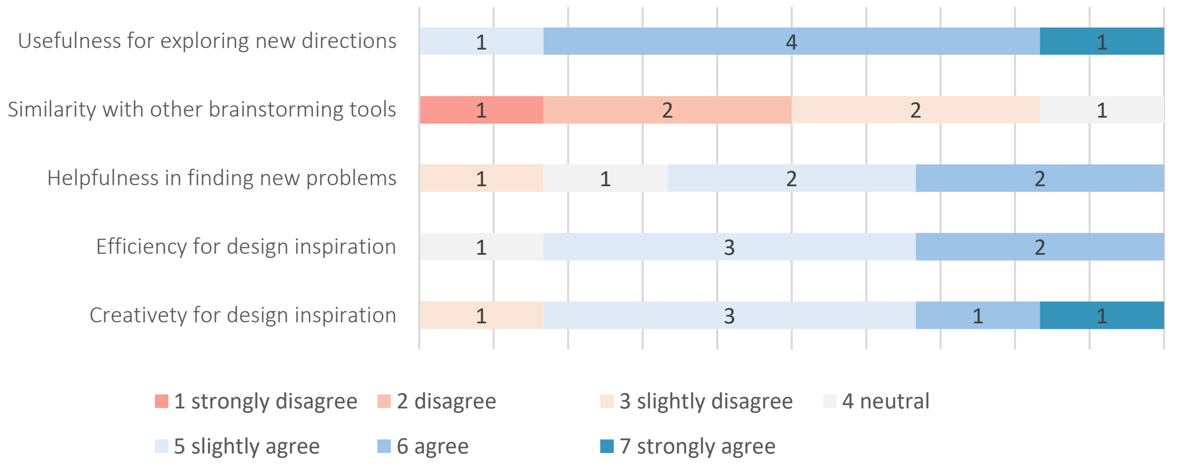


Figure 20 Participants' grading of patent data tool

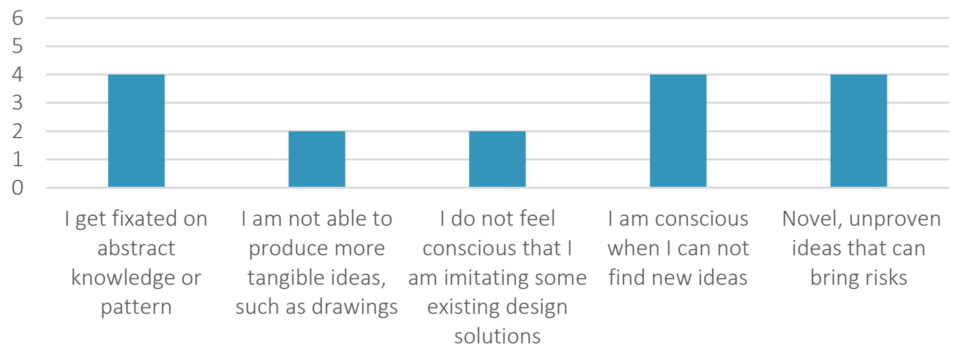


Figure 21 Participants self-reported patent data tool help overcome these types of fixations.

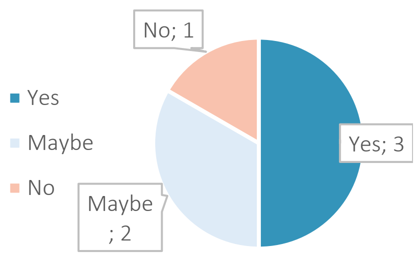


Figure 22 Participants' self-reports on if they need extra design method

P6 described the tool as "a co-worker", although the tool did not have advanced intelligence.

Talking about the challenges of using this tool (Table 8), 6 participants showed similar opinions. The tool appeared to be *"self-explanatory"*. After twenty minutes of introduction, four participants could play with it without obstacles. However, the error rate of the tool was high because 2 out of 6 met frequent error screens. All agreed that the interface and interaction could be improved in different ways. Two expected more visual aspects to save their image search efforts or get inspired from visual elements. Three mentioned difficulty in understanding technical terms or in finding the relevant keywords. P4 mentioned one AI drawing tool could automatically help "*create the image inspiration*" from his input.

In summary, the idea quantities generated in the patent data condition were slightly lower than in the baseline condition. However, participants self-reported that the patent data tool was useful in exploring different design directions and overcoming fixation. Further analysis of the ideation process and fixation rate were conducted in the next section to examine the tool's effect further.

Table 7 Self-reflections on the value of using patent data tool for brainstorming

Participant No.	Which part of Tech-Net website are of most value for you to explore many design directions?
P1	first layer of search results are useful for me to know the knowledge that I do not know. It helps me to expand the knowledge with certain direction.
P2	That it gives relevant keywords, maybe not what you want but something that inspires thoughts.
P3	the branches concept. There is unexpected link between the first word and the branches which helps to make more ideas. For example: I type teeth cleaner and there is endoscope in the branches.
P4	Diverse Brain map, think outside the box
P5	the first round search (the first three tree layers)
P6	it lists a lot of keywords, which can help brainstorming; because they are just like a co-worker brainstorm with you together.

"It helps me to expand the knowledge with certain direction... It (my brainstorming process) usually happens and build on my own knowledge." By P1

"…relevant keywords, maybe not what you want but something that inspires thoughts… it gives relevant ideas, not, relevant keywords…" By P2

"…unexpected link between the first word and the branches which helps to make more ideas …" by P3

"Diverse Brain map, think outside the box… I think I wouldn't give 7 because it's sometime it is useful, sometimes it is not" by P4

Table 8 Self-reflection on challenges of using patent data tool for brainstorming

PARTICIPANT NO.	What are your difficulties of using Tech-Net to explore many different design directions?
P1	bouncing layout*. unclear structure of first search and later search (expanded by myself).
P2	Not difficulties but I missed a visual search aspect.
P3	understanding some technical words.
P4	Word suggestion, Illustrative.
P5	when it shows "error" I feel stopped.
P6	interaction experience; another sub-interface; separated from the searching interface; user more colors to divide the nodes and demonstrate which are the most prevalent keywords

*from author's observation, "bouncing layout" means when the P1 moved or interacted with a keyword node, all keywords would be bouncing for a while.

"…it's quite self explanatory.. it really depends on how you, how your mind works for ideation. At least my, mine does in a very visual way" By P2

"drawings, graphs and shapes. I don't feel like it helped me a lot in that, because I mean, I think those are more visualized…. So you when you see something it helps you to draw like that, but it was not here." By P4

"some of the words Is quite different or quite random, so random suggestion makes you sometimes. It stops you bit." By P4

4.2 Evaluation of Fixation Rate

In this section, the calculation of fixation rate is given in two ways of counting. To evaluate fixation on similar ideas, two external researchers categorized all the ideas based on function-behavior-structure theory.

4.2.1 Calculation of Fixation Rate

Fixation rate is used to examine the effect of the patent data tool because this measurement is relatedly easier to calculate and directly linked with novelty level. According to the design fixation study by Moreno et al. (2014), the higher novelty of ideas indicate a lower level of fixation. Moreno et al. (2014) built the fixation measurement and procedure on Linsey et al. (2010) and Viswanathan & Linsey's (2013b) papers. Their papers counted how each participant repeated a given design example. Moreno et al.'s paper (2014) counted how each participant fixated on previous ideation outcomes. This calculation represented how participants fixated on their ideas and failed to explore potential new design spaces. The fixation rate can be in two conditions (patent data condition, baseline condition) and within each participant.

The equation is to calculate non-repeated ideas and repeated ideas among all ideas generated (Chan et al., 2011; Moreno et al., 2014). The quantity of repeated ideas is the summation of all participants' ideas in Eq.(1).

Total repeated ideas = summation of repeated ideas in each bin from all participants =

$\sum_{j=1}^{b}\sum_{k=1}^{n} F_{jk} - 1 \qquad \forall\, F_{jk} > 1$ (1) (Chan et al., 2011; Moreno et al., 2014)

Where:

- F_{jk}=frequency of repeated ideas in jth bin generated by kth participant.
- b=numbers of bins.
- n = number of participants (6 in this case).

Frequency of repeated ideas should be bigger than 1.

$Q_{total} = 104\ ideas$ (generated by 6 participants)

Fixation rate = $\frac{\text{total numbers of repeated ideas}}{\text{total numbers of generated ideas}} = \frac{\text{R}}{\text{Q}}$ (2) (Linsey et al., 2010; Moreno et al., 2014)

However, Moreno et al. (2014) paper do not mention how to categorize ideas into different bins (variety) and how to decide on repeated ideas. Participants slightly changed the idea descriptions in the experiment, such as problem reframing, or added a minor function in another new idea. It is necessary to decide on criteria to distinguish similar ideas. Besides counting individual repeated ideas, quantities of repeated ideas from all participants in two conditions can also imply the tool's influence on creativity.

4.2.2 Comparing Different Evaluations of Novelty and Variety

The equation of fixation rate and procedure to calculate are given above. Nevertheless, researchers have different opinions on how to count novelty and variety (bin). Jansson & Smith (1991), Shah et al. (2003), and Moreno et al. (2016) both used novelty measurement by counting the repetitiveness of ideas (Fiorineschi & Rotini, 2021). The least frequent ideas are the most novel ideas. This calculation is similar to the logic of the fixation rate equation researchers used in the same studies.

Another distinctive method in the researchers' community is prosed by Sarkar & Chakrabarti (2011). They explain novelty as a new invention different from existing products. According to their evaluation model, all the ideas can be grouped into three levels of novelty by following a flowchart (Figure 23). If the product provides a new function, behavior, or structure from an existing product, it is seen as a high novelty product. A new function can bring the highest novelty level in these three levels, followed by structure or mechanical parts. Lastly, a change in product behavior brings the lowest level of novelty.

Similarly, Qian & Gero(1996) also concluded that describing functions can help transfer the design knowledge to another domain when using design-by-analogy. It is very easy for designers to recognize the surface level of similarities, such as the structure (e.g. color, parts, materials) of two artifacts. The solution and inspirational source can have similar functions or behavior when using analogous designs. But they do not necessarily have alike structures. Researchers recognize challenges for designers to find similarities in higher levels of abstraction, the function and behavior.

Two examples are given to illustrate function, structure, and behavior model (Figure 24). Some participants described ideas on the function level, while others innovate the new structure and behavior. The function of Idea 16 is to produce a fresh smell and clean oral bacteria. The structure is similar to a fake tooth with smart technology. The behavior is not mentioned in the think-aloud protocol. The function of Idea 86 is not mentioned specifically in the protocol. In this scenario, participants did not reframe the problem stated in the design briefs. Evaluators would assign this idea to a function category based on its description. Idea 86 says that the structure is a plastic layer outside an umbrella and flexible metal inside. The behavior is to collapse and fold both the outside layer and the inside mental structure.

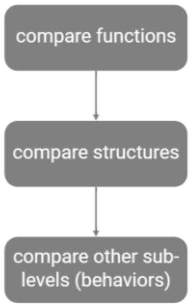


Figure 23 Sarkar & Chakrabarti's (2011) evaluation method

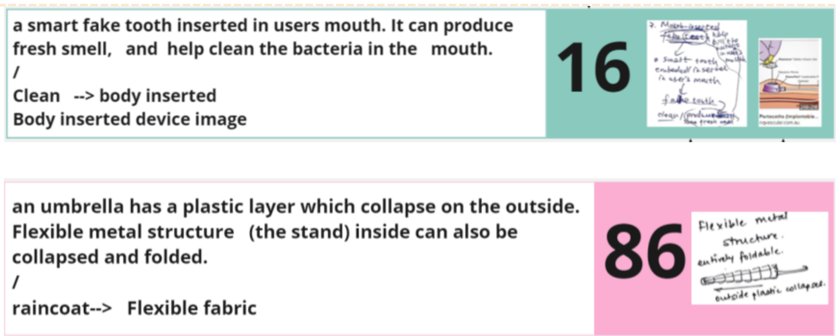


Figure 24 Examples to illustrate function-behavior-structure model (Idea 16 is made by P6 , Idea 86 is made by P2. Both are made in patent data condition)

Sarkar & Chakrabarti(2011) argue that function-behavior-structure method as a broadly accepted model has following strengths in describing product features and novelty evaluation:

- This method is originally used for designers use biological, and technological solution from other domains to solve problems. Design-by-analogy applies function, behavior and structure theory.
- It needs to compare with products on the market. Umbrella/raincoat, toothbrush are selected to be baseline product available on the market for two design tasks.
- The interrater agreement can possibly be high than other evaluation methods.
- It has a different calculation logic from fixation rate and idea frequency equation.
- Novelty score from Shah et al. (2003) method is inconsistent and not accurate to reflect designers' intuitive thinking about one idea.

According to Shah et al., (2003), Moreno et al. (2014), participants with higher novelty scores also generate lower fixation rate, and more varieties. Variety is a measurement to count the extent that participants create new solution spaces and push the boundaries for design. Higher variety means a participant gets less fixated on similar ideas. Function-behavior-structure model can be used to cluster similar ideas based on categorizing function and structure, which are clustered as the first and second layers (Figure 25). External raters used "How" to simplify the clustering process, which means they combined structural and behavioral elements together in the second level. Based on the idea description, different ideas with similar functions can be clustered as one categorization.

