공학박사학위논문

# Developing and Validating Design Heuristics Set for a Design Goal X

## A Design Concept Generation Aid

## 디자인 목적에 특화된 디자인 휴리스틱 세트 개발 및 검증

## 제품 컨셉 디자인 보조 도구

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산업공학과

황 동 욱

## Abstract

# Developing and Validating Design Heuristics Set for a Design Goal X: A Design Concept Generation Aid

Dongwook Hwang

Department of Industrial Engineering

The Graduate School

Seoul National University


The development of innovative product design requires designers' capabilities for creative thinking and problem solving. Throughout the whole process of product design, especially in problem definition and concept generation, the designers use various concept generation methods and tools as a means of enhancing designers' capabilities. Among many, concept generation techniques which offer design heuristics (DHs) for inspiration sources have some obvious advantages for innovative product design. Previous research has indicated that DHs are known to be effective for gaining design insights on how other designers have solved similar problems in the past.

Many of the concept generation techniques offer comprehensive or domain general DHs – the DHs are depicted as useful design knowledge for creating or improving systems in general but which particular aspects (i.e.,

design goals or requirements) of a product/designed system each DH intends to help address is not explicitly put forward.

In this study, a new classification scheme of concept generation techniques using DHs is suggested. Concept generation techniques which offer comprehensive design heuristics (i.e., the TRIZ 40 inventive principles and the 77 Design Heuristics) are referred to as comprehensive design heuristics sets (CDHSs). Other concept generation techniques which offer goal-directed design heuristics (i.e., transformation design theory) are defined as design heuristics sets for X (DHSfX) where X represents a particular design goal. Currently, the effect of the DHSfXs on ideation performance has not been rigorously demonstrated and only few studies on comparisons between the DHSfX and other CDHSs currently exist.

The dissertation consisted of four major studies in relation to the research objectives. In research 1, this study aimed to construct a generic development process of the DHSfX. This process consists of keyword search for describing a design goal X, data collection of relevant inventions, and extraction of the underlying design idea. Two example DHSfXs, DHSf_LHM and DHSf_P, were developed as concept generation aids for creating products for limited hand mobility and portable products, respectively. Accordingly, a total of 13 DHs for DHSf_LHM and 25 DHs for DHSf_P have been extracted.

In research 2, the effects of example DHSfXs (i.e., DHSf_LHM and DHSf_P) on the ideation performance were examined against standard brainstorming. The design briefs were to create new Rubik's cube for one handed people and to redesign the current cup noodle into the more portable product. The results of data analyses showed that the DHSfXs influenced more impact on the ideation performance than standard brainstorming. Overall, the DHSfXs can serve as concept generation aids for creative product concept generation activities.

In research 3, a comparative analysis of information content across the example DHSfX (DHSf_LHM), the TRIZ 40 inventive principles and the 77 Design Heuristics was conducted. The analysis was conducted to evaluate practitioners' similarity judgments between the DHs offered by different concept generation techniques. The results of the data analysis showed that the DHs offered by the DHSf_LHM seem to be differentiated with other TRIZ or the 77 Design Heuristics on many occasions. Overall, the development of the DHSfX added unique value to the existing concept generation techniques such as TRIZ and the 77 Design Heuristics, as DHs offered by DHSfXs were perceived as different with other DHs based on the subjective similarity judgment.

In research 4, the effect of the example DHSfX (DHSf_P) on the ideation performance was examined against the TRIZ 40 inventive principles. The data analyses revealed a significant difference between the DHSfX and the TRIZ 40 inventive principles.

This study examined the effect of the DHSfXs for product concept generation design. The results entailed that the DHSfXs could make unique contributions to product design concept generation in addition to other existing concept generation techniques. Also, the study results provided valuable information that it is worth deriving goal specific design knowledge that was not fully discovered by design knowledge offered by other concept generation techniques. Such results may contribute to the future efforts for

systematically producing more DHSfXs for important design goals, and further, constructing a system of a DHSfX.

**Keywords**: Creativity, Design heuristics, Engineering design, Ideation, Product concept generation

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# List of Abbreviations

List of abbreviations are as follows:

| Abbreviation | Definition |
|---|---|
| CDHS | Comprehensive design heuristics set |
| CGT | Concept generation technique |
| DH | Design heuristic |
| DHS | Design heuristics set |
| DHSfX | Design heuristics set for a design goal X |
| DHSf_LHM | Design heuristics set for limited hand mobility |
| DHSf_P | Design heuristics set for portable product design |
| HCD | Human-centered design |
| KJ method | Kawakita Jiro method |
| LTM | Long-term memory |
| SB | Standard brainstorming |
| SIAM | Search for ideas in associative memory |
| WM | Working memory |

# Chapter 1. Introduction

## 1.1 Research background

The development of innovative product design requires designers' capabilities for creative thinking and problem solving. Throughout the whole process of product design, especially in problem definition and concept generation, the designers use various concept generation methods and tools as a means of enhancing designers' capabilities. In this dissertation research, these methods and tools are referred to as concept generation techniques (CGTs).

Among the CGTs, brainstorming (Osborn, 1957) is the most frequently and widely used in the context of product design. The brainstorming is a CGT which encourages free generation of ideas based on designers' own knowledge and its combinations. Is the brainstorming technique best suited for product designers to come up with satisfactory concept generation outcomes? For those who do not have much prior experience in solving design problems, such as novice designers, it may be difficult to consider various solutions because their collective internal knowledge may not be sufficient to allow to generate creative solutions.

Some other CGTs are introduced to supplement the lack of internal knowledge and experience. One of the prominent CGTs is TRIZ (Altshuller, 1996). TRIZ is a creative problem-solving methodology especially tailored for scientific and engineering problems. It provided design strategies or guidelines (i.e., 40 inventive principles, separation principles, etc.) to which the designers are able to apply to their own design project. In this dissertation research, such design strategies or guidelines are referred to as design heuristics (DHs). Empirically derived from analyzing past examples of design solutions, DHs are known to be effective for gaining design insights on how other designers have solved similar problems in the past (Birdi, Leach, & Wissam, 2012; Chang et al., 2016; Daly et al., 2012; Dumas & Schmidt, 2015; Glier et al., 2014; Hernandez et al., 2014; Hernandez, Schmidt, & Okudan, 2013; Howard, Culley & Dekoninck, 2011; Ogot & Okudan, 2007; Okudan, Ogot, & Shirwaiker, 2006; Yilmaz et al., 2012; Yilmaz et al., 2014; Yilmaz et al., 2015; Yilmaz et al., 2016; Yilmaz, Seifert, & Gonzalez, 2010). In this study, existing CGTs offering such DHs are defined as a design heuristics set (DHS).

Developing DHSs offers some obvious advantages for innovative product design. First, with the utility of DHs, it is possible for designers to rapidly generate a variety of possible solution alternatives as the information offered by DHs comes from the analysis of previous inventions. This wide exploration of searching for solutions may lead to creative insight on solving design problems. Second, designers may use the set of DHs as a tool to overcome individual designers' limited experience. Designers who create revolutionary products which may have unforeseen form factors require information on precedents and design strategies from which designers recognize on how to satisfy a specific design goal. Therefore, designers may have benefits by learning from the others as insight is strongly guided by lessons learned from others' experiences and observations.

## 1.2 Research gap

Previous research efforts have been made concerning the development and utilization of DHSs potentially useful for solving complex design problems and creating innovative artifacts. Some of the well-known DHSs including SCAMPER (Eberle, 1996), the TRIZ 40 inventive principles (Altshuller, 1996), the 77 Design Heuristics (Daly et al., 2012; Yilmaz et al., 2012; Yilmaz et al., 2014; Yilmaz & Seifert, 2011; Yilmaz, Seifert, & Gonzalez, 2010), transformation design theory (Singh et al., 2009; Singh et al., 2007; Weaver et al., 2010; Weaver, Wood, & Jensen, 2008) and DHSfXs (Hwang & Park, 2015) have been adopted in various product concept generation projects.

The existing DHSs can be grouped into two large categories according to the characteristics of DHs. The first category consists of the ones providing DHs without specifying their purposes – the DHs are depicted as useful design knowledge for creating or improving systems in general but which particular aspects (i.e., design goals or requirements) of a product/designed system each DH intends to help address is not explicitly put forward. Thus, the designer/problem solver with a particular design problem specified in terms of design goals would have to apply each DH to the problem on a trial basis without having a prior knowledge on its likelihood of leading to success.

The second category consists of the DHSs providing DHs aimed at addressing a specific, single design goal, for example, 'providing an ability to transform' or 'enhancing portability.' Such DHSs are constructed by identifying DHs that are known to be useful for devising solutions that meet the design goal.

The current study refers to DHSs belonging to the former as comprehensive DHSs (CDHSs) in that the DHs represent a collection of knowledge for potentially addressing a variety of design challenges and their purposes are not narrowly pre-specified, and the latter as DHSs for X (DHSfX) where X represents a particular design goal. SCAMPER and the 77 Design Heuristics can be regarded as CDHSs. Transformation design theory, design guidelines for product flexibility (Tilstra et al., 2015), and portability design heuristics (Hwang & Park, 2015) are DHSfXs as each of them targets a particular design goal. TRIZ 40 inventive principles were originally conceptualized as a collection of DHSfXs – the TRIZ contradiction matrix defined a set of contradictions between engineering parameters and specified which of the 40 principles could be utilized for resolving each contradiction type. However, many TRIZ practitioners seem to use the 40 inventive principles as a CDHS without utilizing the contradiction matrix.

The effect of the CDHS has been empirically demonstrated in many previous studies: multiple studies demonstrated the effect of TRIZ on the ideation performance (Birdi, Leach, & Wissam, 2012; Chang et al., 2016; Dumas & Schmidt, 2015; Glier et al., 2014; Hernandez et al., 2014; Hernandez, Schmidt, & Okudan, 2013; Howard, Culley, & Dekoninck, 2011; Ogot & Okudan, 2007; Okudan, Ogot, & Shirwaiker, 2006). Some other studies have demonstrated the effect of the 77 Design Heuristics on ideation performance – they conducted an empirical investigation of the 77 Design Heuristics in terms of the level of expertise, background knowledge, group and individual performance difference (Daly et al., 2012; Yilmaz et al., 2012; Yilmaz et al., 2014; Yilmaz et al., 2015; Yilmaz et al., 2016; Yilmaz, Seifert, & Gonzalez, 2010). These empirical findings suggest that the

CDHSs in general are effective in generating creative outcomes, and are validated its impact on ideation performance as compared with brainstorming or without any aids.

The concept of the DHSfX has been recently introduced. Due to the newly emerging concept of the DHSfX, its effect on ideation performance has not been rigorously demonstrated. Only few studies are currently existing. Additionally, a new classification scheme of DHSs into the DHSfX and the CDHS is suggested; as a consequence, only few studies on comparisons between the DHSfX and other CDHSs exist – I am not aware of any. Thus, the effect of utilizing 'goal-directed' information (DHs) and benefits of utilizing 'goal-directed' information over utilizing 'comprehensive ones' for creative concept generation have not been discussed.