Comparing fixation rate results via two ways of counting can distinguish the tool's effects on different functions and behavior-structure levels. Two methods of counting categorizations are used to measure the same categorizing results on Miro broad (Appendix 16). The first counting shows categorizations at both function and behavior-structure(F-BS) level. By doing so, ideas using the same function but with different behavior-structures are counted in different categories. The second counting only examines categorizations at every function(F) level. It put ideas with the same function but different behavior-structures into the same group.

Rater 2's categorizing is used for both rounds of counting. In the 1st counting(function-structure behavior), Rater 1 and 2 both showed similar varieties (Appendix 16). In the 2nd counting, two raters have a low agreement. A plot of each rater's grouping results is in Figure 26. Because Rater 2 showed 8 functional groups for each design task while Rater 1 only made 2 groups. Rater 2 saw some ideas with double functions. A large number of ideas shared the basic function "help user stay dry" with different second functions. But, rater 2 defined 8 categorizations for 2 design tasks. Among them, around 5-6 categorizations have double functions. From Rater 2's evaluations for rain and wind design task, participants ideated some of novel sub-functions, such as "storage, stay warm, help users socialize, protect specific bodies" . These ideas include new problems not included in the brief, which can potentially meet consumers' needs (Linsey et al., 2005; Linsey et al., 2010). These diversified function distributions can help to check the patent data tool's effect on innovation on the function level. Rater 2's evaluation which showed more diversified functions, is valid in calculating fixation rate.

An example of how to count based on Rater 2's evaluation is given in Table 9. Group D and Group E are ideas with the same cleaning function and different "How". So they merge into the same group in the 2nd counting. Group M and Group N have a different sub-function. So these two groups keep in different categorizations in 2nd counting.

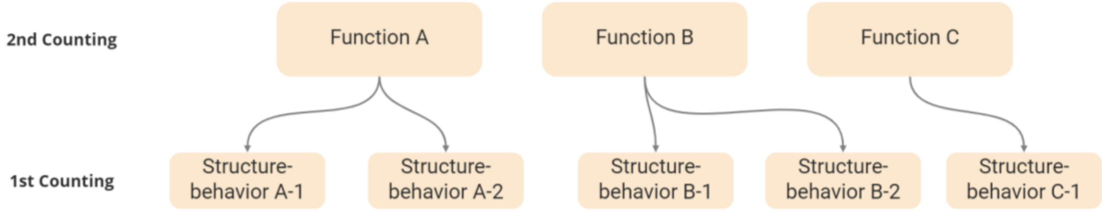
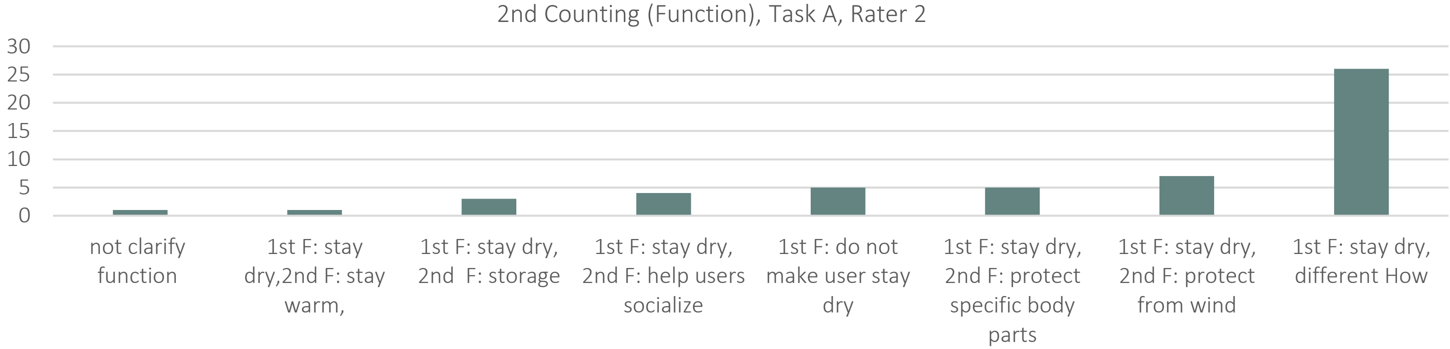


Figure 25 Categorizing function and structure based on Sarkar & Chakrabarti(2011)'s method



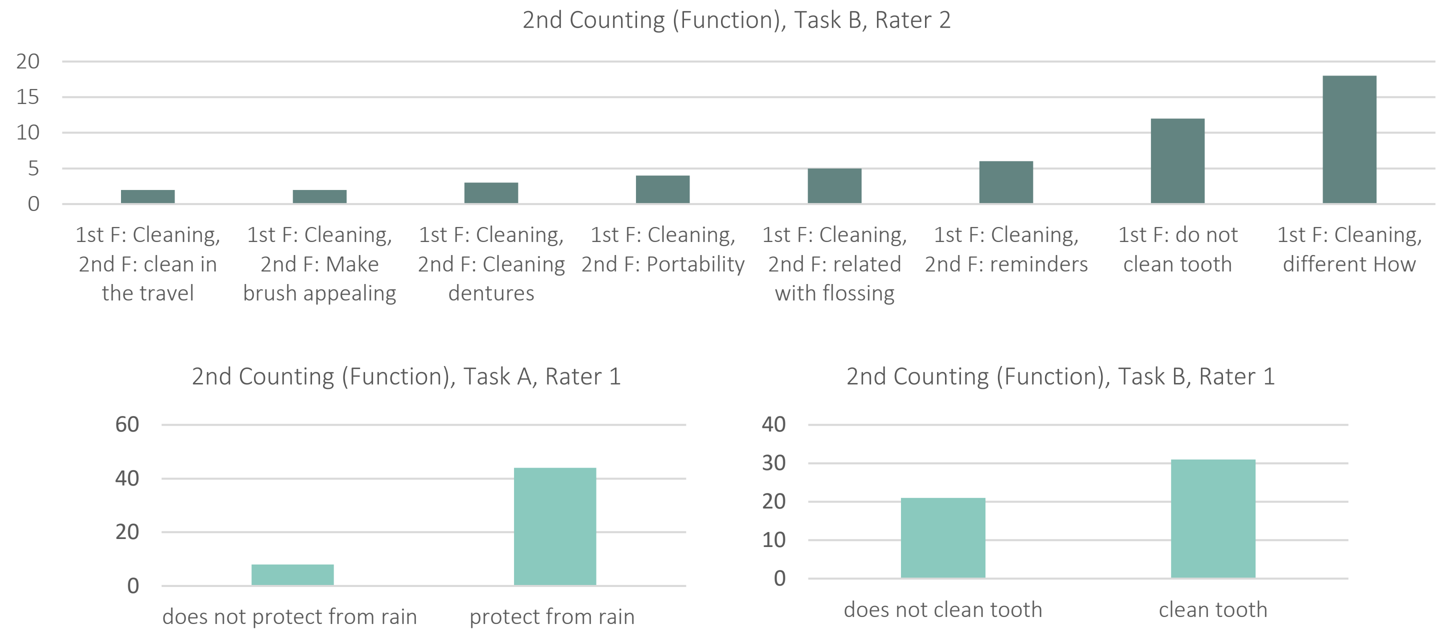


Figure 26 Comparison of idea distributions in 2nd counting

Table 9 Examples of two ways of counting categorizations

Idea No.	Example of Categorizing	1st Counting (F-BS level)	2nd Counting (F level)
7, 10, 24, 39, 40	1st Function: cleaning, How: New kind of brush	Group D	A new group
14, 49, 50	1st Function: cleaning, How: tooth guard	Group E	
38, 9	1st Function: Cleaning, 2nd Function: Make brushing appealing	Group M	Same Group M
12, 47	1st Function: Cleaning, 2nd Function: help cleaning during travel	Group N	Same Group N

Modified from Linsey et al., (2010); Moreno et al. (2014) equation (2)

$$\text{Fixation rate} = \frac{\text{total numbers of categories}}{\text{total numbers of ideas}} = \frac{C}{Q} \quad (3)$$

$F_{(P)}$ is Fixation rate in the patent data condition, $F_{(B)}$ is Fixation rate in the baseline condition

4.2.3 Counting Categorizations: 1st Round

In the first round of categorization, the two raters' evaluations reached moderate agreement, κ = .613, p < .001 (Appendix 16). P5 and P6's experiment data are not counted. They generated fewer ideas because of technic issues in the patent data condition. These issues made their fixation rate abnormal.

It suggests that patent data tool was not as effective as baseline tool on ideation at function and behavior-structure levels. By categorizing on F-BS level (Table 10) with Rater 2's evaluation, participants had slightly higher fixation rate in the patent data condition than in the baseline condition. From individual fixated performance (Table 11, Figure 27), the baseline tool helps P1, P2 and P3 to be less fixated at the function-behavior-structure level. They (except P4) generated similar quantities of ideas and categories in both two conditions. Their fixation rate in the patent data condition is around 10% higher than the baseline condition. Opposite to other participants, P4 generated a lower fixation rate in the patent data tool. One possible reason can be he generated much fewer ideas int the patent data condition than in the baseline condition. So that he can achieve a much lower fixation rate in the patent data condition by generating much fewer ideas. He himself explained that his individual working condition influenced the experiment result. We can not assert that the patent data tool was more effective for him.

4.2.4 Counting Categorizations: 2nd Round

In the second round of categorization, ideas with the same function are categorized as the same group. Two raters' had slight agreement on the categorization (κ = .207, p < .001). Evaluation by Rater 2 is applied. The average fixation rate is similar to the first counting result (Figure 29). $F_{(B)} - F_{(P)} = 5\%$. In both ways of counting, the average fixation rate in the Patent data condition is 5% higher than in the Baseline condition. This means in general, participants produced fewer ideas and categories in the patent data condition.

However, individual fixation situations (P1, P2, and P4) are opposite to the previous counting (Figure 27, Figure 28). P1 had an equal fixation rate, and P2 had a slightly lower fixation rate in the patent data condition. In contrast to P1 and P2's performances, P4 had a lower fixation rate in the baseline condition. P3 will not be discussed here because she had the same fixation results by two counting.

Further studies are needed to examine the patent data tool's impact and individual ideation differences on the function-behavior structure level (Table 12). One possibility can be that the patent data tool helped P1 and P2 explore different functional levels but did not give them much inspiration on the behavior-structure level compared to the baseline tool. Another explanation can be that the same tool affected different people differently. P1 and P2 ideated better on different function levels with the patent data tool. Nevertheless, with patent data tools, P4 generated more ideas with very different functions and behavior structures.

In conclusion, the statistical analysis of the fixation rate can not prove that the patent data tool was more effective in reducing the fixation phenomenon. This result did not align with the post-experiment surveys in which most participants agreed with the tool's value for creative exploration. Further studies are needed to explain the tool's impact on ideation on the function-behavior structure level and different designers. Another explorative analysis on the ideation process are introduced in the next section.

Table 10 1st counting and 2nd counting: an overview of fixation rate in two conditions

	1st Counting		2nd Counting	
(4 participants)	Patent Data Condition	Baseline Condition	Patent Data Condition	Baseline Condition
Categories Generated	25	30	15	19
Ideas Generated	37	41	37	41
Fixation Rate	32%	27%	59%	54%

Table 11 1st counting and 2nd counting: individual fixation rate in two conditions

	1st Counting						2nd Counting					
	Patent Data Condition			Baseline Condition			Patent Data Condition			Baseline Condition		
Participant No.	Categories	Ideas	Fixation Rate	Categories	Ideas	Fixation Rate	Categories	Ideas	Fixation Rate	Categories	Ideas	Fixation Rate
P1	6	9	33%	6	8	25%	4	9	56%	3	8	63%
P2	7	9	22%	8	9	11%	5	9	44%	5	9	44%
P3	6	11	45%	7	10	30%	3	11	73%	4	10	60%
P4	6	8	25%	9	14	36%	3	8	63%	7	14	50%

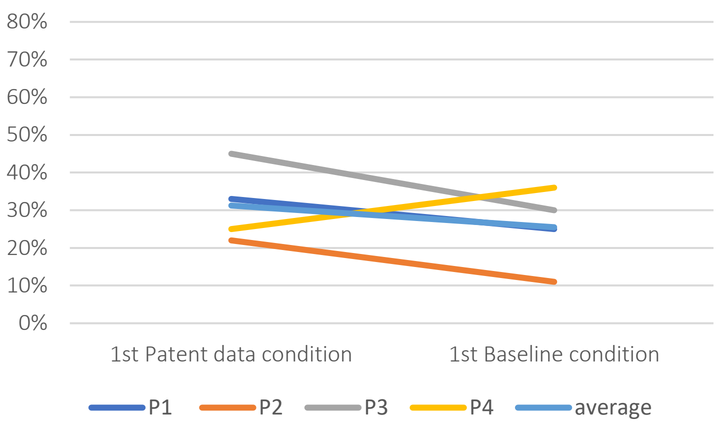


Figure 27 Individual fixation rate in 1st counting

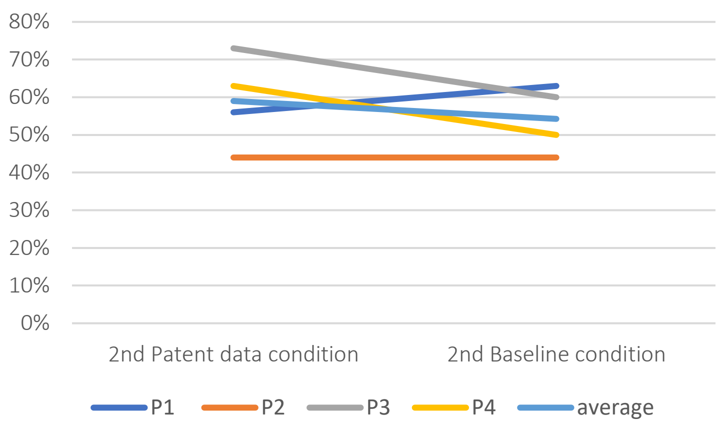


Figure 28 Individual fixation rate in 2nd counting

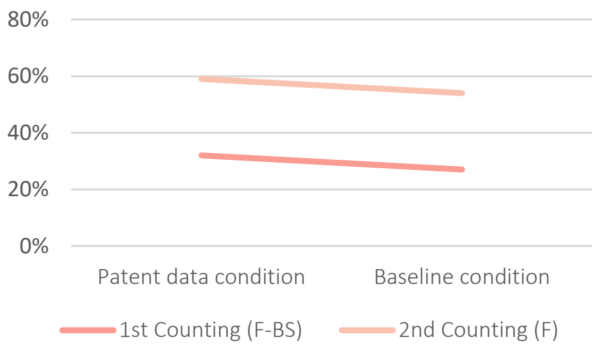


Figure 29 Comparison of fixation rate through two countings

Table 12 The baseline tool and patent data tool had different fixation effect on three participants

Tool's effect on ideation	Patent Data Tool	Baseline Tool
Creative on Function-behavior, structure	P4	P1, P2
Creative on Function	P1, (P2)	P4, (P2)

4.3 Observation on Brainstorming Process

The following section explains participants' interaction with the tools and ideation from think-aloud protocols (Appendix 17) and screen recordings. The following section describes two tools' effects on the solution and problem phase and different fixation effects.

4.3.1 Exploration on Solutions in Baseline and Patent Data Conditions

In the brainstorming session, both the baseline and the patent data tools provided knowledge of existing solutions. Participants interacted with the tools and explored existing products iteratively to find inspiration. The baseline tool provided visual stimuli, while the patent data tool provided textual information.

Participants wanted unexpected inspirations by using a broad search term in the baseline condition. So that they would embrace the "Aha!" moment when the search results showed them results beyond conventional products (e.g. umbrella, raincoat or toothbrush). Participants searched names of a broad categories, such as "portable device", "teeth cleaning tool", "best tooth cleaner". Some of them also included functions in the search term, e.g. "resist wind", "keep dry", "Wind capture device" into the baseline tool (Appendix 14).

It can be found that participants borrow the existing structure and behavior of one solution once the baseline tool showed existing solutions. Because the visual stimuli usually reveal the structure of different solutions. They modified the functional design to fit design brief. For example, when P1 used search word "resist wind", the wind turbine image (Figure 30) inspired her. She made an idea of a similar rotor blade on user's head to resist rain and wind (Idea 97). Afterwards, she scrolled down and found a stylish sunglasses image (Figure 30). It reminded her to use transparent material, and design a folded hair band which could be changed into a transparent mask solution (Idea 98). She adopted the behavior and structures from existing solutions, but modified product function to fit design task. Similarly, P6 also searched for "portable device" and "portable technology" to get inspirations from the image search tool. A wearable watch (Figure 31) gave him the idea that the solution could be a wearable device (Idea 89). He also felt excited with an unconventional product image (Figure 31), a futurist mobile on human skin. This product structure helped him think out of the box and came up with smart skin solution (Idea 93).

The patent data tool also provides diversified existing solution names. Unlike the baseline tool, the patent data tool itself did not show visual and design structure. Usually, participants ideated structures and behaviors of the existing solutions, put them into new ideas and adjusted functional design accordingly. Participants imaged the structures and behaviors of a patent solution from their knowledge or used the baseline tool to facilitate understanding.

For example, P1 found a new phase “pneumatic cleaning system” from the patent data tool (Figure 32). Pneumatic cleaning refers to an air-pumping cleaning mechanism, which inspired her to have a new mechanism of cleaning tooth by air force (Idea 30). P1 also found "arch wire" interesting for her (Figure 34). "Arch wire" was a dental device installed on tooth to correct tooth positions. Inspired by "arch wire" appearance, she added a water piping function to her design (Idea 34). In this scenario, she still used the baseline tool to understand the meanings of both "pneumatic cleaning system" and "arch wire", and developed structure of her new idea.

“What about glasses, big glasses... Like that covid-19... maybe you can use another mechanism. it can be folded, so he might usually be like a hair band” by P1 in the baseline condition

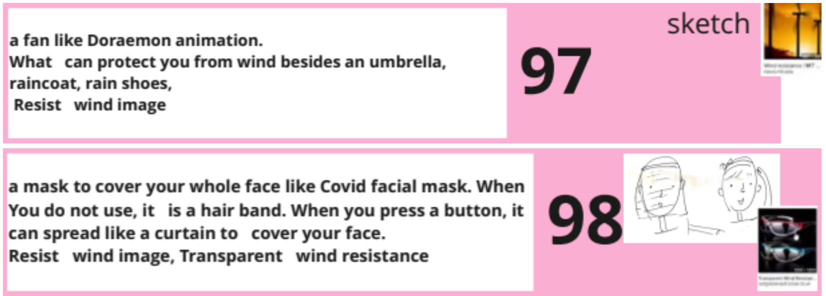


Figure 30 P1 got inspirations from wind turbine and sunglasses images in the baseline condition

“This looks nice. Prevention. It can be artificial human skin... It is waterproof. And, can be digital.” By P6 in baseline condition

Figure 31 P6 found inspirations from wearable bracelet and futurist mobile images in the baseline condition

“right, pneumatic. it's a feeling that there’s air blowing, and then it's, uh, and the doctor cleans you tooth up. and then after washing your teeth, it will clean up small dirt...” by P1 in patent data tool condition

Figure 32 P1: “Pneumatic cleaning system” in the patent data tool (upper), image search in the baseline tool (middle), ideation(lower)

Apart from using visuals to understand patent keywords, participants can also think in an abstract functional way and free from exploring structural details in the brainstorming process. When P6 searched for “clean” in the tool, he got the phrase “robotic cleaning system” (Figure 33). The word “robot” implies new possibilities for the device, usually an autonomous tooth-brushing process controlled by a smart system (Idea 15). Similar ideation examples can also be found from other participants (Figure 35). P4 directly integrated "weather data", "handle grip", and "modular towel" product into solutions(Idea 58 and 59). P2 also applied "backflap, stylish backpack" to an adoptable raincoat in the form of a bag (Idea 87). It can be found from these examples that participants used the mind map technic to describe their thinking process instead of drawing solution sketches.

"arch wire…You can put something in the middle of your tooth and gums, and then maybe it will spray water over time. sprays water this morning, and other time. Then you don't have to do anything, you simply turn it on, and then easily let it squirt for 5 minutes." By P1 in patent data tool condition

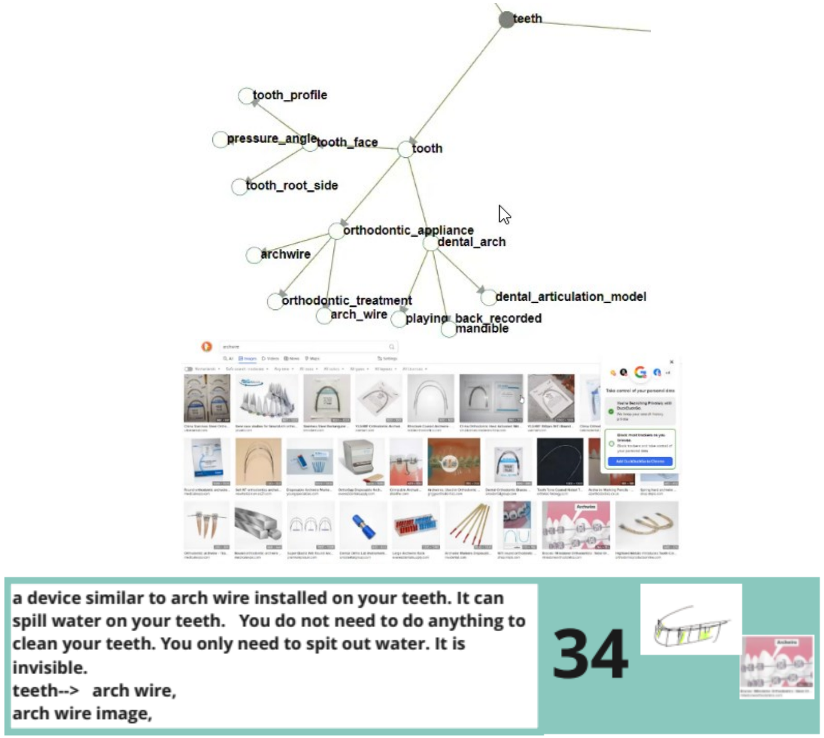


Figure 34 P1: "arch wire" in the patent data tool (upper), and image searches of "arch wire" in the baseline tool (middle), ideation (lower)

"Clean, clean system, yeah, robot… Yeah, reminding robot maybe. Social robot send, send notifications to user. Regular, regulate their Teeth brushing activities." By P6 in patent data tool condition

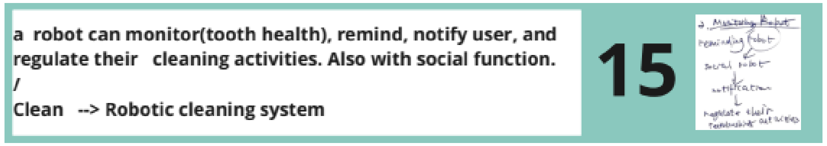


Figure 33 P6: "Robotic cleaning system" as design stimuli

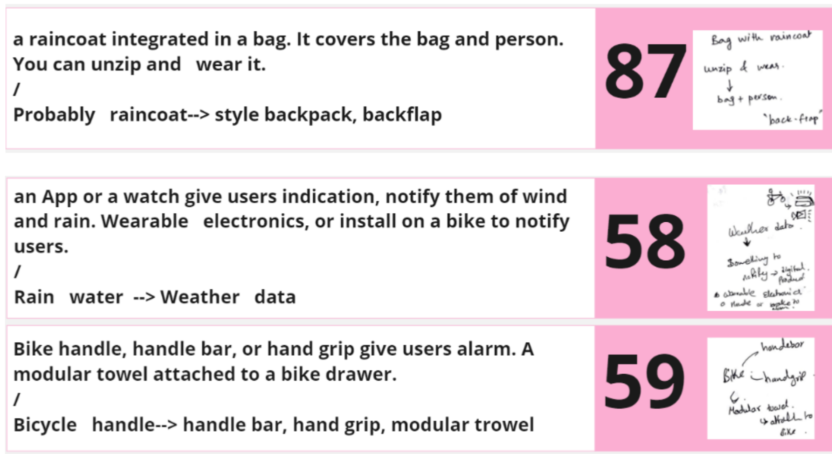


Figure 35 Examples of integrating patent solutions directly: Idea 87 by P2(upper), Idea 58, 59 by P4 (middle and lower)

Participants not only linked the existing keywords to their design but also used patent keywords to explore new solution possibilities. Because the keyword provided in the patent data tool condition did not explain further why it was related to the query and the innovation behind the textual stimuli. Participants had to build a connection creatively between patent analogy and the design task skillfully through their interpretation. Figure 36 lists an example of using patent keyword for further exploration. Participants (P2) extracted functions from different objects. The phase after → was the textual inspirations from the patent data tool. P2 used "flexible material" stimuli to imagine a collapsible and foldable umbrella structure (Idea 86). A possible stimuli “tent” reminded her of something foldable and portable. Because she read “tent” keyword in the protocol before ideation.

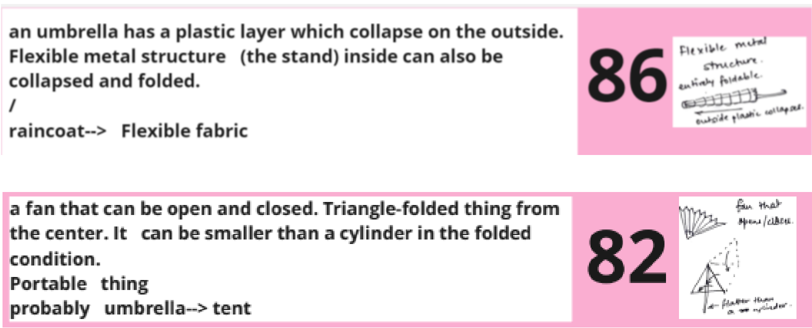


Figure 36 P2: Examples of using patent data solutions to explore new possibilities

When participants wanted to explore solutions, they need to realize that the query rule for two tools were extremely opposite. The two tools require different interaction processes (Appendix 14). In the baseline condition, participants need to come up with search keywords from their knowledge and experience. The patent data tool, on the other side, could save participants’ input efforts and did not require specific knowledge or experience in the domain.