In this regard, some fundamental research questions still remain to be addressed. Four research questions are as follows:

- How can we develop a DHS specifically for a design goal X?
- Does a DHSfX offer useful information for enhancing designers' creative thinking as compared with other non-DH-based CGTs?
- What are the similarities and differences between a DHSfX and a CDHS?
- Would a DHSfX help designers produce better outcomes than a CDHS when solving a design problem given with a particular design goal X?

To address the above research questions, a series of research studies will be conducted to do so. The first question relates to a generic process of constructing a DHSfX. In the past, several methods for the development process of DHs have been introduced (Fu, Yang & Wood, 2016); however, the DHs are not aimed at satisfying a particular design goal X. This study provides a generic process of constructing the DHSfX. The second question above pertains to the lack of empirical studies that confirm the utility of DHSs in performing concept generation, especially in comparison with non-DH-based CGTs such as standard brainstorming. Obtaining an empirical evidence that the use of DHs improves ideation outcomes is an important step towards further research on the development and utilization of DHSfXs. This dissertation research develops two DHSfXs, DHSf_LHM and DHSf_P, for the design goals of creating assistive products for the individuals with limited hand mobility and creating portable products, respectively. The utility of the DHSfXs with different design goal Xs is demonstrated in this study. The third and fourth questions are concerned with the possible advantages of DHSfXs in comparison with the existing CDHSs. If a DHSfX produces better outcomes than the other CDHS when solving a problem with a particular design goal X, it will justify future efforts for systematically producing more DHSfXs for important design goals, and, eventually, constructing a system of DHSfXs. Also, understanding the differences between the DHSfX and the other CDHS in ideation outcomes may help develop effective strategies for concept generation.

## 1.3 Research objectives

This dissertation research introduces a new DHS for product design concept generation. The main purpose of this research is to identify a set of useful DHs for achieving a particular design goal X and explore how their use may impact creative thinking in product design concept generation. This study proposes a generic process for developing DHs for a particular design goal X to be achieved, and evaluates their utilities on an empirical basis in the context of real world design problems. The specific objectives of this dissertation are as follows:

- To introduce a DHS for a particular goal X (DHSfX) as an approach to concept generation in product design,
- To compare the effects of the DHSfXs and standard brainstorming on creative ideation outcomes,
- To perform a comparative analysis of DH contents between the DHSfX and two CDHSs (i.e., the TRIZ 40 inventive principles and the 77 Design Heuristics), and
- To evaluate the effect of the DHSfX and compare it against the TRIZ 40 inventive principles on the basis of empirical evidence.

## 1.4 Organization of the Thesis

This dissertation consisted of four major studies in relation to the research objectives presented in Chapter 1.3. In research 1, a generic process of developing a DHSfX was introduced. In research 2, the effects of two DHSfXs on ideation performance measures were examined against standard brainstorming. In research 3, the difference between an example DHSfX and CDHSs in terms of DH contents was analyzed. In research 4, the effect of an example DHSfX on ideation performance was examined against one of the CDHSs, the TRIZ 40 inventive principles. The overall structure of this dissertation took the form of eight chapters (Figure 1.1). Brief descriptions of the chapters were presented below.

In Chapter 1, research background and purposes of the study were described. The overall structure of this study was also presented.

In Chapter 2, the definition of the DH, and new classification scheme of DHSs were presented. Previous studies on the effects of DHSs including CDHSs and DHSfXs were also reviewed.

In Chapter 3, a generic process of developing a DHSfX was introduced, and two DHSfXs, one for creating assistive product for individuals with limited hand mobility (DHSf_LHM) and the other for creating new portable product (DHSf_P), were derived from analyses of existing inventions and patents. A three-step process for constructing the DHSfX and its application during ideation tasks were discussed.

In Chapter 4, the effects of example DHSfXs on ideation performance were examined against standard brainstorming. Two case studies on the effects of DHSf_LHM and DHSf_P were conducted for the empirical purpose.

In Chapter 5, a comparative DH content analysis between the DHSf_LHM and two CDHSs (i.e., the TRIZ 40 inventive principles and the 77 Design Heuristics) was conducted. The difference in DH contents across the DHSf_LHM and the two CDHSs was examined on the basis of designers' perception.

In Chapter 6, the effect of an example DHSfX on ideation performance against the TRIZ 40 inventive principles was examined. Especially, the DHSfX for portable product design (DHSf_P) was illustrated for the empirical purpose.

Finally, a brief summary and implications of the study were presented in Chapter 7. Some limitations of this study were also described along with future research ideas.

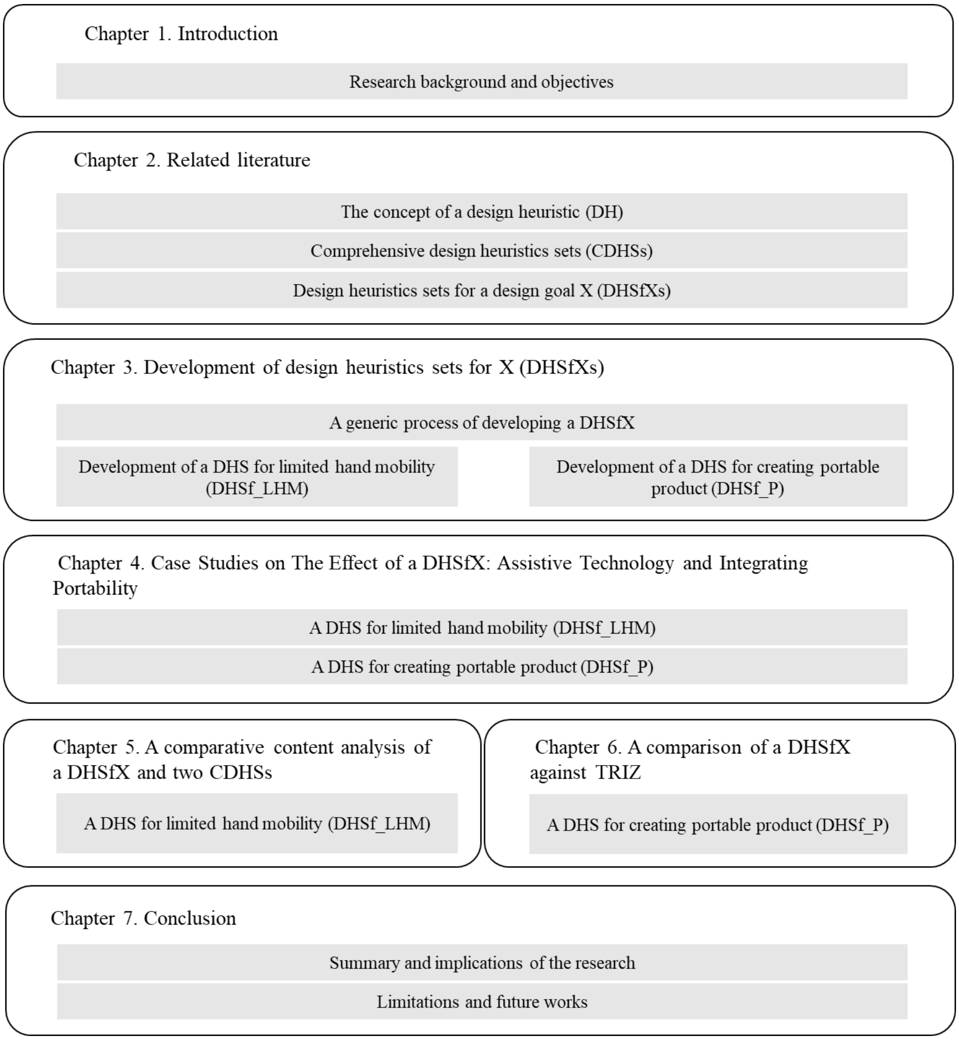



**Figure 1.1** The overall structure of the dissertation

# Chapter 2. Related literature

## 2.1 The concept of a design heuristic (DH)

Heuristic, by definition, refers to using experience to learn and improve; involving or serving as an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods (Heuristic, 2016). A heuristic method helps rapidly arrive at a solution that is reasonably close to the best possible answer.

In engineering, a heuristic acts as an experience-based problem solving aid. Employing such heuristics can reduce the time it takes to solve problems, which may be very valuable. For example, TRIZ is a powerful theory for solving inventive design problems, which was developed through extensive analyses of previous technological innovations (patents) across many different fields of engineering (Altshuller, 1996). It provides a variety of design heuristics (e.g., TRIZ 40 inventive principles) for solving problems represented in the form of contradictions.

In operations research, a heuristic estimate is used to provide a better guess for shortest path searches. Heuristics are intended to gain satisfactory estimates, potentially at the cost of accuracy or precision.

In usability testing, a heuristic evaluation is an informal method of usability analysis where a number of evaluators are presented with an interface design and asked to comment on it (Nielsen & Molich, 1990). The nine basic usability principles from Molich and Nielsen (1990) were introduced as the basis for practical heuristic evaluation. They include ‘simple and natural dialogue,’ ‘speak the user’s language,’ ‘minimize user memory load,’ ‘be consistent,’ ‘provide feedback,’ ‘provide clearly marked exists,’ ‘provide shortcuts,’ good error messages,’ and ‘prevent errors.’

In decision making, human judgment depends on simplified heuristics. Kahneman, Slovic, and Tversky (1982) identified three heuristics that can be applied in thinking and decision making under uncertainty: representativeness, availability, and affect heuristics. The availability heuristic involves making decisions based upon how easy it is to bring something to mind. Some frequently-occurring or easily achieved information is more readily available in memory, so that people will likely judge and make decisions based on the availability. The representativeness heuristic involves making a decision by comparing the present situation to the most representative mental prototype. The affect heuristic involves making choices that are strongly influenced by the emotions that an individual is experiencing at that moment.

Across a few disciplines, the concept of the heuristic shares a common definition, that is, an educated guess based on one’s own experience. As a means for solving problems, heuristics provide necessary knowledge in situations where the optimal solution cannot be formally derived, but educated guesses to satisfactory solutions are required.

In the context of product design, a DH can be defined as a context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provided design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution (Fu, Yang, & Wood, 2016). The DH is also considered ‘rules of thumb’ (Nisbett & Ross, 1980), an explicit rule derived from human experiences and tacit knowledge (Bolc & Cytowshi, 1992), an educated guess, intuitive judgment, a strategy (Pearl, 1984), short-cut (Yilmaz et al., 2012) or simply common sense (Rechtin & Maier, 2010). It is expected that designers will be able to benefit from the use of DHs in the context of product innovation because DHs may provide designers with some well-educated guesses to satisfactory design solutions.

## 2.2 Comprehensive design heuristics sets (CDHSs)

Previous research efforts have been made on the creation of various CDHSs. Some of the CDHSs found in the literature include SCAMPER, the 77 Design Heuristics and the TRIZ 40 inventive principles.

### 2.2.1 SCAMPER

SCAMPER provides a set of operators with a set of idea prompting questions that redirect analogical search to solve a problem. SCAMPER is an acronym for (S) Substitute, (C) Combine, (A) Adapt, (M) Modify/Magnify/Minimize, (P) Put to other uses, (E) Eliminate, and (R) Reverse/Rearrange (Eberle, 1996).