In the baseline condition, participants input a broad search terms to think outside box. For example, P2 inputted “tooth cleaning”, “tooth health”, and “mouth hygiene products”. P6 input “Dry from rain”, “Dryer” “Skin dryer”, “Face dryer”, “Hands dryer”, “Dryer”, and “Dryer design” (Appendix 14). Sometimes, these iterative search words expressed very similar meanings, but the baseline tool provided different product categories as results. Besides inputting broad search terms to get knowledge, participants(P4, P6) also made creative combinations of phases, “necklace brush”, “bracelet umbrella ” in the baseline tool to validate if their ideas existed in the market.

In contrast to the baseline tool, participants had to input very specific product names in the patent data tool. Considering the limited semantic capability of the patent data tool, participants would better input existing product names, such as "umbrella" and "bicycle helmet". P1 inputted "clean" and "clean teeth", which also showed results. P5 formulated compound phases such as “quick clean daily”, “clean small”, “clean tongue”, and "fake tooth". These could work with the baseline tool. It is discussed in the next chapter that the patent data tool's semantic capability limit participants' exploration.

4.3.2 Exploration on Problems in Baseline and Patent Data Conditions

Besides exploration on the solution phase, participants also used the tools to envision problematic situations and user contexts. By thinking of potential users and problems, participants redefined a specific group of users, and got more understanding of them.

The baseline tool helped participants to understand user scenarios and pain points visually, although sometimes participants did not search for problems intentionally. For example, when searching for "portable device" in the baseline condition, P6 pointed at an image of different size digital screens (Figure 37), intuitively connected with users who might ignore weather forecasts from mobile phones(Idea 92). A strong storm news image (Figure 38) from "wind and rain" query also reminded P3 that in extreme weather condition drone can sent raincoat to users on site (Idea 66). P4 also searched "teeth clean habits" and saw lots of kids smiling and brushing tooth images (Figure 39). This type of visual stimuli gave him the idea to design tooth brushing toy for children (Idea 38, 39).

"Because weather forecast can also be a preparation...So just portable devices can be a portable forecast. Em. Can be a portable forecast device embed lights to raise awareness. Because the smart phone can also provide the forecast, but people usually ignore it."

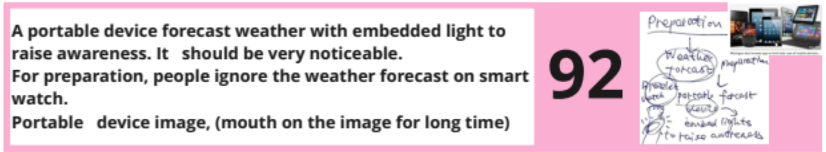


Figure 37 P6's search results of "portable device" in the baseline tool

"Maybe also the device that can ask someone to bring a raincoat for you. using a drone." By P3 in baseline condition

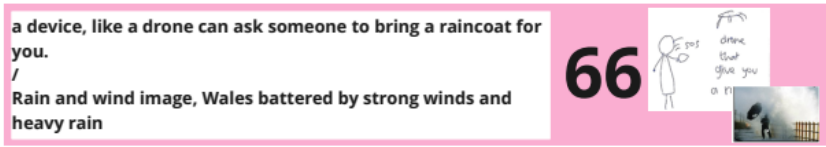


Figure 38 Storm image from "wind and rain" reminded P3 design for extreme scenarios in the baseline condition

The baseline tool also supported participants to explore on an insight visually when participants suddenly got interesting user scenarios from their intuitions. For example, P3 came up with an interesting user scenario for rain protection design and searched the keyword "party under the rain". The common forms of umbrella images did not excite her. Nevertheless, a lady wearing a cloud-shape costume on the head made an "Aha!" moment for her (Figure 40).

It also happened that the baseline tool did not show valuable information when participants wanted to get more understanding of users. For example, P3 input “what makes teeth dirty” into the baseline tool. He reacted with “*horrible images…very scary*”. These search results did not provide him with answers (Figure 41).

“…I also see a lot of kids, so I think I would try to design something like a toy…” by P4 in the baseline condition

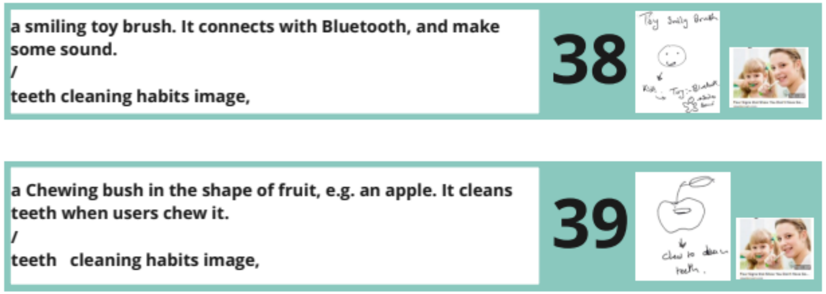


Figure 39 P4 found kids smiling images as design stimuli in the baseline condition

“People want to have party during the rain... I'm looking for “Party under the rain” for the images. There's an umbrella. But it looks so boring, Like people don't want to use this umbrella…Oh, this is so Cool, so there's a girl with the Cloud, it's just like an umbrella on top...” By P3 in baseline condition

Figure 40 Boring umbrella image (left), cool party costume image (right) by P3 in the baseline condition

“Oh horrible images …Very scary. But it doesn't say a lot about what makes them Bad. ” by P4 in the baseline condition

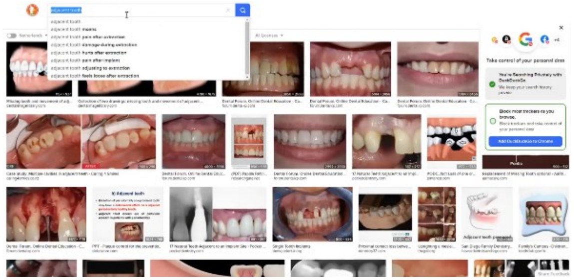


Figure 41 P4 found “horrible oral images” in the baseline condition

Different from baseline tool bringing about user context in the visual form, the patent data tool showed existing patent solutions which reminded participants of potential problems occasionally. These terms shared some similar features with problematic issues and gave a quick hint for participants to associate with possible problems intuitively. For example, when P1 saw “tooth profile” appeared in the patent data tool (Figure 42), she ideated a tooth cleaning product with a personalized tooth profile function that could help users clean plaque (Idea 31). Because she had the question already in her mind of how users know the cleanliness level of their teeth. “Tooth root side” was a specific term for tooth structure, which also reminded P1 of the problem of what if users did not clean the tooth side properly. She developed a colorful mouth wash to remind users to clean the teeth root side (Idea 33). Similarly, "dental arch" also gave P1 inspiration to users of fake teeth in Idea 35.

“Tooth profile. Oh, well, so I think it's kind of interesting. that you might have an image, or a light, and then it can know how much plaque in your teeth now...” By P1 in the patent data tool condition

“Tooth root side. so yes, so it will also have different sides, so I think there are three surfaces of one tooth, but only one side is clean. then is it possible that this stuff is to help you clean, tell you that you have cleaned every side... and then you have a mouthwash, something like a mouthwash. you use it to rinse. and if you don't make it clean, There will be colors on tooth” By P1 in patent data tool condition

“OK, oh, tooth implant, uh, tooth root, oh, good, so it is also possible. um, for those who wear fake tooth, it is possible, uh your tooth root, tooth root.” By P1 in patent data tool condition

a 2-sided tooth brush. One side can clean the teeth. The other side can generate a light to detect cleanliness of you teeth.
/
teeth--> tooth profile

31

a mouth wash can change the color of your unclean teeth area. It remind you to clean unclean teeth.
How to clean every side of your teeth
teeth--> Tooth root side

33

If you wear fake tooth, the dental arch can automatically spray water to clean the fake teeth for you.
/
teeth--> Dental arch
Dental arch image, dental implant

35

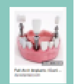


Figure 42 P1’s ideas in the patent data condition

When P4 inputted "raincoat" into the patent data tool, he saw a valuable environmental problem outside the brief from the word "dispensing" (Figure 43). He developed a stylish rain jacket to substitute disposable plastic raincoat (Idea 55). "Safety umbrella" also showed him the importance of being safe when a person using an umbrella in strong wind (Idea 54).

P6 found out "body inserted" result from the patent data tool. So he tried to find this phase's meaning using the baseline tool (Figure 44). Results showed him medical devices inserted into the patient's body, which reminded him of fake tooth users, so he redefined the problem of fake tooth users and made it an idea (Idea 16). Another search result "password recovery system" (

Figure 45), inspired P3 that users might forget where their toothbrushes were (Idea 21). The word "Hemo clip" helped P3 associate with the difficulty of cleaning small food sucked in the tooth and the importance of a specially designed device (Idea 24).

Nevertheless, not all participants reframed problems and investigated in user context. Some participants came up with solutions intuitively without reframing the problem. When they iterated ideas, they added possible problems in which their solutions could fit. P4 used this intuitive approach of having solution first (Figure 46). For example, P4 made interesting phrases like “pen and toothbrush” (Idea 41) and “necklace and toothbrush” (Idea 42) as solutions. Afterward, he redefined the problem and described user scenarios.

“it says here about like safety of umbrella which also gives me …It's about safety of umbrella that they have like a different spikes in them, which can be or say like a better that it cannot hurt any children or some other people.” by P4 in patent data tool condition

Eh, dispensing… sometime it gives me like an idea about like those rain jacket which is like more you know one time use, Which is not good for the environment.” By P4 in patent data tool condition

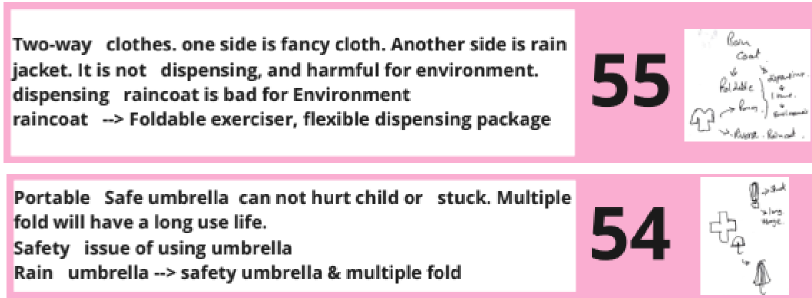


Figure 43 P4’s search result showed “flexible dispensing package” in the patent data tool

"What is body inserted, body inserted... Body inserted device. Maybe most inserted. Fake teeth, Fake tooth... It's actually a smart tooth Banded insert or inserted in mouth... Produce some fresh, fresh smell. And also it can help kill bacteria In user's mouth." By P6 in patent data tool condition

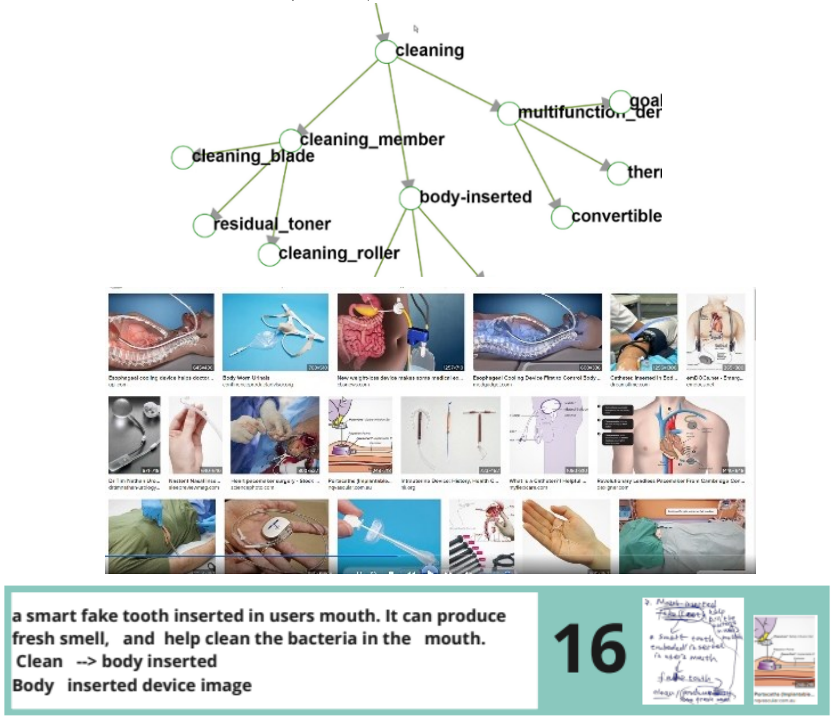


Figure 44 P6 using image search in the baseline tool to interpret "body inserted device" from patent data tool

"There is password recovery system on the Tech-net, so maybe the problem would be If you are with the family. Yeah, what else, We lost our tooth brush. It's a problem. So then the solution will be. Finder of brush." By P3 in patent data tool condition

"Maybe it is hemo clip system. Maybe it's something that the problem. I think. It's difficult to clean the teeth. So there's sometimes difficult to clean the teeth. In the. In the hole, or in detail. So we need to. Something, something like hemo clip. That can reach the difficult Position... OK. so I have micro teeth brush." By P3 in patent data tool condition

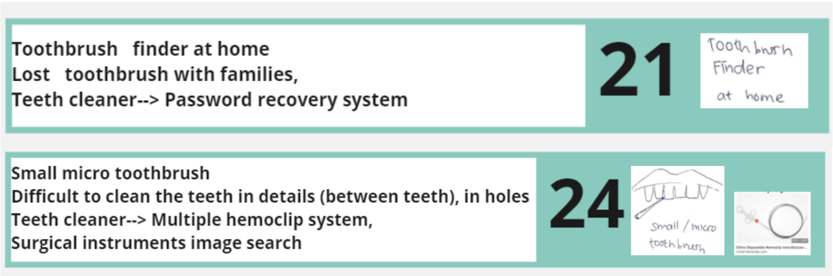


Figure 45 P3's search results helped reframing problems in the patent data tool condition

"when you look at the best tooth cleaner, it, it shows a lot of image ...like more electrical cleaning devices... It also looks like a bit ...pen. So I can maybe combine it with the pen, tooth brush pen. And yeah, so that pen because you keep it all the time with you. It also gives you, how do you say you can just go to, when you're working. You can just go to the office and like. Go to the washroom and clean your teeth whenever you want." By P4 in baseline condition

"So maybe I can think of a necklace brush... It's also you can clean this brush. so you can just keep it with you whenever you go. And it can be also self cleaning. So you don't have to really. Ah, put a lot of efforts in cleaning it." By P4 in baseline condition

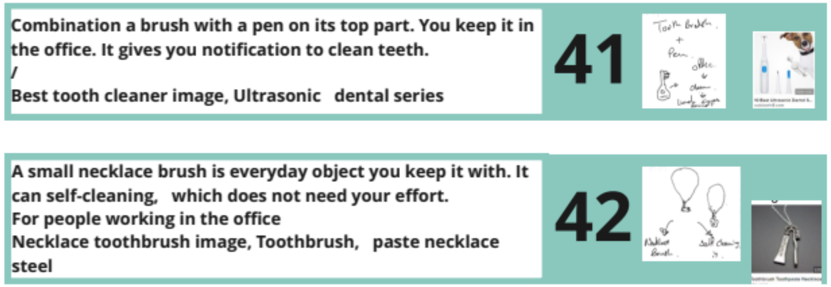


Figure 46 Examples of reframing problems after solutions by P4 in the baseline condition

4.3.3 Design Fixation and Patent Data Tools' Effects

Design fixation in both conditions can also be observed from the protocol and recordings. In the baseline condition, participants experienced knowledge-based fixation on effective query and imitated visual stimuli. The patent data tool helped to release knowledge-based fixation in the query stage but, on the other side, caused participants to get stuck with difficult search results.

In baseline conditions, some participants experienced difficulties to formulate an effective query or find something interesting from search results. They failed to formulate iterative search terms from their previous knowledge and life experience. When they inputted a common daily object name, the image search tool showed many conventional images that did not inspire. This type of fixation is considered as knowledge-based fixation. Because participants fixated on a form of abstract knowledge or fixated on the knowledge of the search tool. Interestingly, most participants talked about their difficulties in finding different query, and getting conventional results from the baseline tool. This showed that the challenge happened to most participants, who were fully aware of their knowledge-based fixation.

P5 inputted "rain coat", "umbrella", "raincoat pack", which made her get struck with these low novelty product images. When using the baseline tool, P1 inputted "resist rain". She did not find anything out of the box from these conventional products. P3 got fixated on the baseline search when she changed search keywords many times and failed to find inspiring solutions. P2 did not know what to feed the image search tool. During 12'35"-15'26" in the experiment, P2 kept searching random images and did not come up with new ideas. P6 got fixated on the search term "portable device" several times. He tried several similar search terms, "Portable umbrella, Portable device, Portable instrument, Portable technology" to find inspiring images.

"Yeah, these are some ideas. But how can I get more inspirations from here? It's not really fun." by P5 in the baseline condition

"Uh, raincoat, umbrella. Uh, rain boots... OK. So what else can block the wind?" By P1 in the baseline condition

"I can't really think of anything more… And I don't know what to search also…I can't really think of anything… I can not really think of anything… but I can not think anything." By P2 in the baseline condition

"yeah, this is the same. No…I don't know…It's Very difficult." By P3 in the baseline condition

Compared with other participants, P4 was also aware of his fixation on previous ideas and kept on iterating different search terms. To avoid fixation on query, participants needed to think about a broad category or find out a new phase to feed the baseline tool.

> "...OK, that's what I already saw... What else, yeah, maybe I'm thinking about more. What is the everyday object which you keep it or entire day object which You keep it with?" by P4 in the baseline condition

Moreover, if image stimuli from baseline tool provided participants with interesting solutions, it would be likely that participants also fixated on image stimuli. Few participants reported this type of *conceptual fixation* in the post-experiment surveys. Some examples of participants (P2, P3, P5 and P6) imitating functions and appearances from stimuli are listed (Figure 47). The sketches on the left represented participants' ideas, and the color images on the right were visual inspirations and existing products from the baseline tool.

Figure 47 Conceptual fixation examples in baseline condition: Idea 67, moon-shape umbrella by P3 (upper left), Idea 79, raincoat inside a bag by P5 (upper right), portable body dryer by P6 (middle left), cloud-shape hat by P3 (middle right), automated tooth scanner by P2, magnifying glass scan by P2 (lower left and right)

In the patent data tool condition, participants had less challenge with what to input. Participants built ideas on different search results. But they had more difficulties understanding the technic terms and filtering out useful analogies for them to finish the design task. These technic terms are beyond their existing knowledge and experience. Unless they knew how to filter useful content, they would get fixated on many useless results and waste their brainstorming time.

Participants said in the think-aloud protocol that they were just clicking the keywords passively and killing time. P1 felt she was done with the patent data tool, not generating ideas from 16’45” till 20’ in the end. P2 did not generate ideas from 1’50” to 6’10” because she got stuck with technical terms. P4 provided one example to avoid this fixation on the search results. He did not further look into the difficult technical terms. He did not use the baseline tool to explore the meaning of these terms. Instead, he only read through understandable words and then moved to another query iteration.

“I think I am done. Now I am just clicking random nods.” By P1 in the patent data tool condition

“Maybe I should search for the raincoat… nothing interesting… multiple fold, telescopic centerfolds. Nothing really Comes to mind…let’s see what this (bag body opening portion) shows…multimode travelling…Than does not make sense. Separate fluid bladder, What? …This is very random.” By P2 in the patent data tool condition

Conceptual fixation also happened to some participants (e.g. P1) who used the baseline tool to find visual representations of difficult technical words. They intended to imitate functions and appearances from the visual stimuli. This *conceptual fixation* was similar to the situation in the baseline condition.

The summaries of analysis sections are in

Table 13.

Table 13 Summaries of the patent data tool's effect on ideation and fixation

Method	Method Description	Patent Data Tools' Effect on Exploring Solution	Patent Data Tools' effect on Reframing Problem	Patent Data Tools' Effect on Reducing Fixation
Post-experiment Survey	Self-report with online survey	to a slight extent efficient and creative for design solution.	to a slight extent helpful in finding new problems.	useful in exploring different design directions (avoid fixation in general); Helpful in overcoming knowledge-based fixation, conscious adherence, and intended resistance to new ideas.
Quantitative Analysis of Fixation Rate	Counting fixation rate by categorization on functional level, and categorization on functional, behavioral, structural level	/	/	did not find obvious effect of reducing fixation compared to baseline tool; need more studies to examine the tool's effect on ideation at different functional, behavioral and structural levels.
Qualitative Analysis	Observation on think-aloud protocol, process recordings, and ideation results	provided names of relevant solutions, not show detailed structure designs; participants chose to either think in an abstract way, or rely on external visuals to apply patent analogy; provided interesting keywords, and inspired participants to explore further possibilities.	did not aim to show design problems specifically; some solution names inspired participants of variable user contexts and problematic situations by chance.	reduced *knowledge-based fixation* in the query stage; some technical keywords from specific engineering domains were not interesting or even confusing for participants.

Chapter 5 Discussions

This chapter discusses experiment results compared with previous researches and experiments. It firstly give interpretation on patent tool's effect on understanding users and context, design fixation. Afterwards, it show the tool facilitates participants using functional analogies and their user experience. In the end, SWOT analysis is shown to explore future opportunities for creative ideation process.

5.1 Understanding Users with Patent Data Tool

Different from Gonçalves's findings (2017), the participants did not see the patent data tool as a hindrance to creativity or reject the tool in the experiment. All participants agreed to some extent that the patent data tool helped explore both problem and solution space. They recognized the tool's value as inspirational materials.

Different from the problem solution co-evolution (Dorst & Cross, 2001; Helms & Goel, 2014), participants used patent solutions to reframe a new problem or to ideate a new solution. Dewulf & Childs (2021) also support applying an existing solution to formulate a new solution directly. The benefit is that designers can immediately test if this solution can solve their problem. As a result, designers do not necessarily need to know the problem mentioned in the original patent solution. This also happened in the experiment when participants ideated without knowing the original patent context. This approach is different from TRIZ method proposed by Bonino et al. (2010). Instead, they argues that both problem and solution from patent files need to be present to users but at an abstract level.

During the experiment, the random encounter with unexpected search results and within less control of the process is not an efficient way for users to explore either problem or solution. As Gonçalves et al. (2016) observed this ideation behavior in the experiment and suggested several reasons. Because participants did not reframe the problem, not find a clear design direction, nor use an effective search keyword before using computational stimuli. They find out that these processes are the most challenging process for designers. Having "uncertainty and ambiguity" features (Li et al., 2019) with search results in the patent data tool, participants experienced both surprise and frustration from the patent data tool. Unlike Gonçalves et al.'s ideation experiment results (2016), participants need to input very specific keywords into the patent data tool. But, they can not expect what keywords would appear. Participants embrace this uncertainty to help them think outside of the box. Similar to Gonçalves et al.'s suggestion on the awareness of the design process, some participants (P1, P6) reframed the problem and structured their search efforts, which helped them to make the most out of the tool.

The patent data tool used in the experiment includes over 4 million technical and engineering terms (Sarica et al., 2020). But it does not provide keywords to link with problems in the patent data. From the observation of ideation processes, participants encountered some solution phases which help them envision user contexts by chance. These useful terms were shown with other solution terms altogether in the tree graph. For participants who want to know specific knowledge about one domain, the baseline tool can provide pages of articles to answer them. However, it would take too long for the participant to read through in a short brainstorming exercise. For example, P4 wanted to know "teeth clean habits" and "what makes teeth dirty" by searching webpage but this was not an effective way to work out. The patent data provided an inconsistent way to understand problems through reading existing solutions.

Dorst & Cross (2001) pointed out the importance of reframing the problem by providing enough information to facilitate designers. For example, from their trash bin design experiment, they shared information about thrown-away newspapers on several information sheets. Observation of context and data collection from different perspectives is also important before reframing the problems (Beckman & Barry, 2007; Beckman, 2020). They suggest that the observation and context inquiry stage is also divergent thinking on the concrete experience. Afterwards, reframing the problem built on these data becomes an abstract thinking process.

Similarly, the brainstorming process supported that human perspectives are important considerations for industrial designers to conduct design inquiry(Stappers, 2006; Jiang & Yen). Some examples are given in 3.3.2. Participants empathized with different users and their obstacles, such as fake tooth users, people who are having a party in the rain, tooth-brushing tools for kids, and people who forget to read the weather forecast. For industrial designers, having empathy and understanding of users are important in human-centered design (Stappers, 2006). Participants in the experiment reported that surveys, interviews and focus groups are commonly to collect user insights. Two participants mentioned "*UX design workshop, interview*" (by P1), "*discussion, dot voting*" (by P3) as regular design methods. This aligns with Jiang & Yen's experiment (2010), industrial engineering students paid lots of attention to human-centered elements, imagine the user profile, and empathize with users' pain points. This distinguished their different design thinking mode from engineering students who spent more time on engineering parts and systems. Understanding users' needs are fundamental to formulating the right problems, which is used as the preliminary step before functional design (Liu & Lu, 2020).

Nevertheless, the traditional methods such as interview, survey also have their limits to collect user insights. They require designers to have knowledge and hypotheses about users' needs and conduct the interviews, surveys with users in a structured process. But, these processes are less effective in exploring something unknown to designers and users. One participant (P5) mentioned that the patent data tool is similar to brainstorming with a "*coworker*". It is worth investigating what new tools can potentially help designers explore unknown situations more efficiently.

5.2 Patent Data Tool's Effect on Design Fixation

The participants' self-reflection supports the importance of external tool to reduce fixation (Csikszentmihalyi, 1997). From participants' self-report, 4 out of 6 participants agreed, and 1 strongly agreed that the patent data tool could help overcome *knowledge-based fixation* and explore new design directions. Participants saved their search efforts; not relying on their experience and knowledge in the initial query stage can be the reason for this positive feedback. Gonçalves et al. (2016) addressed the importance of formulating effective keywords, which is usually an obstacle for designers exploring the computational knowledge base. Most design-by-analogy tools miss this important function for designers to explore analogical knowledge base. The patent data tool shows its strength in that participants only needs to input the most straightforward keyword in this domain. The tool can automatically build a connection with relevant terms. Besides, from Gonçalves's experiment (2017), 81% of participants see using computational stimuli as an effective strategy to overcome fixation. At the same time, nearly 20% of participants did not want to be attached to the stimuli. They reported being unable to ideate after using the tool, which did not happen in this study. One possibility can be that the sample size is small. Another explanation would be all the recruited participants showed affiliation with learning tech-driven brainstorming tools, so they agreed to join the study.