The effect of SCAMPER on ideation performance was demonstrated in previous studies (Chulvi et al., 2013; López-Mesa et al., 2011; Moreno et al., 2016). In the work of Chulvi et al. (2013), SCAMPER has been shown to help generate more feasible and high-quality ideas than brainstorming and ideation without any aids. López-Mesa et al. (2011) showed that SCAMPER questions helped teams to produce non-obvious solutions at the action function level, since the two types of teams, innovative and adaptive, produced a higher percentage of non-obvious solutions when inspired by SCAMPER. Moreno et al. (2016) conducted a study in which the effect of SCAMPER and WordTree on the degree of creativity was demonstrated. It was found that both SCAMPER and WordTree provided defixation capabilities and enhanced designers' creativity during concept generation activities.

### 2.2.2 The 77 Design Heuristics

The 77 Design Heuristics were developed as a CGT by analyzing past award-winning innovative products and identifying recurring solution principles (Daly et al., 2012). The CGT provides a total of 77 DHs that may be useful for addressing various design problems. They were intended to help designers better explore the solution space and develop non-obvious solutions.

The previous empirical investigations demonstrated that the 77 Design Heuristics were effective at generating creative and distinct design solutions (Daly et al., 2012; Daly et al., 2016; Yilmaz et al., 2012; Yilmaz et al., 2015; Yilmaz et al., 2016; Yilmaz, Seifert, & Gonzalez, 2010). Daly et al. (2012) showed that the concepts created without the 77 Design Heuristics were less developed, and were often replications of known ideas or minor changes to existing products. However, concepts created using the 77 Design Heuristics resulted in more developed, creative designs. Daly et al. (2016) compared three different CGTs: brainstorming, morphological analysis and 77 Design Heuristics. It was found that the elaboration of the concepts and the practicality were significantly higher using the 77 Design Heuristics. Yilmaz et al. (2012) found that using the 77 Design Heuristics helped students generate more creative, and more diverse concepts. Yilmaz et al. (2015) conducted a study in which the effect of the 77 Design Heuristics in differing disciplines was examined. The results showed frequent use of the 77 Design Heuristics in both mechanical designers and industrial designers and a significant relationship to the rated creativity of the concepts. Yilmaz et al. (2016) examined outcomes from a classroom study and found that concepts created using the 77 Design Heuristics were rated as more creative and varied. Yilmaz, Seifert, and Gonzalez (2010) found that the 77 Design Heuristics appeared to help the participants 'jump' to a new problem space, resulting in more varied designs, and a greater frequency of designs judged as more creative.

To summarize the literature stated above, several studies that analyzed the effects of the 77 Design Heuristics in engineering design contexts. However, only few studies have compared the 77 Design Heuristics to the existing, prominent approaches to concept generation in the context of product design.

### 2.2.3 The TRIZ 40 Inventive Principles

TRIZ has been widely recognized as a systematic concept generation methodology that can help generate novel solutions to problems by using the condensed knowledge (patents) of past inventors. TRIZ developed by Altshuller and colleagues provides standard and recursive inventive solutions depending on the characteristics of engineering systems which can be described by engineering parameters that quantify certain aspects of the design. These parameters are given in Table 2.1. By reformulating the problems in terms of the engineering parameters, Altshuller identified the solution ideas used in each invention and distilled them into the TRIZ 40 inventive principles. These principles are summarized in Table 2.2.

**Table 2.1** 39 engineering parameters

| | | | |
|---|---|---|---|
| 1 | Weight of moving object | 21 | Power |
| 2 | Weight of stationary object | 22 | Energy loss |
| 3 | Length of moving object | 23 | Substance loss |

| | | | |
|---|---|---|---|
| 4 | Length of stationary object | 24 | Information loss |
| 5 | Area of moving object | 25 | Waste of time |
| 6 | Area of stationary object | 26 | Quantity of a substance |
| 7 | Volume of moving object | 27 | Reliability |
| 8 | Volume of stationary object | 28 | Accuracy of measurement |
| 9 | Velocity | 29 | Manufacturing precision |
| 10 | Force | 30 | Harmful actions affecting the design |
| 11 | Stress or pressure | 31 | Harmful actions generated by the design project |
| 12 | Shape | 32 | Manufacturability |
| 13 | Stability of object's composition | 33 | User friendliness |
| 14 | Strength | 34 | Repairability |
| 15 | Duration of action generalized by moving object | 35 | Flexibility |
| 16 | Duration of action generalized by stationary object | 36 | Complexity of design object |
| 17 | Temperature | 37 | Difficulty |
| 18 | Brightness | 38 | Level of automation |
| 19 | Energy consumed by moving object | 39 | Productivity |
| 20 | Energy consumed by stationary object | | |

**Table 2.2** TRIZ 40 inventive principles

| | | | |
|---|---|---|---|
| 1 | Segmentation | 21 | Rushing through |

| | | | |
|---|---|---|---|
| 2 | Removal | 22 | Turning harm into good |
| 3 | Local quality | 23 | Feedback |
| 4 | Asymmetry | 24 | Go between |
| 5 | Joining | 25 | Self-service |
| 6 | Universality | 26 | Copying principle |
| 7 | Nesting | 27 | Inexpensive short life |
| 8 | Counterweight | 28 | Replacement of a mechanical pattern |
| 9 | Preliminary counteraction | 29 | Hydraulic or pneumatic solution |
| 10 | Preliminary action | 30 | Flexible or fine membranes |
| 11 | Protection in advance | 31 | Use of porous materials |
| 12 | Equipotentiality | 32 | Use color |
| 13 | Opposite solution | 33 | Homogeneity |
| 14 | Spheroidality | 34 | Discarding and regenerating parts |
| 15 | Dynamism | 35 | Altering an object's aggregate state |
| 16 | Partial or excessive action | 36 | Use of phase changes |
| 17 | Moving to a new dimension | 37 | Application of thermal expansion |
| 18 | Use of mechanical vibrations | 38 | Using strong oxidation agents |
| 19 | Periodic actions | 39 | Using an inert atmosphere |
| 20 | Uninterrupted useful action | 40 | Using composite materials |

The engineering parameters can be used to formulate the technical contradictions within a system. Technical contradictions refer to the standard engineering trade-offs (i.e., improvement in one parameter to make an aspect of the system better resulting in another aspect of the system becoming worse). The contradiction matrix recommends inventive principles for a typical technical contradiction. A portion of the matrix is shown in Table 2.3. Note that the column headings represent the worsening engineering parameters in the contradiction and the row headings represent the improving parameters. The recommended inventive principles are listed at the intersection of a particular row and column. For example, in a design situation where increasing the speed of an object (improving parameter) will result in a heavier moving object (worsening parameter), inventive principles such as ‘removal’ of unnecessary parts and opposite solution can be considered to resolve the contradiction instead of compromising on both parameters (i.e., speed and weight). Then, ideators should use recommended inventive principles with standard brainstorming to come up with new concepts to address the design problem. They must restrict themselves only to ideas that fall within the current inventive principle under consideration. In the event that a solution cannot be found from the recommended inventive principles, the ideators should consider all 40 inventive principles.

**Table 2.3** Contradiction matrix fragment: Improving engineering parameters 1-6 vs. Worsening engineering parameters 1-6

| Improving / Worsening | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | - | | 15, 8, 29, 34 | | 29, 17, 38, 34 | |
| 2 | | - | | 10, 1, 29, 35 | | 35, 30, 13, 2 |
| 3 | 8, 15, 29, 34 | | - | | 15, 17, 4 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 | | 35, 28,<br>40, 29 | | - | | 17, 7<br>10, 40 |
| 5 | 2, 17,<br>29, 4 | | | | - | |
| 6 | | 30, 2,<br>14, 18 | | 26, 7<br>9, 39 | | - |

TRIZ has repeatedly been demonstrated empirically to improve design ideation performance (Birdi, Leach, & Wissam, 2012; Chang et al., 2016; Dumas & Schmidt, 2015; Gero, Jiang, & Williams, 2013; Glier et al., 2014; Hernandez et al., 2014; Hernandez, Schmidt, & Okudan, 2013; Ogot & Okudan, 2007; Okudan, Ogot, & Shirwaiker, 2006). The main findings of the previous research are described as follows:

- Birdi, Leach, and Wissam (2012) found that engineers who received TRIZ-based creativity training program displayed better performance in creative problem-solving than the non-trained group of engineers.
- Chang et al. (2016) studied the effect of TRIZ on engineering students' creative performance and revealed that TRIZ enhanced creativity with which the students designed products, including their ability to develop and implement novel ideas.
- Dumas and Schmidt (2015) found that TRIZ instruction significantly increased the novelty of participant's generated solutions and that the degree of the increase in the novelty of a participant's generated ideas was linked to their relational reasoning ability.
- Gero, Jiang, and Williams (2013) conducted an experimental study, in which the students' design cognition was affected by the degree of structuredness of the CGTs they applied in their designing. The

more structured a CGT is, the more likely that designers tend to focus more on problem-related aspects of designing. Among CGTs such as brainstorming, morphological analysis and TRIZ, TRIZ was considered the most structured.

- Glier et al. (2014) conducted an experiment in which a directed approach (i.e., bioTRIZ) is more useful in engineering design than intuitive ideation methods. Also, this study revealed no significant difference in the performance of novice designers using no CGT and the directed approach in terms of the quantity of non-redundant ideas and the quality, novelty, and variety of solutions generated.
- Hernandez et al. (2014) showed that the TRIZ 40 inventive principles improved students' ideation performance in terms of the novelty and variety of concepts generated.
- Hernandez, Schmidt, and Kremer (2013) found that the TRIZ instruction led to significant gains (novelty) in students' ability to redesign traffic lights to reduce snow build-up.
- Ogot and Okudan (2007) found that teams using the TRIZ method produced more unique solutions compared to other teams without any aids, along with more feasible concepts.
- Okudan, Ogot, and Shirwaiker (2006) compared TRIZ and brainstorming used together with using brainstorming alone in terms of ideation effectiveness. Results indicated significant gains in novelty when TRIZ is used with brainstorming.

Previous studies have conducted comparative analyses of TRIZ against existing CGTs such as brainstorming and idea checklists which call upon the designer to look inward for inspiration. Unlike brainstorming and similar CGTs, TRIZ provides designers to use a set of readily accessible knowledge for inspiration. TRIZ ensures that designers perform concept generation using the existing techniques, which others have previously used for solving a similar general design problem, in a systematically directed manner. Drawn from solution patterns and standard inventive principles synthesized from design knowledge contained in thousands of patents, TRIZ supplements the limited knowledge the designer may have by suggesting possible solution directions applicable to the current design problem.

Previous studies have also investigated the effect of TRIZ compared with existing CGTs that provide some knowledge for inspiration (Chulvi et al., 2013; Howard, Culley, & Dekoninck, 2011). Chulvi et al. (2013) studied the effects of TRIZ, SCAMPER, brainstorming, and no method on concept novelty and utility. According to the study, brainstorming produced the best creative outcomes; TRIZ produced solutions with more novelty but similar utility than SCAMPER. Howard, Culley, and Dekoninck (2011) found that the TRIZ 40 inventive principles with the contradiction matrix provoked creative stimuli; however, internally sourced stimuli were shown to provide useful and more practical alternatives than TRIZ.

Overall, TRIZ seems to have benefits for supporting creative ideation performance; however, it remains unclear whether the TRIZ 40 inventive principles offer more useful knowledge when facing a specific design goal to resolve as compared to DHSfX.

## 2.3 Design heuristics sets for a design goal X (DHSfXs)

Transformation design theory (Singh et al., 2009; Weaver et al., 2008; Weaver et al., 2010) offers a set of transformational principles and facilitators for developing transforming/state-changing products. The transformation design principles and facilitators are heuristic rules that are extracted by studying key design features and functional elements that make up a transforming product. The principles describe different ways in which transformation is achieved, and the facilitators are design constructs that aid in transformation. The principles are validated and applied to conceptualize transforming products as part of an innovative design process (Camburn et al., 2010; Singh et al., 2009; Singh et al., 2007; Skiles et al., 2006; Wang et al., 2009; Weaver et al., 2008; Weaver et al., 2010). The effect of the transformation design theory has been empirically investigated that using the transformation design theory increased the number of concepts (Weaver et al., 2009).

Currently, the lack of empirical studies that confirm the utility of the DHSfX approaches in performing design concept generation exist. It is possible to hypothesize that the new design knowledge (DHs) offered by the DHSfX help break out the routine thoughts. A comparison between the DHSfX and standard brainstorming, which is one of the most widely used CGTs has not been investigated yet. Related to this, the following hypothesis is going to be tested in this study: designers who utilize the DHSfX as a CGT would perform better outcomes than others who utilize standard brainstorming.

The DHSfX and the CDHS differ in the scope of the targeted design problems, and, may have relative strengths and weaknesses. It is possible to hypothesize that for design problems involving a design goal X, a DHSfX in general may produce better ideation outcomes than a CDHS. However, no empirical evidence is currently available that supports this claim. One objective of the current study is to test this hypothesis on the basis of empirical data.

# Chapter 3. Development of design heuristics sets for X (DHSfXs)

## 3.1 Introduction

Providing information about the existing inventions (products, services, processes, etc.) may greatly help ideators perform product design concept generation. It may be due to the fact that the existing inventions may represent excellent design outcomes produced through systematic research and hard work of previous design experts. Thus, each of the existing inventions can be thought of as containing one or more useful design principles/ideas. By analyzing existing inventions, designers may discover useful design ideas or DHs. Such analysis of existing inventions is one of the most promising, DH extraction methods.

In previous research, a few other methods for extracting DHs have been introduced. According to a review paper by Fu, Yang, and Wood (2016), the DHs have been extracted from the following methods: observations from experts or their experience, derivation from design practice or existing principles, and analysis of design repositories/empirical data sets.

However, the lack of knowledge on how to extract DHs for addressing a particular design goal X has not been considered. As the DHs offered by DHSfXs are more likely focused on involving a particular design goal X (i.e., creating new transformers, creating portable products, etc.), the development process of constructing DHSfXs may require to collect data related to the specific design goal.

Proposing a process of constructing goal-directed DHs may be beneficial for creative concept generation due to the following reasons: first, by adopting a generic development process, the DHSfX may provide DHs with a consistent level of relevance to the specific design goal. Consequently, a variety of DHSfXs can be developed while addressing various design goal Xs in a more consistent manner. Second, systematically adding new inventions into the process of constructing the DHs may benefit from updating the up-to-date, useful design knowledge for addressing the design goal X. This would make it possible to further expand goal-directed design knowledge efficiently and effectively, and thus, help designers explore wide solution space.

Despite the benefits, to the authors' best knowledge, the development process of DHs aimed at satisfying a particular design goal has not yet been introduced. This current study introduced a three-step procedure of constructing the DHSfX, and developed two example DHSfXs representing different product domains: assistive products and portable products for further empirical evaluation purposes.

## 3.2 A generic process of developing a DHSfX

A three-step process was developed for empirically constructing a DHSfX for product design concept generation. The design goal X can be assumed to be specified as: 'creating a transformer or improving a product's portability.' The generic process is described in the following.

### *Phase 1: Selecting search keywords and databases*

The DHSfX development process starts with determining relevant search keywords for finding example products and patents that successfully accomplishes the given design goal X. This keywords selection is important as it determines the search outcome, and, in turn, the quality of DHs extracted from them.

This study proposes utilizing three categories of keywords for the examples searches. The first category consists of words describing 'product,' and their synonyms and related words – both the singular and plural forms of the words are included. Thesauri, such as Roget's thesaurus (Jarmasz, 2004) and Wordnet (Budanitsky & Hirst, 2006), can be used to identify the synonyms and related words. Some words for the first words category include: product, device, invention, apparatus, appliance, tool, mechanism, contraption, contrivance, gadget, accessory, commodity, goods, ware, concoction, innovation and novelty.

The second keywords category consists of adjectives and nouns describing the design problem situation, for examples, the disabling condition for the disabled utilizing assistive products and the product's condition for realizing portability. The synonyms and related words can be identified by examining encyclopedia and possibly medical dictionaries. Also, relevant keywords can be identified from consulting domain experts.

The third category is composed of words describing target users of the product and their synonyms – both the singular and plural forms of the words are included. Again, thesauri can be used to identify the synonyms. The third category may be necessary if the target user group exists for a specific product usage.

The search formula combines the keywords within each category with the Boolean operator OR, and, then, further connects the resulting expressions for the three keywords categories with the operator AND as follows: ((the expression for the first category) AND (the expression for the second category) AND (the expression for the third category)).

Along with the search keywords, adequate databases need to be chosen for the examples searches. The most relevant ones are available product databases. Also, internet search engines (e.g., the Google search engine) and patent databases (e.g., the US Patent and Trademark Office [USPTO] database) can help identify relevant examples.

### *Phase 2: Collecting and pre-processing examples data*

After the selection of search keywords and databases, searches are conducted to retrieve documents describing example products and patents. Then, the retrieved documents are screened using predetermined inclusion/exclusion criteria. This study recommends selecting only those documents that 1) describe relevant and commercially successful/available/promising inventions and 2) provide a detailed account of how the inventions addressed their predecessors' limitations, that is, previous situations where the original products' usage is being limited. In addition to the screening, duplicate examples or examples that are very similar to one another in terms of functions, behaviors and structure are consolidated.

The documents describing the example products and patents are in different formats. They are converted into a standard format, each of which contains sections for describing: 1) the limitations recognized in the invention's precedents and 2) the underlying design idea based on which the invention addresses the precedents' limitations and accomplishes the design goal. The formatting process can help the analysts understand the inventions (Ross, 2006) and facilitate the ensuing data processing for discovering design heuristics.

In the standard format above, the 'underlying design idea' of an invention corresponds to the structure and/or behavior of the invention, in terms of the Function-Behavior-Structure (FBS) ontology of design objects proposed by Gero (1990) – in the FBS ontology, structure describes the components of a design object and their relationships, and, behavior, the attributes that are derived (or are expected to be derived) from the structure of the object. Function, on the other hand, corresponds to the teleology of the object, which, in the context of the DHSfX construction process, is the 'X.'

### *Phase 3: Discovering design heuristics using the Kawakita Jiro (KJ) method*

The example inventions (products and patents) collected in Phase 2 are analyzed to discover DHs. A team of product designers or experts in related domains work together to conduct the analysis. The analysis procedure is a modification of the widely used Kawakita Jiro (KJ) method (Kawakita, 1991). The KJ method helps analysts organize a large amount of unordered language data and discover patterns and meanings hidden in the dataset through inductive reasoning. The analysis procedure is described in the following:

Step 1. For each invention, a card is prepared that describes how it resolves its predecessors' limitations and accomplishes the design goal X. The description in each card should be concise and easy to understand; it may contain graphical illustrations. The standard format used for describing the example inventions (Phase 2) facilitates preparing the cards. The cards are randomly spread on a large work surface so that all cards are visible to the team members.

Step 2. The team members work individually and in silence. Each team member looks for cards that are similar or related to one another in the way the inventions accomplish the design goal X and places them close to one another on the work surface. This operation repeats until no further grouping occurs. Some cards may remain as loners becoming single-card groups. Each team member can move a card that someone else has already moved. If a card seems to belong to more than a group, duplicates are made and each is placed in the appropriate group.

Step 3. The team members discuss grouping patterns on the work surface and also possible interpretations of each group. If necessary, minor modifications can be made to the grouping results. For each group, the team members examine the inventions belonging to it and identify the similarities between them in the underlying design idea (that is, behavior and/or structure) through which they resolve their predecessor's limitations and accomplish the design goal X; then, the team expresses the commonality in the form of a directive providing design process a particular direction for achieving the design goal (Fu, Yang, & Wood, 2016). The design directive becomes the DH corresponding to the group. An example illustrating how a DH is extracted from a group of inventions is provided in Section 3.3 and 3.4 – please see Figure 3.2 and 3.6.

Step 4. The team members combine the groups (the DHs) into super-groups; then, for each super-group, the team members examine the DHs belonging to it, identify the similarities between them in the underlying design idea and express the commonality they represent in the form of a higher-level directive, in a way similar to Step 3. This higher-level design directive becomes a higher-level DH corresponding to the super-group. This repeats until no further grouping of groups or super-groups occurs. This repeated grouping operation results in a tree-like hierarchy of DHs, in other words, a DH-tree. The DH-tree has multiple levels of heuristics in a tree hierarchy, from the lowest to the highest. The top-level DHs are termed the first-order DHs, the DHs in the next level, the second-order DHs, and so on. The DH-tree presents design knowledge at different levels of abstraction and constitutes the DHSfX. The DHSfX development process is graphically depicted in Figure 3.1.

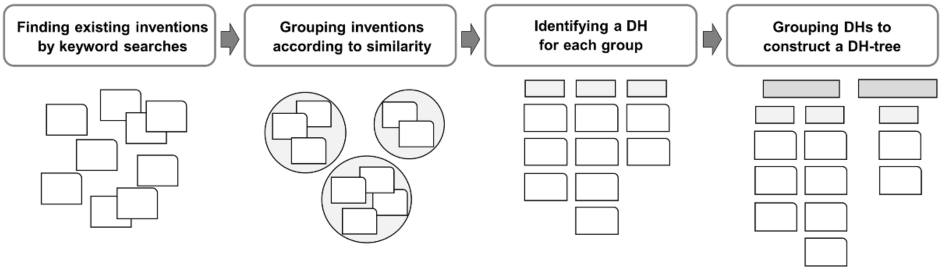



**Figure 3.1** The DHSfX development process

The current study proposes that a DHSfX may best be presented to a designer or a design team in the form of a booklet, which describes each DH along with the previous example inventions based on it. Such booklet is to be used during an ideation session for new product design concept generation, in combination with different CGTs, including the widely-used 'brainstorming' procedure. The standard brainstorming procedure consists of the idea purge and idea trigger phases – during the idea purge phase, the designer or the design team quickly generates seed ideas individually; and, during the idea trigger phase, the design team works together to generate more ideas from the seed ideas (Baruah & Paulus, 2008; Glier et al., 2011; Kohn & Smith, 2011). The standard brainstorming procedure typically does not require using any design aids but relies on the knowledge in the heads of the design team. The booklet can be utilized in either or both of the two phases to boost idea generation – the designer is encouraged to study the DHs of different levels and the corresponding examples as design inspirations to solve the given product concept generation problem.