The fixation rate is a calculation based on the analysis of the function-behavior-structure model. It can compare how participants explored on function-behavior-structure level or got fixated. It did not aim to distinguish *knowledge-based fixation* or *conceptual fixation*. Two participants showed equal or lower fixation rates on the functional level in the patent data condition. Oppositely, Gonçalves (2017) did not agree that the quantitative method of counting idea features can reflect fixation rate because the design is an ongoing process in which participants need to integrate previous ideas. Further mixed-method studies are needed to distinguish the tool's effect on functional behavioral structural level and the participants' thinking capability at an abstract level.

Most participants felt aware of the moment they did not produce new ideas. Participants mentioned that they did not find stimuli inspiring, failed to formulate new search keywords, or were stuck. Gonçalves (2017) received similar reports from participants on reporting their stuck moment. On the other side, none of the participants mentioned that they felt aware of *conceptual fixation*. Participants were imitating existing product images in the baseline condition unintentionally, which was similar to previous fixation studies (Jansson & Smith, 1991; Youmans & Arciszewski, 2014; Crilly & Cardoso, 2017; Gonçalves, 2017). The patent data tool did not provide visual stimuli, which helped to reduce *conceptual fixation* mostly found in the baseline condition. Some participants searched for visual stimuli to understand technical terms can also be fixated on the existing design.

Premature fixation was also found in the experiment. Robertson & Radcliffe (2009) and Gonçalves (2017) tested different computational stimuli and premature fixation. Computational stimuli should help designers to explore in the early stage instead of developing design details. In Gonçalves's experiment (2017), groups with access to computational stimuli experienced less premature fixation phenomenon compared with controlled group. According to Robertson & Radcliffe (2009), designers with better performances should better produce large quantities of sketching in this stage. They are not suggested to use the computer to build details on premature ideas. Otherwise, designers who developed their solutions with details and visualizations, would be unwilling to explore new solution. They would get fixated on their premature ideas. This premature fixation happen mostly in the conceptual stage. It can also be seen as a type of *conceptual fixation*. In the experiment, some participants developed more detailed ideas compared with other participants. When participants spend more time developing details, the idea descriptions would usually have longer sentences to say more structural details. It can be seen that they would like to repeat these ideas or develop similar ideas. For example, Ideas 96, 98, and 99 (Figure 48) were generated by P1 in chronological order, which used longer sentences in the solution descriptions. It can be seen that idea 97 borrowed blowing function from idea 96. Ideas 99 and 98 both described a transformative panel to prevent rain in different scenarios. Her fixation rate on the functional and structural level is also relatively higher than the other two participants who did not go into structural details.

The patent data tool did not help users to develop abstract knowledge into sketches or CADs. P4 recommended text-to-image generative tools. He mentioned that he tried out DALL·E 2, an AI text-to-image generative tool to help him develop idea into images in minutes. Other tools which do not expose participants to visuals of existing solutions and help participants to conceptualize are needed to eliminate *conceptual fixation*.

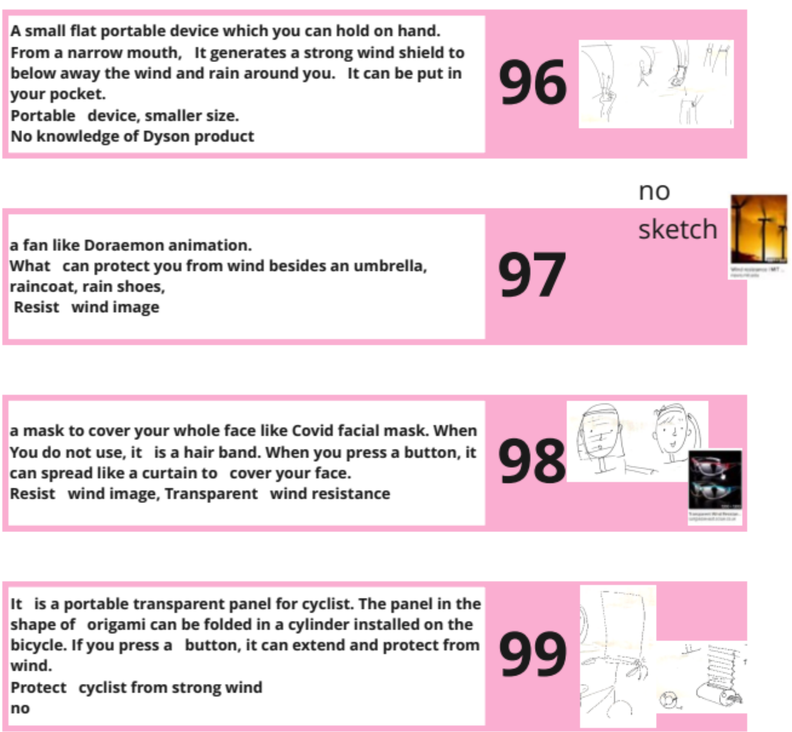


Figure 48 Examples of ideas with more details by P1 and premature fixation effect in the baseline condition

5.3 Participants Using Functional Analogy from Patent Data

In analogical design, representing functional elements from other domains is seen as a useful method to generate novel solutions and overcome design fixation (Murphy et al., 2014). The functional terms extracted as design inspirations need to be expressed at an abstract level and not imply too many details of the solution. In this way, designers will consider a large number of new ideas beyond existing solutions. Sarkar & Chakrabarti's novelty evaluation model (2011) also sees functional elements as the most important attribute of the novelty score. In the early ideation stage, designers should co-evolute functional requirements with different problems. They should not quickly dive into structural details in the premature stage.

Designers tended to generate the most straightforward solution provided by patent data tools without redefining functions. When using an analogical tool for ideation in a limited time, designers also experience cognitive challenges and fixation (Linsey & Viswanathan, 2014). Designers try to borrow features from analogy on the surface but find it hard to build a deep connection. Even with a data-driven analogy tool, choosing the functions that best solve the problems remains challenging (Linsey & Viswanathan, 2014).

Similar to research results (Gonçalves et al.,2016), designers prefer to use existing solutions similar to their problems. They can apply the stimuli to solutions quickly. Most participants chose the easy-to-apply patent analogy by intuition. By following this way, they could be quick and generate as many ideas as possible. They transferred an analogy directly into their solution when this term was a product name from another domain. For example, when they saw words such as "backpack" (Idea 83 by P2, Idea 87 by P2), "endoscope imaging" (idea 29 by P3) and "robotic system"(Idea 15 by P6) from the patent data tool, they would use these words as solutions directly (Figure 49). Some examples of extracting functions from the tool were uncommon. One participant (P2) extracted functions from search results "tent", "flexible material" to formulate new solutions (Figure 50). This thinking process requires more cognitive efforts and training in applying analogy from the functional level.

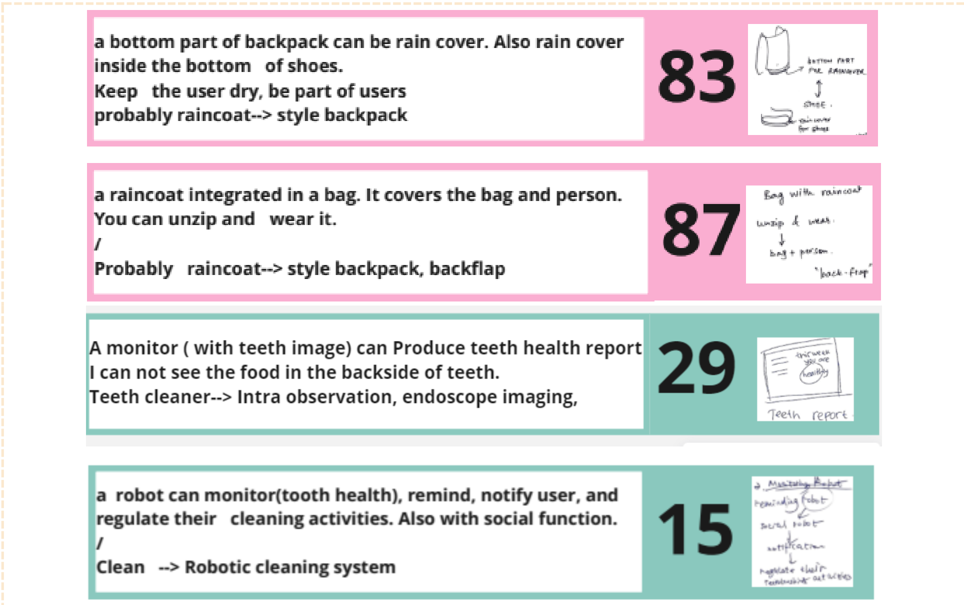


Figure 49 Ideas by using analogies directly, "backpack" by P2 (upper two), "endoscope imaging" by P3 (middle), "robotic cleaning system" by P6 (lower)

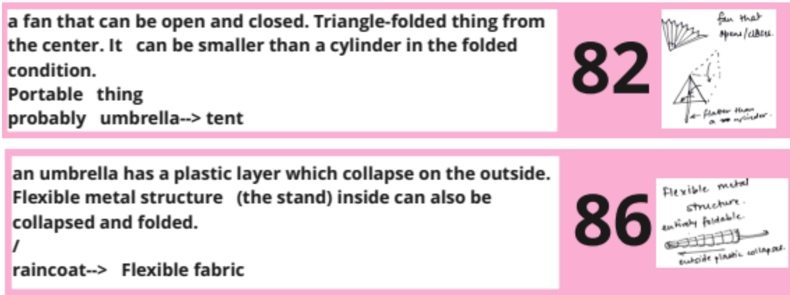


Figure 50 Ideas from P2 by extracting features from search results, "tent" (upper), "flexible fabric" (lower)

5.4 User Experience of Using Patent Data Tool

When designers develop a new product, easy to use, engagement, and authenticity are three important criteria for user experience (Desmet & Hekkert, 2009). These three elements also apply to designing a brainstorming tool or a new method for professional designers and students as targeted users. Some technological products failed to deliver this easy-to-use value to users because they required more cognitive workload from users. Similarly, if a new method, such as design-by-analogy, requires more cognitive efforts and did not fit into designer's understanding, designers would be unwilling to learn it.

Participants mentioned in the surveys that they expected visuals in the brainstorming process to make it more engaging. Some of the tools, such as *"Dribble, Behance, Pinterest, and Instagram"*, said by participants in the survey bring authentic contents as inspirational sources, and engage designers. This also aligns with the previous finding that designers prefer visual stimuli to textual stimuli (Cardoso et al., 2012). However, visual elements should be provided in a way which will not cause *conceptual fixation*.

In addition, there are others reasons that users would expect the brainstorming process with the tool should be more fluently and engaging. Firstly, Participants mentioned that some keywords confused them, not helpful for their creativity. The tool did not provide explanatory information on why research result was linked with a search term. Users need to look for meanings of some specialized engineering terms in another tool, which is not efficient.

As design-by-analogy is considered to be effective in bringing new ideas and overcoming design fixation. the tools that can facility designers to apply analogy easily should be considered. The frequent error screen and search capability of patent data tool influenced users' brainstorming pace. This suggests that the search capability is underdeveloped. Other well-developed, user-friendly analogical knowledgebase should also be put into considerations. Besides patent data, the biological domain is another important knowledge source for design-by-analogy with some recognized tools.

5.5 SWOT Analysis of Patent Data Tool

To sum up, the patent data tool has strengths in showing designers valuable knowledge and helping reduce fixation to some extent. The tool's interface is easy to use on one side for designers. But it requires designers' experience to be familiar with the design-by-analogy method. Similarly, Shneiderman (2000) also pointed out that the basic design requirement of a supportive creativity tool should be "low thresholds, high ceilings, and wide walls".

SWOT (Strengths, Weaknesses, Opportunities and Threats) is an effective tool to understand the status quo of a business project and plan future strategies (Namugenyi et al., 2019). According to them, many organization managements use SWOT tool to analyze internal and external resources and examine influences on the business. Researchers recognize its advantages, especially when working with multiple stakeholders across industries.

Patent data tool and relevant method is for creative ideation in the early stage. The goal of eliminating fixation and finding novel ideas efficiently can also be a end goal that needs strategic planning. Nevertheless, we can also borrow a business tool to provide a strategic landscape in this domain. So that designers can understand benefits and pitfalls of using this tool from both internal and external perspectives.

For the patent data tool, strengths stand for the internal advantages of this tool and its positive influence on the ideation outcome. Weaknesses are the internal issues which prevent the tool from achieving its goal. Opportunities are what external tools or methods can bring to maximize the goal of achieving creativity. Threats also refer to external issues to hinder the goal.

Strengths, weaknesses, opportunities and threats of the patent data tool are listed (Table 14) .

Table 14 SWOT analysis of the patent data tool for ideation purpose

	Strengths	Weaknesses
Patent data tool (Tech-net)	▪ Show patent keywords for ideation, add new knowledge, ▪ Ease of use in the query phase, ▪ Do not reveal product image, help to minimize *conceptual fixation*, ▪ Open platform, free to use.	▪ Not provide explanations of technical words, their relation with users' queries, ▪ Some patent keywords are not shown in clear way for readers, ▪ Require users to know analogical thinking and abstract functional features, ▪ Underdeveloped search capabilities and error screen.
	Opportunities	**Threats**
	▪ Look for new tools to explore problems and user's needs before searching for existing solutions, ▪ Look for new design-by-analogy tools in biological domain. ▪ Look for new tools to transfer knowledge into the concept, facilitate structural design, and overcome *conceptual fixation*.	▪ Designers are not familiar with using patent data tool, lack of supporting method, ▪ Designer's preferences on easy-to-apply analogy from similar domains (efficiency and novelty seem to be opposite goals).

Chapter 6 Conclusion and Future Work

In this chapter, the author will give conclusions, and suggest future studies on technology-aided design-by-analogy tools as external stimuli besides patent data tool. These tools are common- sense knowledge tool, biological design knowledge tool and automated conception tool. They are selected by easy to use, engagement, and authenticity as principles. Researchers can look into how these tools help eliminate design fixation and at which level of function-behavior-structure the suggested tools can be valuable.

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From the SWOT analysis in last chapter, researchers can work on internal threats to make patent data tool more effective. The author will suggest future studies on technology-aided design-by-analogy tools as external facilitation of patent data tool. These tools are selected by easy to use, engagement, and authenticity as principles. Researchers can look into how these tools help eliminate design fixation and at which level of function-behavior-structure the suggested tools can be valuable.

6.1 Alternative Knowledge and Conception Tools

In the design process, experienced designers are good at combine data from different sources and use divergent thinking to formulate their ideas(Cross, 2004; Liu & Lu, 2020) . Collecting limited data from narrow sources will not help for divergent thinking. In this case, combining different well-developed knowledge bases and conceptual tools can be an alternative to help design exploration and eliminate fixation. In this chapter, some design explorations on the alternative tools are provided to explore how these alternative tools can fit into the early ideation process. Further test are needed to test their effects on eliminating fixation.

6.1.1 Common-Sense Knowledge Tool to Explore User's Needs

Designer collect information to understand user's need and context in the concrete level before they proceed to reframing problems (Beckman & Barry, 2007; Beckman, 2020)). Common-sense knowledge tool is the first assumed tool to fulfill this goal. Han et al. (2021) found that engineering design researchers use the semantic knowledge base to develop new design methods. These tools are trained from different data sources. The most widely tested tools are open platform ConceptNet (Speer et al., 2017) and WordNet (Miller, 1995). ConceptNet is a good source to extend user scenarios and provide basic knowledge from common sense reasoning. By exploration of WordNet and ConceptNet interface (Appendix 18), ConceptNet is selected because of its clear information structures. It shows different aspects of a query in short phases, which fit easy-use criteria. WordNet presents information in long sentences and details, which is believed to add cognitive workload for designers in a brainstorming session and does not fit in the early ideation stage.

From exploration of the website and using "tooth" as a search term, the website (ConceptNet, n.d.) shows basic biological knowledge, tooth functions, and cleanliness in Figure 51 (Appendix 18). Some basic knowledge of tooth structure is provided, e.g. "back tooth", "front tooth", and "baby tooth". The tooth structure information is similar to what P1 got inspired from the patent data tool.

"baby tooth" search result also reminded users that there are different age groups and different user needs. "Chew food" and "creating smiles" results are similar to the user scenario images which P4 got inspired in the baseline condition. Other unexpected results can be "attracting fairies" and "keeping dentists in business". P2 also developed several ideas modified from various dental toolkit images in the baseline condition. None of the participants mentioned the function of "attracting fairies". But, some mentioned that the tool provides a fresh smell for oral, which can potentially valuable for social purpose. If a user puts a frequently used verb or adjective into ConceptNet, it is also interesting that it shows user scenarios in a structured representation. For example, when the user inputs the word "clean", the machine will tell that "clean requires", "find where dirt is". It also mentions several ways of cleaning, such as "vacuum" and "disinfecting". These new ways of cleaning are similar to some participants' ideations.

Figure 51 Search results of word "tooth" in ConceptNet (n.d.)

However, the "umbrella" search result does not provide many surprises compared to the "tooth" search result. The usage of "umbrella" can be used to "keep you dry" and "protect you from the sun". The umbrella location provides different places, such as "suitcase" and "umbrella stand".

6.1.2 Biological Design Knowledge Tool to provide Analogical Inspiration

Besides the patent database, the rich, inspirational source for design-by-analogy can also be found in the biological domain (Smith et al., 2011). DANE software(Goel et al., 2012) and the Asknature website (Deldin & Schuknecht, 2014) are two representatives of biological design knowledgebase. DANE uses Function-Behavior-Structure to guide its knowledge representation. It applies a hand-build knowledge structure which includes limited biological information (Han et al., 2021). Compared with DANE, Asknature is an open website which developed more than 1300 pages of biological inspirations from peer-reviewed research papers edited by professional biologists (Deldin & Schuknecht, 2014). Users do not require preliminary biological knowledge but can just input function terms on the biological strategies page. Some functional terms are given on the web page, such as “produce color, protect from harm, distribute resources, manage disturbance, conserve water” (The Biomimicry Institute, n.d.). This interface makes it easier for users to transfer abstract analogical knowledge and fit easy use criteria. Today, the page number has increased to more than 1750. From my observation, the function search bar on the website provides easy accessible biological information. High-quality photographs illustrate each biological information to explain biological function and behaviors. Each article is written in a short language, easy to interpret.

Using the tooth cleaning tool, for example, when the user input “clean tooth” in the search bar, 41 biological strategies will be shown in Figure 52 (Appendix 18). In the left column is the Functions bar, where each main function is categorized into several subgroups with numbers of inspirations. Some relevant functions and subgroups are shown in
Table 15. The website provides biological functions and behaviors in standard function-behavior form, such as “Microbes strip plant fibers clean, bacteria” and “How Fungi can clean up pollution, Fungi”.

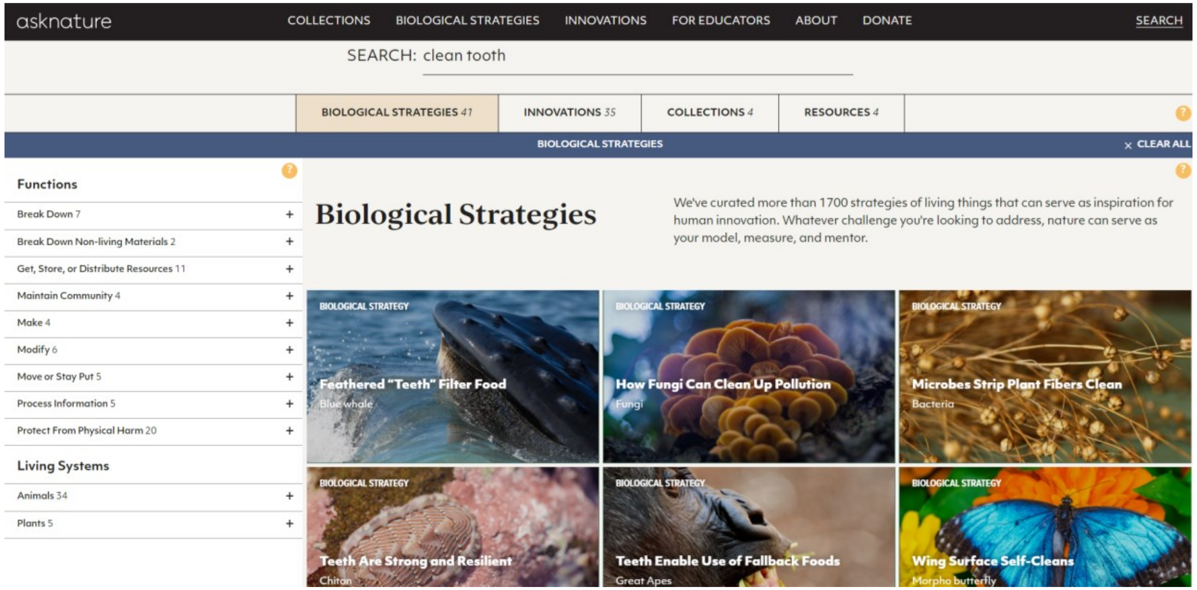

Figure 52 "Clean tooth" function search on biological strategies page, AskNature website (The Biomimicry Institute, n.d.)

Table 15 "Clean tooth" function search results, AskNature website (The Biomimicry Institute, n.d.)

Main Function	Subgroup of Function	Inspiration Tittle
Break down 7	Chemically break down 2	"Microbes strip plant fibers clean, bacteria"
Get, store or distribute resources 11	Capture, absorb, or filter resources 8	"Feathered teeth filter food, blue whale" "Mouth sorts and grinds food, platypus"
Modify 6	Modify chemical/electrical state 2	"How Fungi can clean up pollution, Fungi" "Crystals co-orient, purple sea urchin"
Move or stay, put 5	Move 2	"Feet are super sticky but do not get dirty, Tokay gecko" "Tissue slices go undetected, White-winged vampire bat"

6.1.3 Automated Conception Tool to Reduce Conceptual Fixation

Besides the above knowledge base presented in textual forms, possible conception tools to reduce *conceptual fixation* and facilitate structure design will be introduced in this paragraph. Most user cases looked at online creative communities, and illustrations as inspirations. Most of these beautiful images present existing concepts, which do not help reduce *conceptual fixation*. The author argues that latest text-to-image generative tools can also play an important role as visual stimuli, an effective defixation approach for industrial designers.

In 2021, deep generative models overcame main technical obstacles, and enabled users to generate masterpiece quality images from a short text input (Oppenlaender, 2022). This tool soon becomes popular in the designer's community and will influence designers' creative process in the future. Users do not need to master sophisticated drawing skills or programming skills. They input a sentence in natural language and will get a combination of several images in minutes. According to Oppenlaender (2022), this text-to-image process is state-of-the-art. Users try out different textual messages and let the machine run by chance. However, users do not have any other controls over the image generation process except for the original textual input. It requires users' knowledge and experience to write effective textual input. Some experienced users can make satisfactory images with short and critical textual input, while other novice users put long texts and fail to get the expected results.

Using previous design tasks as examples, the author tried several text inputs (Appendix 19). It was interesting that, on some occasions, the tool could generate a combination of images with different product structures from the same input. "A toothbrush in the shape of a woodpecker" and "a fan mounted on human head to protect from rain and wind" visual results are shown in Figure 53. P2 and P1 contributed these two ideas during the brainstorming experience. Both two text inputs described a rough structure. The woodpecker toothbrush images presented different structures and how the functional brush was connected with the authentic woodpecker part. The second one showed product function and slightly different umbrella structures. The two lower images showed an unexpected double-layer umbrella covering the human head, different from most regular umbrellas. However, the tool did not present a fan as textual query. In the experiment, participants built analogical connections with "woodpecker" and "fan". But, they did not come up with similar novel structures and appearances in the brainstorming session. These unexpected visual stimuli can trigger designers to think about why they use this structure and how to apply this structure or appearance in the conceptual stage.

In other try-out cases, the combinational images showed an extraordinary look of daily product with similar structures. This novel appearance and artistic effect could possibly bring “Aha” moments, and extend designer’s imagination space. Examples of “an umbrella in the shape of a drone”, “a raincoat in the shape of a cloud” are in Figure 54. The tool can help designers conceptualize their crazy idea, such as “drone and umbrella” and “cloud and raincoat”, and express their ideas with very few manual efforts. This helps designers to avoid premature fixation in the conceptual stage. More text-to-image examples can be found in Appendix 19.

Figure 53 Different structure designs, textual input “a toothbrush in the shape of a woodpecker” (left), “a fan mounted on human head to protect from rain and wind” (right) generated by Midjourney (2022)

Figure 54 Similar structure designs "an umbrella in the shape of a drone" (left), "a raincoat in the shape of a cloud" (right) generated by Midjourney (2022)

6.2 Towards a New Paradigm for Technology-Aided Design-by-Analogy Practices

The new design-by-analogy approach using a combination of tools is explained in this section. A combination of the different knowledge bases can be used collect design stimuli from different sources. Users can iterate and swift between these tools based on their design tasks and known knowledge.

6.2.1 Introduction of New Technology-Aided Method

A new design process and tools is given in Figure 55. Firstly, designers need to understand problems, user context and existing knowledge in an abstract level. Designers mainly inquire through a combination of ConceptNet (common sense knowledge for user context). ConceptNet would give users a more structured overview of one query or issue in providing related terms. Afterwards, designers want to learn existing knowledge from patent data and biological domain. TechNet (engineering terms from patent data tool) and AskNature (biological function, behavior, and structure) are the tools to facilitate. Both of them are knowledge bases specifically for analogies in engineering and biological domains.

During the query process, users describe the idea in textual prompt, say function and behavior prompt. Using "design something for rain and wind" as an example, users want to get some new ideas outside the umbrella. They input "umbrella" into the common sense tool. They can understand the context of using an "umbrella". The result shows "umbrella is used for", "location of the umbrella", "umbrella is a type of", "umbrella is a type of", "parts of the umbrella", and "properties of the umbrella" (Appendix 18). It is necessary to find the most frequently used baseline word. If we compare the umbrella, raincoat, or garment, we can find that the "raincoat" dataset is very small, with fewer results compared with the "umbrella" data set. As a result, we would better look for a new query, such as "garment", which provides more knowledge.

The last step is to build the concept with text-image generative tool (Midjourney), explore different possibilities of structure. Designers describe function and behavior, AI tool automatically generate different structures and visualize the ideas. Some general tips for the brainstorming are:

- Query iteratively,

- Explore and remember some different verb and noun to describe functions, and prepare for iterative query,
- Write down different random ideas about functions first,
- Do not develop details in the early stage,
- Choose dataset which show more query results.