## 3.3 Development of a DHS for limited hand mobility (DHSf_LHM)

### 3.3.1 The extraction process of DHSf_LHM

As an illustrative example, a DHSfX for creating products for individuals with limited hand mobility was developed on the basis of the generic process suggested in Section 3.2. This study refers to the DHSfX as a DHS for limited hand mobility (DHSf_LHM).

A search formula was devised utilizing three groups of keywords: 'product' and its synonyms, 'one-handed' and similar adjectives, and 'person' and related nouns. The first keywords group included 'product,' 'invention,' 'gadget,' 'device' and their plural forms. The eight keywords in the first group were combined using the OR operator. The second, 'one-handed,' 'one-armed,' 'single-handed,' and 'single-armed.' The third, 'person,' 'individual,' 'user' and 'patient' and their plural forms. The second and third keyword categories produced a total of thirty-two ($32 = 4 \times 8$) two-word phrases (e.g., 'one-handed person,' and 'single-handed users'). The thirty-two phrases were combined using the OR operator. The two resulting expressions were connected via the AND operator to produce the search formula. As for the databases, Abledata (Fitzpatrick, 2010), an assistive products database, and the Google search engine were chosen to search for relevant existing products, and the USPTO database, for relevant patents.

A total of 139 examples (100 existing products and 39 patents) were identified from the keyword searches. Out of the 139 examples, ninety distinct inventions that met the inclusion criteria described earlier were selected. Each product/patent document was converted into the standard format. Then, the grouping analysis based on the KJ method depicted in Figure 3.1 was conducted.

An example illustrating how a DH is extracted from a group of similar/related inventions is provided in Figure 3.2 – in Figure 3.2, five inventions grouped together by the KJ process are presented. These inventions intended to accomplish the design goal ‘creating products for individuals with limited hand mobility.’ The structural similarity shared by the five inventions is that each of them consists of a top and a base part connected by a spring joint (revolute or prismatic). This structure enables the user to repeat gripping/squeezing and releasing the device with one hand so as to generate repeated relative motions between the two parts and thereby accomplish the intended work task. The DH was expressed as ‘replace bi-manual motions with a single hand’s gripping/squeezing.’ The structure (two parts connected by a spring joint) shared by the example inventions was intentionally not described in the DH so that the designer could conceive other structures that achieve single hand operation based on repeating one-hand gripping/squeezing.

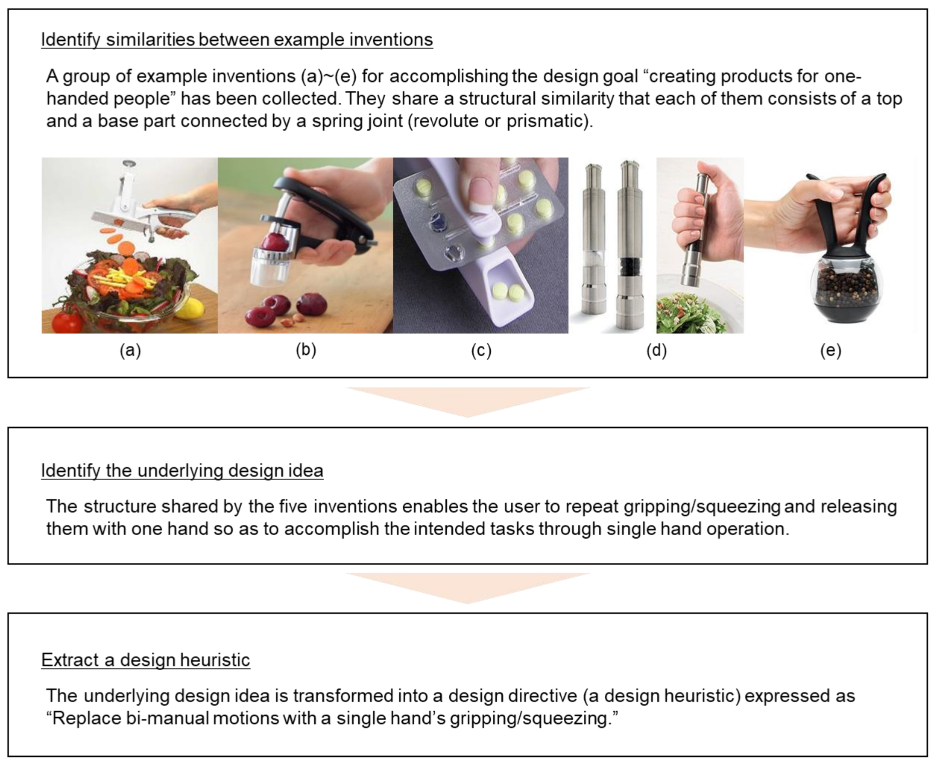



**Figure 3.2** An example illustrating the extraction of a DH from a group of similar/related example inventions

## 3.3.2 The set of DHs in the DHSf_LHM

The KJ method-based analysis was conducted, and as a result, a total of 13 DHs for designing assistive products were identified. The resulting DHSf_LHM were presented in Table 3.1. The thirteen DHs in the DHSfX varied significantly in the number of example inventions that contributed to the identification of a DH – the numbers ranged from 3 to 14 (Table 3.1). The grouping analysis further identified a tree structure with three levels of DHs. The DH tree is provided in Figure 3.3.

**Table 3.1** Thirteen DHs for creating products for one-handed people

| No. | Design heuristics | Description | No. of examples |
|---|---|---|---|
| 1 | Attach the product to a body part(s) | A product can be manipulated with one hand by attaching the product to a body part(s) using additional components (i.e., straps, holders, etc.). | 13 |
| 2 | Design the product operable with one hand and a non-hand body part | A product can be manipulated using one hand with the help of a non-hand body part. | 3 |
| 3 | Fix the product using a holding or support aid | A product can be manipulated with one hand by fixing the product to a certain position. | 14 |
| 4 | Integrate one-hand gesture control to the product | A product can be manipulated with one hand by integrating one-hand gesture control to the product. | 3 |
| 5 | Merge two products into one | A product can be manipulated with one hand by integrating multiple functions originally accomplished by separate products into the product. | 5 |
| 6 | Offer an attachable accessory for the product | A product can be manipulated with one hand by offering an attachable accessory for the product. | 7 |
| 7 | Permanently integrate | A product can be manipulated with one hand by integrating | 3 |

| | | | |
|---|---|---|---|
| | hand/finger rings into the product | hand/finger rings into the product. | |
| 8 | Place controls/grips of the product within the hand's functional range | A product can be manipulated with one hand by placing controls or grips within the hand's functional range. | 11 |
| 9 | Provide a mechanical extension along with the product | A product can be manipulated with one hand by providing a mechanical extension (i.e., a reacher grabber, a button hook, etc.) to extend the user's hand reach and manipulation abilities. | 6 |
| 10 | Provide a shape maintaining aid along with the product | A product can be manipulated with one hand using a shape maintaining aid (i.e., a shell, a frame, etc.). | 10 |
| 11 | Replace bi-manual motions with a single hand's gripping/squeezing | A product can be manipulated with one hand by replacing a bi-manual motion with a single hand's gripping/squeezing. | 5 |
| 12 | Replace bi-manual motions with a single hand's pressing/pushing | A product can be manipulated with one hand by replacing a bi-manual motion with a single hand's pressing/pushing. | 5 |
| 13 | Turn the product into a motion-activated one | A product can be manipulated with one hand if its operation is fully or partially automated with sensors | 5 |

| | | | |
|---|---|---|---|
| | | and actuators. | |

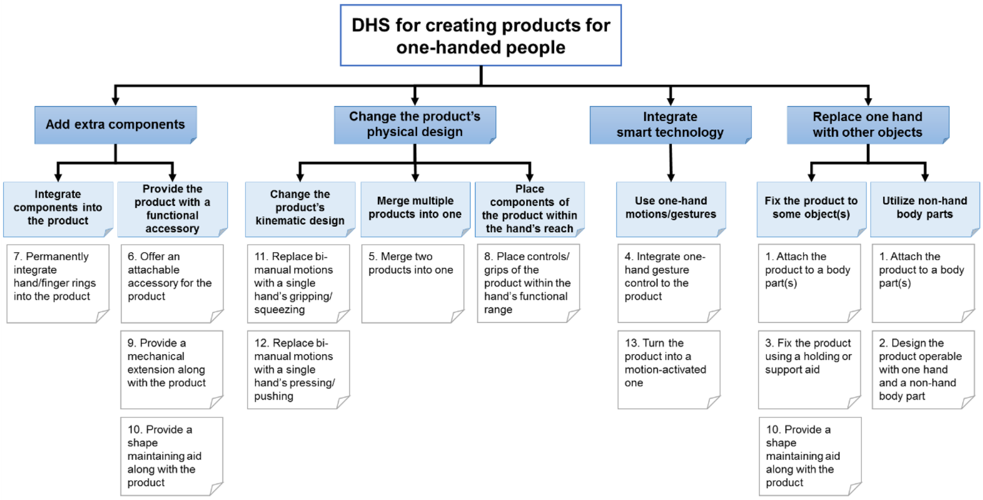



**Figure 3.3** A hierarchical structure of the design heuristics set (DH tree) for creating products for individuals with limited hand mobility

### 3.3.3 Utilizing DHSf_LHM for design idea generation

The DHs of the DHSf_LHM as shown in Table 3.1 are thought to be able to help a designer or a design team generate solution concepts for creating products for one-handed persons. As a means for effectively utilizing the DHs, this study proposes using a booklet describing the details of the DHs as reference during an individual brainstorming session. A booklet describing each DH and corresponding example inventions is created as a design aid. A part of the content of the booklet is provided in Figures 3.4 and 3.5 for illustration purpose.