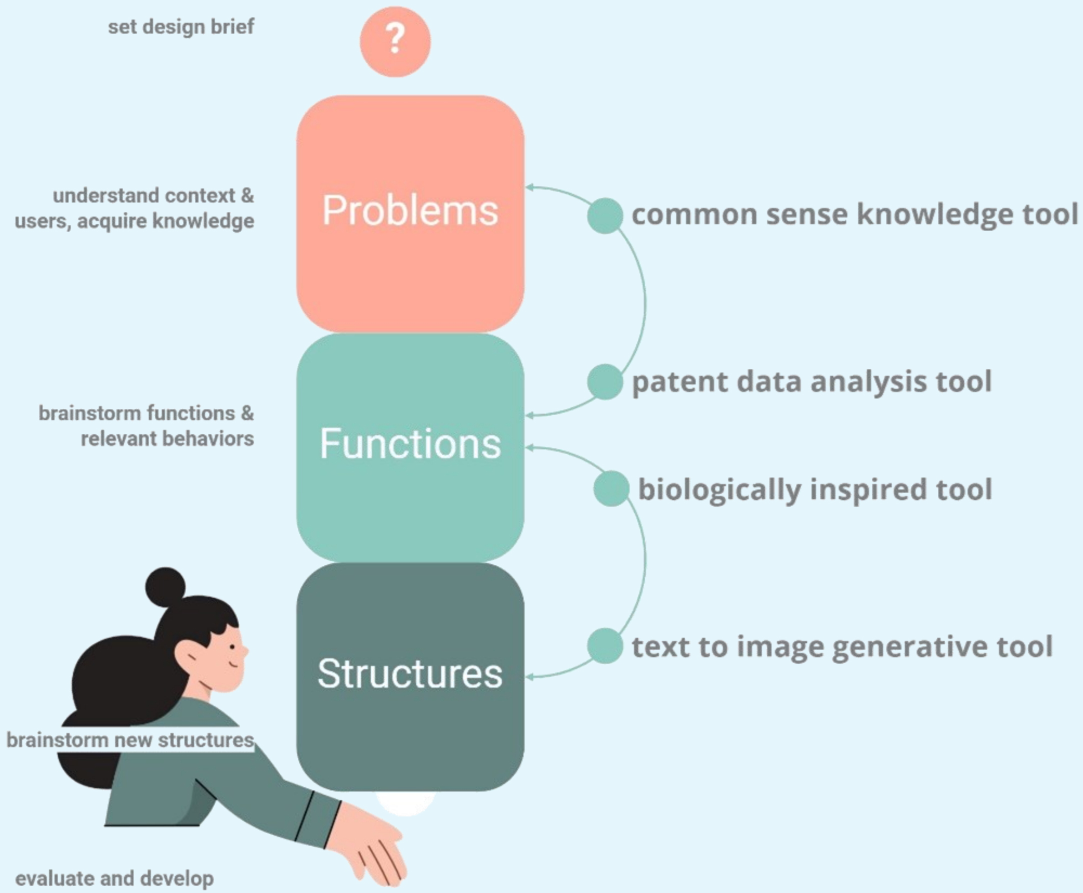

Figure 55 New ideation method with combined tools

6.2.2 An Example of Using New Method

A list of "umbrella" query into common sense tool and patent data tool are shown in Table 16 and Figure 56.

To validate the meaning of one technical term, designers can use a baseline search tool to check the meaning of phrases. For example, I want to know if our existing products are available on the market or if newly invented structures, "retractable greenhouse", "stretcher rib", or "portable painting". They do have different meanings. Portable painting means a moveable construction with a transparent cover that workers paint and coat.

Then, I input some textual stimuli from the above brainstorming process into AskNature website, finding biological inspirations. Both these queries showed more than 24 results (

Table 17). It means that these functional inspirations in the database are in large quantity. Some application examples (

Table 18) are also given as case studies from the tool.

I tried "against wind". The tool showed examples of Animals/ plants keeping their body cool from sun exposure, which are not selected.

Table 16 Exploration of combinational use of common sense tool and patent data tool (ConceptNet, n.d.; SUTD Data-Driven Innovation Lab, n.d.)

Common sense tool provides:	Brainstorming of new functions:
Help keep dry	1. make user dry, dry (verb), dryer(noun)
Your car	2. install on car, provide shelter
An umbrella stand	3. umbrella stands on the ground
Shade bathers	4. shade(noun & verb)
Shield one from sun or rain	5. shield (verb & noun),
Break in high wind	6. do not break in strong wind, how to open?
Be any color	7. Change color?
Union	8. Many umbrella can unite together
Scope	9. Umbrella can extend scope depending on how many people
Weather protection	10. Can know the weather,
Shelter providing artifact	11. Shelter (verb & noun)
Patent data tool provides:	**Brainstorming of new functions:**
Upper umbrella- Double story,	12. Has two layer protection
Multiple fold- easily folded,	13. fold easily

Umbrella rib- stretcher rib,	14. shape stretch with wind,
mini umbrella- Anti windforce,	15. anti wind, provide force to move in the wind
	16. has mini size, easy to carry,
Canopy- tent	17. user walk inside a transparent tent,
Tent- Portable painting	18. paint on the body, prevent water
Collapsible bassinet, infant seat-	19. protect for small baby, provide seat and rain cover,
Retractable greenhouse	20. keep warm, retractable greenhouse shape,

Useful verbs inspired from previous steps :
Dry, Stretch, Shelter, Shade, Shield, Extend the size, Protect from water, Fold easily, Against wind, Change color, Change shape, Unit in the rain, Know the weather, Provide force, Keep warm, Protect baby, Has double layer to protect

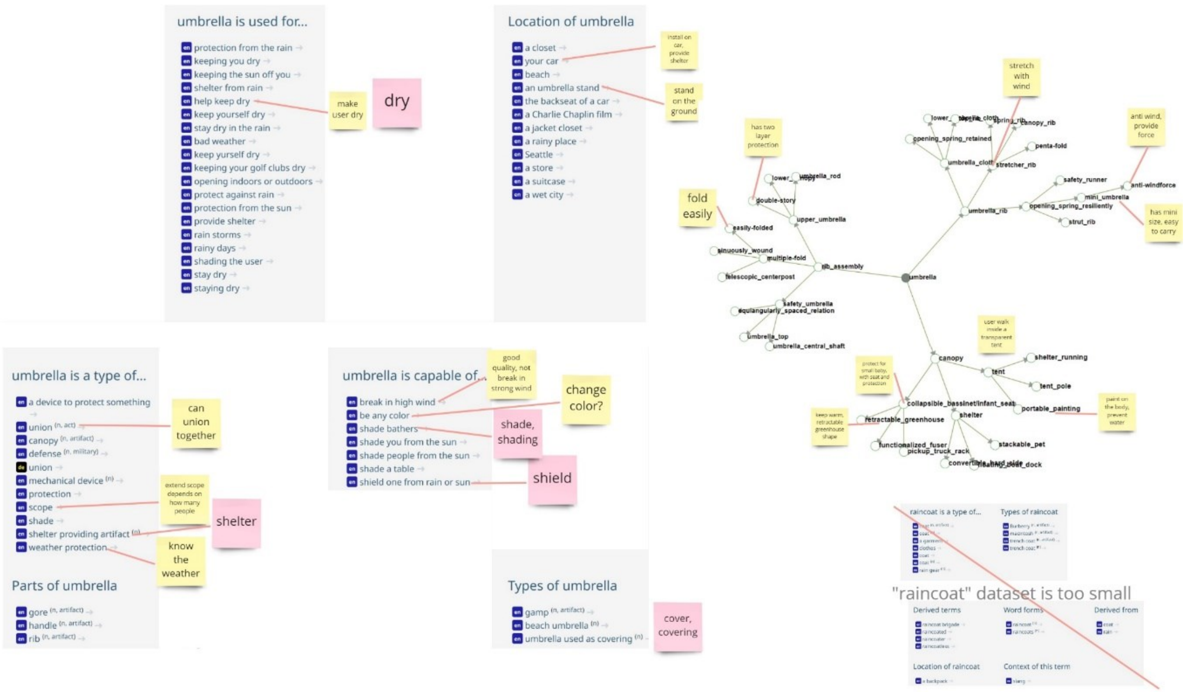

Figure 56 Example of using common-sense tool and patent data tool

Table 17 Biological design inspirations from AskNature website (the Biomimicry Institute, n.d.)

Inputs:	Biological Inspirations:	Functions:
Protect from rain	Structures of flowers protect their pollen from rain by various physical structures.	Protect From Excess Liquids, Modify Size/ Shape/ Mass/ Volume, Modify Position, Adapt Phenotype,
Protect from rain	The wings of a clearwing butterfly provide camouflage because they lack scales, allowing whatever background the butterfly has landed on to show through its wings.	Optimize Shape/Materials, Protect From Animals, Physically Assemble Structure, Modify Light/Color, Modify Material Characteristics
Protect from rain	Pill millipedes protect themselves from predators by rolling their jointed skeletons into a ball	Protect From Animals, Manage Impact, Modify Size/Shape/Mass/Volume
Protect from rain	The feathers of doves and other birds shed water due to nanoscale grooves on their surfaces.	Protect From Excess Liquids
Protect from rain	Pollen grains of flowering plants are protected because of a stable, rot-resistant outer rind.	Protect From Excess Liquids, Protect From Microbes, protect From Fungi
Dry	Skin of blowfly maggots grows more waterproof as it dries because it forms strong, stable, cooperative structures when water is reduced.	Modify Material Characteristics
Dry	Quick movement dries mammalian fur by ejecting droplets using centripetal force.	Modify Material Characteristics, Expel Liquids, Maintain Homeostasis, Protect From Excess Liquids, Protect From Temperature,
Dry	Air bubbles on the foot of the green dock beetle enhance foot grip by providing a dry area on underwater surfaces.	Move in/on Liquids, Attach Temporarily
Dry	Fur of mammals is optimally dried by changing shaking frequency.	Protect From Excess Liquids

Keep warm,	Ectotherms keep their temperatures from dropping too low in the cold by heading underground.	Protect From Temperature
Keep warm,	Otters and seals have a two-layer fur system that prevents water penetration and creates an insulating layer.	Maintain Homeostasis, Protect From Temperature,
Keep warm,	Microtubules fray when protective molecules degrade, then grow again when they reform.	Physically Assemble Structure Move in/on Solids, Modify Size/ Shape/ Mass/ Volume, Move in/on Liquids,
Keep warm,	The ears of otters protect from water via ear-flaps.	Move in/on Liquids, Protect from Excess Liquids
Keep warm,	The ribbed underside of the Amazon water lily provides structural support to keep the leaf afloat and sustain small loads.	Prevent buckling

Table 18 Biological design case study of "keep warm" function from AskNature website (the Biomimicry Institute(n.d.)

Inputs:	Biological Design Examples:	Functions:
Keep dry, Keep warm	Nikwax Analogy from Nikwax is a dual-layered fabric that draws water away from the body, helping keep the user dry.	Protect From Excess Liquids, Protect From Wind
Keep warm	SLIPS Zero from Adaptive Surface Technologies has an ultra-thin slippery surface that allows containers to be emptied completely.	Move in/on Liquids, Capture, Absorb, or Filter Liquids, Protect From Temperature

6.3 Conclusions

To answer RQ1: *What are the current effects of using patent data as stimuli to explore creative space in both problem definition and conceptual design phase?*

From the participants' self-report, the tool received positive feedbacks for acquiring new knowledge and divergent ideation. From qualitative analysis on the ideation process, the patent data tool effectively reduced *knowledge-based fixation* in the query stage. Its textual stimuli helped to release *conceptual fixation* to some extent. The stimuli inspired participants with existing solutions directly but did not provide problems nor user context consistently. By clustering ideas by function-behavior-structure categories, the results suggest the overall fixation rate in the that patent data condition did not bypass the baseline condition.

To answer RQ2: *How can designers collaborate with patent data stimuli effectively to explore problems and solutions?*
Patent data tool has its limitations in providing users' needs and transfer abstract knowledge into concepts. Besides, to help designers explore creative space and use the design-by-analogy method, it is limited to use only one tool and single data source to fulfill all these creative requirements. It is valuable to zoom out from the patent knowledge base to broad knowledge base and automated conception tools.

6.4 Limitations

Several limitations in the study need to be addressed. Only three participants joined the pilot tests, and six were involved in the final experiment. Future studies with larger samples are needed to present more opinions in the industrial design community. Participants were in different fatigue conditions during the experiment, which can also influence their brainstorming performances.

Most participants were university graduates or PhD researchers. They were not familiar with the patent data tool. Besides, design-by-analogy demand more cognitive efforts. Evaluating the tool's effect from a limited 20-minute experiment is difficult. More case studies or experiments that endure longer are needed to understand how designers use the tool to brainstorm.

It is unknown how the tool facilitates designers to brainstorm on different function-behavior-structure levels, which can be included in future studies. Designers also need more learnings on how to use design-by-analogy method and think abstractly from the early stage of ideation.

The study uses the function-behavior-structure model to categorize ideas and evaluate fixation rate and knowledge transfer from different domains. It focuses on designing functional elements of an artefact. The model excludes other important human-centered elements in industrial design, such as user journey design or user emotion.

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