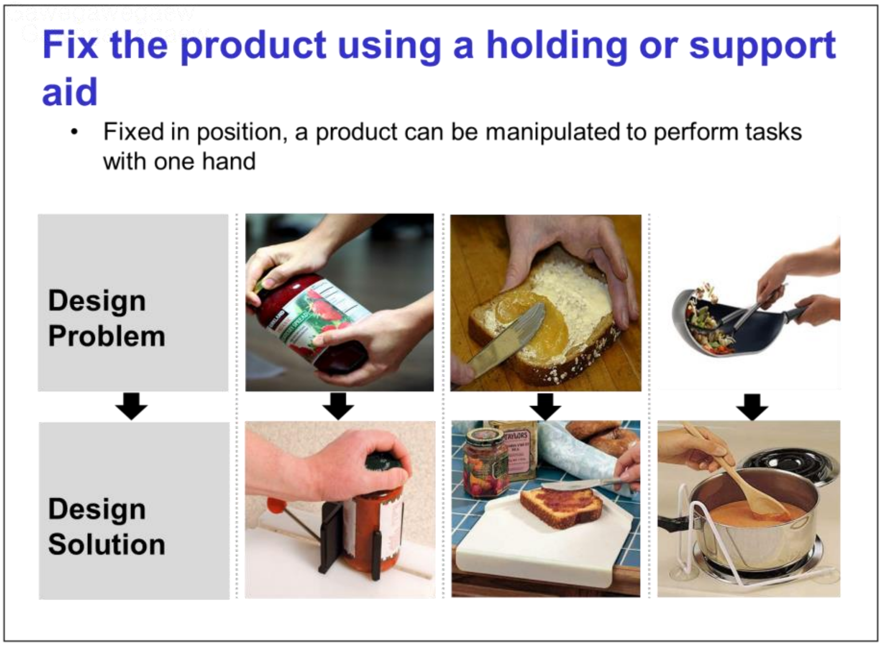



**Figure 3.4** The design heuristic, 'Fix the product using a holding or support aid,' and corresponding example inventions described in the booklet

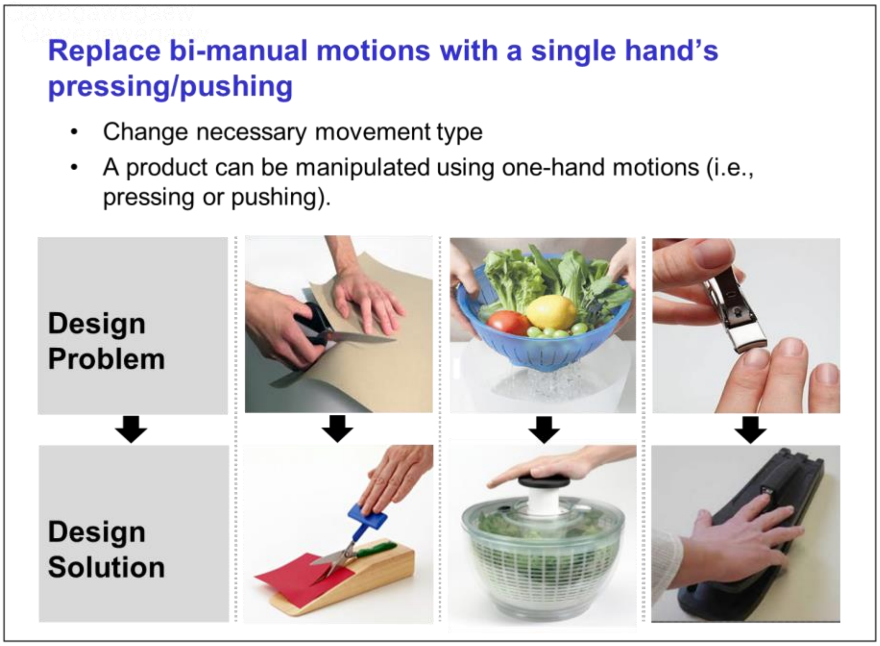



**Figure 3.5** The design heuristic, 'Replace bi-manual motions with a single hand's pressing/pushing,' and corresponding example inventions described in the booklet

## 3.4 Development of a DHS for creating portable products (DHSf_P)

### 3.4.1 The extraction process of DHSf_P

As another illustrative example, the DHSfX where X is to create portable product design (DHSf_P) was developed. The process for developing the DHSf_P starts with collecting existing example inventions which are collected mainly through searching for keywords that represent the most relevant information. Please refer to Chapter 3.2 for the generic process of constructing a DHSfX.

A search formula was devised utilizing two groups of keywords: 'product' and its synonyms, and 'portable' and similar adjectives. In this case, the target user group does not exist, so that only two keywords categories have been adopted.

The first keywords group included 'product,' 'invention,' 'gadget,' 'device' and their plural forms. The second keywords included synonyms of 'portable' such as 'handy,' 'light,' 'convenient,' and 'compact.' Thesauri can be used to identify the synonyms.

The search formula combined the keywords within each category with the Boolean operator OR, and, then, further connected the resulting expressions for the two keywords categories with the operator AND as follows: ((the expression for the first category) AND (the expression for the second category)). The eight keywords in the first group and the four keywords in the second group were combined using the AND operator. The first and second keyword categories produced a total of thirty-two (32 = 8 x 4) two-word phrases (e.g., 'handy product,' 'convenient invention' and 'compact device'). As for the databases, the Google search and patent database were chosen to search for relevant existing products.

After the selection of search keywords and databases, searches were conducted to retrieve documents describing example products. Then, the retrieved documents were screened using predetermined inclusion/exclusion criteria. This study selected only those documents that 1) described relevant and commercially successful/available/promising inventions and 2) described relevant products that satisfy the definition of 'portability' (Mital, Genaidy, & Fard, 1989). In addition to the screening, duplicate examples or examples that were very similar to one another in terms of functions, behaviors and structure were consolidated.

A total of 140 examples were identified from the keyword searches. Each product document was converted into the standard format. Then, the extraction process of the DH suggested in Chapter 3.2 using the grouping analysis based on the KJ method (Kawakita, 1991) was conducted.

An example illustrating how a DH was extracted from a group of similar/related inventions was provided in Figure 3.6 – in Figure 3.6, five inventions grouped together by the KJ process were presented. These inventions intended to accomplish the design goal 'creating portable products.' The structural similarity shared by the five inventions was that each of them was attached with a grip or a handle that can be hold by users with one or two hands, or structured with a hand shape so as to easily hold without excessive fatigue. This structure enabled the user to hold the inventions without any excessive fatigue, move them around and thereby conveniently accomplish the intended work task elsewhere. The DH was expressed as ‘Provide a product with grips or handles.’

Identify similarities between example inventions

- A group of example inventions (a)~(e) share a structural similarity.
- The structural similarity, “each of the inventions was attached with a grip or a handle that can be hold by users with one or two hands, or structured with a hand shape so as to easily hold without excessive fatigue” is identified.


Define an underlying design idea

- The similar structure shared by the five inventions listed above enables the user to hold the inventions for a long time without excessive fatigue and use them conveniently so as to accomplish the design goal.
- The underlying design idea is to create an invention (i.e., a new invention or a modified invention from the predecessor) based on the structural similarity which induces new behaviors (i.e., gripping and holding) for portability.

Extract a design heuristic

- The underlying design idea is transformed into the directive form of an idea.
- The design heuristic, “Provide a product with grips or handles,” is extracted.

**Figure 3.6** An example illustrating the extraction of a DH from a group of similar/related example inventions

### 3.4.2 The DHs of the DHSf_P

The KJ method-based analysis was conducted, and as a result, a total of 25 DHs for designing portable products were identified. The resulting DHs in the DHSfX varied significantly in the number of example inventions that contributed to the identification of a DH – the numbers ranged from 3 to 13

(Table 3.2). The grouping analysis further identified three first-order DHs and eight second-order DHs in a form of tree structure as shown in Figure 3.7.

**Table 3.2** Twenty-five DHs for portable product design

| No. | Design heuristic | Description | No. of examples |
|---|---|---|---|
| 1 | Make a product that can transform its shape for easy carriage | A product can be turned into a portable product by transforming its shape for easy carriage (e.g. fold, roll, etc.) | 13 |
| 2 | Divide all components of a product into independent parts | A product can be turned into a portable product by dividing it into independent parts or making it sectional. | 7 |
| 3 | Place a product inside another product | A product can be turned into a portable product by placing it inside another product. | 5 |
| 4 | Use elastic materials in product | A product can be turned into a portable product by utilizing elasticity. | 6 |
| 5 | Use waterproof materials in product | A product can be turned into a portable product by integrating waterproof materials into the product. | 4 |
| 6 | Use flexible materials in product | A product can be turned into a portable product by integrating flexible materials into the | 3 |

| | | | |
|---|---|---|---|
| | | product. | |
| 7 | Use light materials in product | A product can be turned into a portable product by using light materials, light enough to be held for manipulation. | 5 |
| 8 | Use a rigid outer protection on a product | A product can be turned into a portable product by using a rigid outer protection on the product. | 7 |
| 9 | Shape a product as a container | A product can be turned into a portable product by making the product shaped like a container. | 6 |
| 10 | Utilize a product with what is already portable | A product can be turned into a portable product by utilizing what is already portable for the use of the product. | 8 |
| 11 | Extract essential parts from a product | A product can be turned into a portable product by extracting only essential parts of the product. | 10 |
| 12 | Standardize components of a product | A product can be turned into a portable product by standardizing its components and interfaces, making the product adaptable with others. | 5 |
| 13 | Utilize an intermediary or connector for the use | A product can be turned into a portable product by utilizing an intermediary or a connector | 4 |

| | | | |
|---|---|---|---|
| | of a product | when two or more products are not standardized. | |
| 14 | Integrate a battery into a product | A product can be turned into a portable product by integrating a battery into the product. | 4 |
| 15 | Make an energy-harvesting product | A product can be turned into a portable product by making the product harvest energy by itself and utilize the energy during its use. | 3 |
| 16 | Attach an energy conversion device on a product | A product can be turned into a portable product by making the product self-generate the energy necessary for its use via an energy conversion device. | 3 |
| 17 | Organize/unclutter all the components of a product | A product can be turned into a portable product by grouping the functional components in performing a function(s) of the product. | 10 |
| 18 | Combine multiple products into one | A product can be turned into a portable product by combining multiple entities with different functions into one entity. | 3 |
| 19 | Add multiple functions to a product | A product can be turned into a portable product by adding multiple functions to the product. | 5 |

| | | | |
|---|---|---|---|
| 20 | Make a product less stressful on human body | A product can be turned into a portable product by making it inflict less stress on the human body. | 5 |
| 21 | Provide a product with grips or handles | A product can be turned into a portable product by providing a product with grips or handles. | 13 |
| 22 | Attach wheels to a product | A product can be turned into a portable product by attaching wheels to its body. | 6 |
| 23 | Provide a product with adjustable components | A product can be turned into a portable product by providing a product adjustability to enhance flexibility. | 7 |
| 24 | Make a product fixed to a certain position | A product can be turned into a portable product by fixing it to a certain position, preventing it from falling down and getting damaged. | 10 |
| 25 | Attach a product to other body parts | A product can be turned into a portable product by designing the product to be wearable. | 3 |

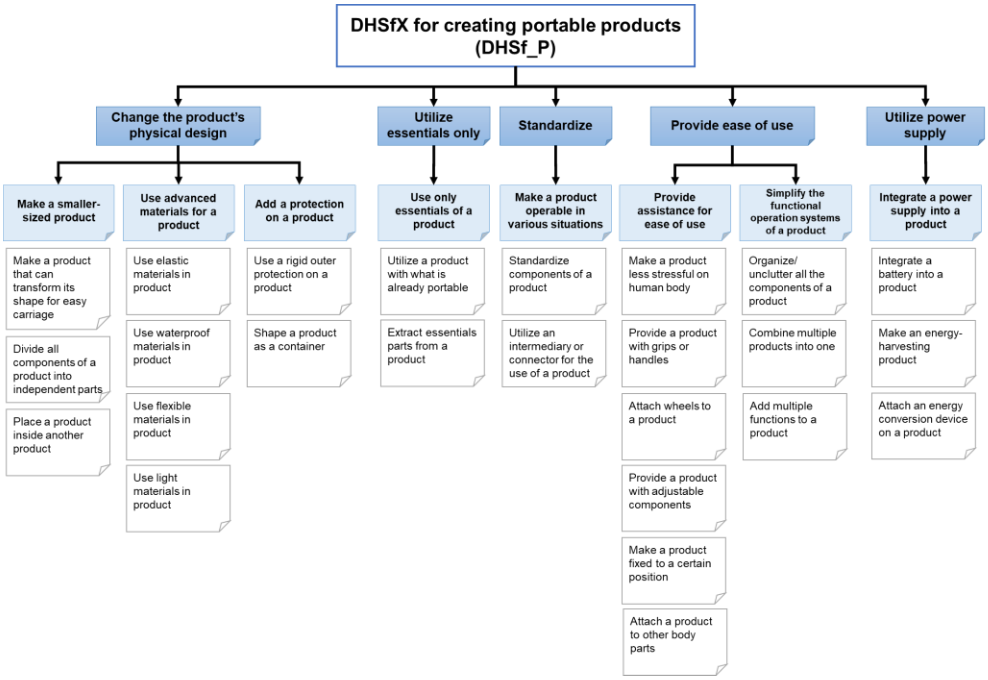



**Figure 3.7** A hierarchical structure of the design heuristics set (DH tree) for creating portable products

## 3.4.3 Utilizing DHSf_P for design idea generation

The DHs and the collected previous inventions for extracting the corresponding DH are described in a booklet. This study proposes using the booklet as reference during an individual or a group brainstorming session. The DHs and the previous example inventions in the booklet provide insights into how the previous inventions can be redesigned for new design context, and, help the designers effectively and efficiently explore the solution space. Some parts of the booklet are provided in Figures 3.8, 3.9 and 3.10 for illustration purposes.

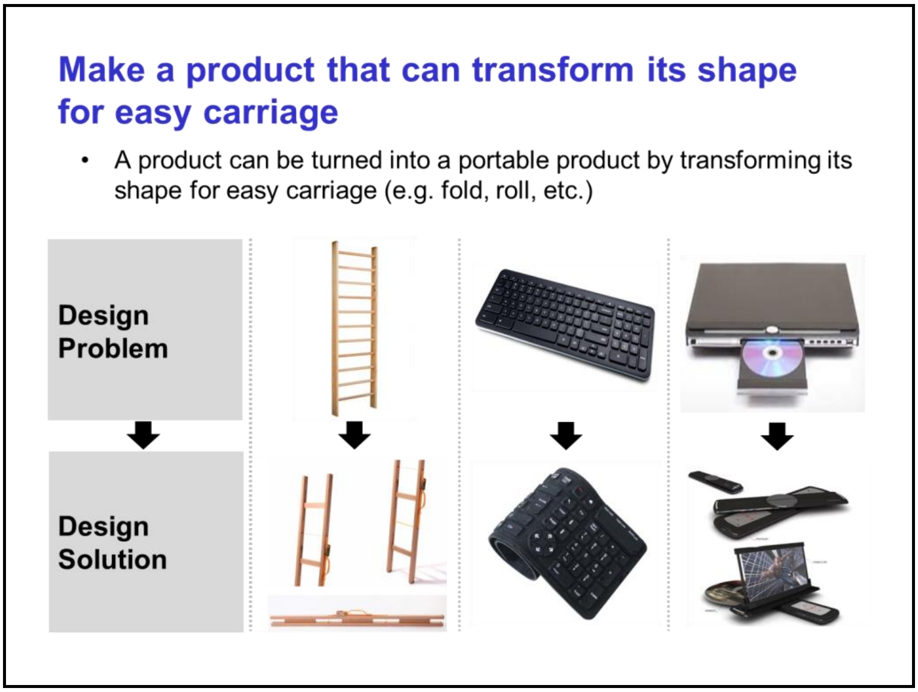



**Figure 3.8** The design heuristic, 'Make a product that can transform its shape for easy carriage,' and corresponding example inventions described in the booklet

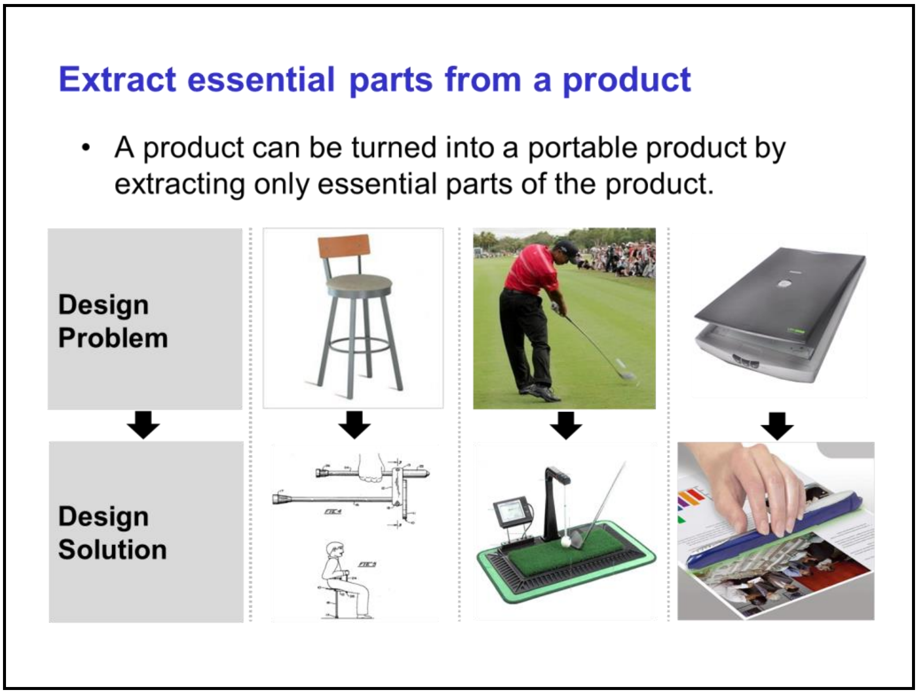


**Figure 3.9** The design heuristic, 'Extract essential parts from a product,' and corresponding example inventions described in the booklet

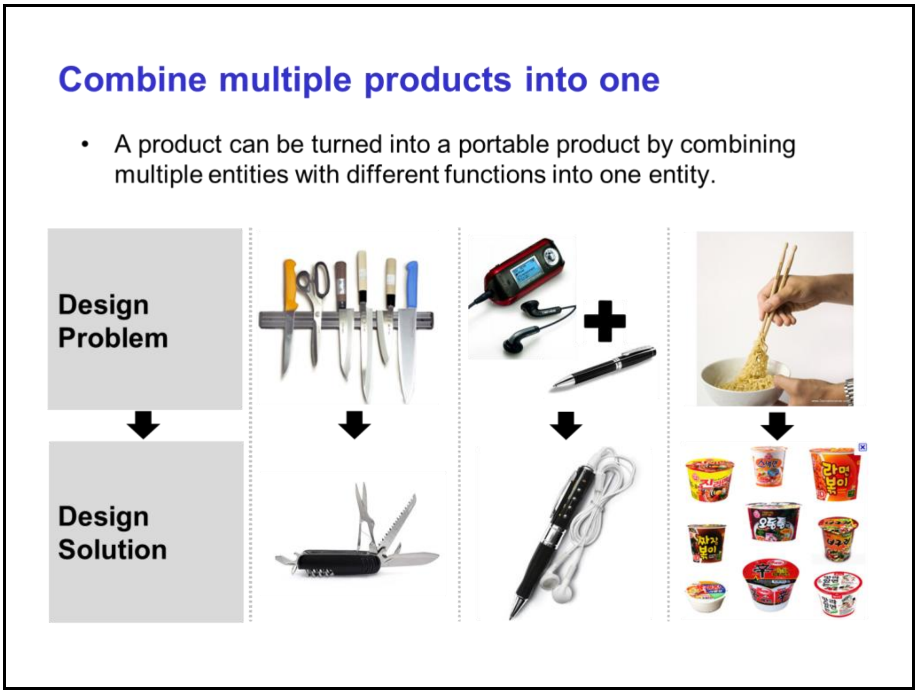



**Figure 3.10** The design heuristic, 'Combine multiple products into one,' and corresponding example inventions described in the booklet

## 3.5 Discussion

This study introduced a generic process of developing DHs for addressing a particular design goal X. A step-by-step process for constructing a DHSfX for creative product design was presented (Figure 3.1). At first, keywords which described the design goal X were determined, and then keyword search was conducted to identify relevant inventions for addressing the goal X. In order to identify DHs from the example inventions, the KJ method was employed in an inductive manner.

This study developed two different example DHSfXs: one for creating assistive products for individuals with limited hand mobility (DHSf_LHM), and the other for creating portable products (DHSf_P). For assistive product design, thirteen DHs were derived by analyzing ninety example assistive products/patents found from keyword searches (Table 3.1). For portable product design, a total of twenty-five DHs were derived by analyzing one hundred forty example products/patents found from keyword searches (Table 3.2). The grouping analysis based on the KJ method identified a DH tree consisting of three levels of DHs (Figure 3.3 and 3.7). This study also suggested using a booklet describing the details of the DHs as reference during an individual brainstorming session.

A generic process of constructing the DHSfX enables developing DHSs for addressing a specific design goal X. One obvious benefit of a generic process development would be that the designers are able to develop new DHSfXs for their currently working design projects. It could be also beneficial for the designers to gain a great amount of up-to-date, goal-directed design knowledge on solving a specific design goal.

In this current study, example DHSfXs (i.e., DHSf_LHM and DHSf_P) with the two different design goal Xs, that is, creating for assistive products and creating portable products were constructed. In order to demonstrate the effects of DHSfXs on ideation performance, two separate case studies were conducted. The case studies in the following sections demonstrate the use of DHSfXs using design problems in the domains of assistive products and portable products. The target users for assistive products and portable products include extraordinary people who have some issues on their conditions and ordinary people without any conditions, respectively. The design problems involving such wide range of target user groups were selected to perform a more thorough investigation on the effects of DHSfXs. Also, it is a challenging task for designers to create new assistive products that designers have never used before and new design alternatives deviated from the typical portable product design. Designers may benefit from the use of the DHSf_LHM and DHSf_P for enhancing their creative thinking abilities to efficiently and effectively solve the challenging design problems.

# Chapter 4. Case studies on the effect of a DHSfX: creating assistive products and integrating portability

## 4.1 A case study on the effect of DHSfX in assistive product domain

### 4.1.1 Introduction

Assistive products refer to any products that can be used by persons with disabilities (International Organization for Standardization [ISO], 2016). The design of assistive products is an important part of our effort to enhance the quality of human life through engineering design. Well-designed assistive products help individuals with disabilities gain independence in performing daily life and work activities (Cook & Polgar, 2014; Hersh & Johnson, 2008); and, by doing so, they support numerous members of our society in maintaining dignity as a human being and also realizing their full potential.

In the fields of research concerned with 'design-for-human,' efforts have been made to advance the practice of assistive product design. Much of the recent research has been focused on the application of human-centered design (HCD) methods, such as the methods of participatory design (Allen et al., 2008; Frauenberger, Good, & Keay-Bright, 2011; Mayer & Zach, 2013; Meiland et al., 2014; Wu, Baecker, & Richards, 2005), ethnography (Carmien & Fischer, 2008; Forlizzi et al., 2005), and empathic design (Chen, 2011; McDonagh & Thomas, 2010). These HCD methods emphasize incorporating the human perspectives into the design process – they aim to make artefacts usable and useful by focusing on the users, their needs and requirements and by applying human factors/ergonomics, usability knowledge and techniques (ISO, 2010). The HCD approach has been shown to benefit the development of assistive products.

Despite the advances in the various design methods, however, today's design teams developing assistive products still face multiple challenges. One of the challenges is the lack of knowledge necessary for generating alternative solution concepts for a given design problem.

A design team put together to develop an assistive product ideally includes product designers, target users and subject matter experts (e.g., clinicians, nurses, caregivers, family members, relatives, etc.) (Allen et al., 2008; Allsop et al., 2010; Bühler, 1996; Hengeveld et al., 2008; Mayer & Zach, 2013; Newell, 2002; Orpwood, 1990; Wu, Baecker, & Richards, 2005). The product designers in most cases lack the knowledge specific to the disability under consideration and the experience of the target users – they typically do not have substantial prior exposure to the disability type under consideration. The use of HCD methods, which involves the target users and subject matter experts, effectively bridges this knowledge gap, and, therefore, helps the designers understand and properly define the design problem. However, once the problem is defined and the ideation phase begins for solution concept generation, the design team runs into another 'lack of knowledge' problem.

Currently, design teams mostly rely on the knowledge in the head of the team members to generate and explore solution concepts – the brainstorming method and its variants seem to be the most frequently used ideation methods (Gulliksen, Lantz, & Boivie, 1999; Sharples et al., 2012; Steen, Kuijt-Evers, & Klok, 2007). The difficulty lies in that the collective internal knowledge of a design team may not be sufficient to allow efficiently and effectively exploring the design space. The designers, despite their design expertise, typically do not have much prior experience in solving design problems similar to the given assistive product design problem – human disabilities vary greatly in type and extent and finding a designer who has substantial experience in designing assistive products for a particular disability type or case is difficult in reality. To make matters worse, sometimes professional designers are not even available at all, due to insufficient project budget; cases have been reported in which student volunteers or target users themselves designed assistive products due to the unavailability of professional design supports (Hersh, 2010; Lhotska et al., 2014). As for the target users and subject matter experts within the design team, they typically do not have much knowledge for generating solution concepts – they have the knowledge useful for understanding the problem context and the user needs but they are not the design experts who specialize in creating solution concepts. The lack of knowledge necessary for generating solution concepts represents a significant problem as it hampers producing high-quality assistive products in a timely manner.

As an effort to address the aforementioned problem associated with assistive product design, this study proposes the utility of the DHSfX approach in the context of assistive product design where design goal X is expressed as 'creating products for individuals with limited hand mobility.' It is our belief that creating DHSfXs for different disability types and making them available to assistive product design teams can greatly alleviate the aforementioned lack of knowledge problem. The current study presents a concept generation process on how to use it during brainstorming. To demonstrate the utility of the DHSfX approach in the design of assistive products, this study empirically evaluated the utility of the DHSf_LHM in terms of the outcome of new product concept generation.

### 4.1.2 Method

In order to demonstrate the effect of the DHSf_LHM on ideation performance for new assistive product concept generation, the empirical evaluation was conducted through comparing the outcomes of two ideation sessions: brainstorming sessions with and without the use of the DHSf_LHM.

#### 4.1.2.1 Study participants

Thirty-two Seoul National University undergraduate students majoring in industrial engineering participated in the empirical evaluation. Participants' age ranged from 20 to 31, with 21–24 being typical. All of the participants had previously taken a course on engineering design and had studied some of the widely used CGTs, including standard brainstorming. They had prior experience in performing standard brainstorming for solving design problems. To help them recall the brainstorming procedure, a lecture on standard brainstorming was provided along with a one-hour ideation practice session prior to the experiment.

The participants were randomly divided into two groups of sixteen. One group, named the standard brainstorming group (Group SB), was to use standard brainstorming without any additional stimuli or tools for ideation, and the other group, named the DHs group (Group DH), was to perform brainstorming with the DHSf_LHM. Each participant in Group DH was provided with the booklet described in Section 3.1.

### 4.1.2.2 Experiment task

The experiment task was to generate as many new product concepts as possible for a given concept design problem within the limited time. Each participant conducted idea generation individually. The new product concept design problem was to redesign the Rubik's cube for one-handed users. The problem statement used is as follows: *"Currently, one-handed users find it difficult to play with the Rubik's cube. Develop new Rubik's cube concepts (as many as possible) that allow one-handed users to easily and efficiently play the game of Rubik's cube. The new design concepts do not have to resemble the original Rubik's cube in the mechanism design and/or other aspects as long as they realize the original game of Rubik's cube."*

The participants were instructed to use sketches and/or written words to clearly describe their ideas, and, also to generate as many ideas as possible. The time limit was one hour. As mentioned earlier, the participants in Group SB conducted standard brainstorming without using any external design aids. Those in Group DH were allowed to freely use the DHs and example inventions in the DHSf_LHM booklet while brainstorming.

### 4.1.2.3 Experiment protocol

The experiment protocol is illustrated in Figure 4.1. It was approved by the Institutional Review Board of Seoul National University.

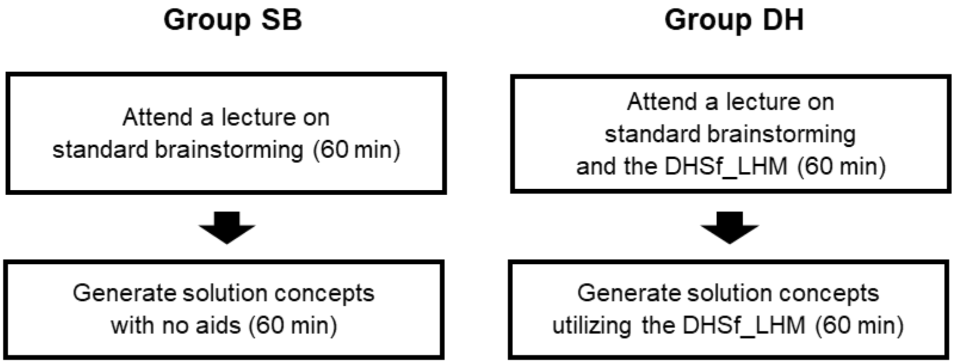



**Figure 4.1** The experiment protocol

#### 4.1.2.4 Metrics for evaluation

For each participant group, the ideas (new Rubik's cube product concepts) generated individually by its members were collated. For each group, the authors examined all the ideas and eliminated duplicate ones; the resulting idea set containing distinct ideas was utilized in subsequent ideation performance evaluation and analyses. Additionally, for each participant group, the number of ideas each participant generated was counted and recorded.

The ideation performance of each participant group was evaluated employing four evaluation criteria: quantity, variety, novelty and quality. These criteria have been widely used to evaluate design ideation outcomes in the previous research studies (Nelson et al., 2009; Oman et al., 2013; Shah, Kulkarni, & Hernandez, 2000; Shah, Smith, & Hernandez, 2003; Smith et al., 2006; Wodehouse & Ion, 2011). Also, this study evaluated the effect of design fixation which was a detrimental factor for creative concept generation (Jansson & Smith, 1991), and employed the additional metrics to measure how many 'good' ideas are generated by each participant group.

Quantity is the number of ideas generated (Nelson et al., 2009; Shah et al., 2003). In this study, both the total number of distinct ideas within an idea set and the number of ideas per participant (including all ideas within each participant) were considered for the quantity measure. The total number of distinct ideas within an idea set was counted for a participant group; and, the average number of ideas per participant was determined for a single participant.

Variety measures the size of the explored solution space during the idea generation process (Nelson et al., 2009; Shah et al., 2003). In most cases, variety is calculated as the number of bins a participant's ideas occupy divided by the total number of bins, where the bin refers to a category of distinct ideas (Linsey et al., 2011; Viswanathan & Linsey, 2013). To realize each bin, this study utilized the KJ method to cluster ideas that can be characterized with similarity. The number of bins was computed for each participant, and the total number of bins was computed as all bins found by all participants within the same group.

Novelty refers to how unusual or unexpected an idea is as compared to other ideas. An idea's novelty was quantified through experts' subjective ratings. The novelty metric pertained to a single idea. In this study, an additional quantitative evaluation metric, that is, a rarity metric proposed by Viswanathan and Linsey (2011), was employed to supplement the subjective ratings of the experts who may be unfamiliar with the design problem at hand, which is to create assistive product designs. The computation for rarity metric is provided in Eq. (1).

$$Novelty = 1 - frequency = 1 - \frac{number\ of\ ideas\ in\ a\ bin}{total\ number\ of\ ideas} \quad (1)$$

Quality pertains to the feasibility of an idea and how close it comes to meeting the intended design goal. An idea's quality was quantified through experts' subjective ratings. The quality metric pertained to a single idea.

In addition to the above idea evaluation metrics, two additional metrics were employed to measure how many 'good' ideas were generated by each participant group. In this study, a 'good' idea was defined as an idea with a high quality score, and, simultaneously, a high novelty score (Amabile, 1998; Diehl & Stroebe, 1987; Sternberg & Lubart, 1999). To compare the amount of 'good' ideas, the good ideas count and the good ideas proportion were employed. For each participant group, the good ideas count was determined by counting the number of distinct ideas whose novelty and quality scores based on the experts' subjective ratings both exceeded a predetermined threshold – in the current study, the threshold was set at the midst of the rating scale (i.e., four on the seven-point rating scale). The good ideas proportion was determined by dividing the good ideas count by the total number of distinct ideas within an idea set. The good ideas count and good ideas proportion measures can be considered as overall group ideation performance measures as the ultimate goal of concept generation is to generate 'good' ideas, that is, ideas that are both highly novel and of high-quality.

This study also quantitatively evaluated the severity of design fixation (Jansson & Smith, 1991; Youmans, 2007) in the ideation outcome of each participant group. This was to test if the use of the DHSf_LHM increased the level of design fixation in comparison with that of the standard brainstorming method. The fixation metric used was that of Moreno et al. (2016) and is shown in Eq. (2). The fixation score was computed for each idea in the idea set of each participant group.

$$Fixation = \frac{Total\ \#\ of\ repeated\ ideas}{Total\ \#\ of\ generated\ ideas} \tag{2}$$

#### 4.1.2.5 Evaluation process

Two judges subjectively evaluated the individual ideas within the two idea sets using the novelty and quality metrics. Both judges had a bachelor's degree in engineering and a master's degree in a product design-related discipline; they also had conducted numerous product development activities, including multiple assistive product design and universal design projects. The judges used 7-point rating scales (one: extremely low, seven: extremely high) to subjectively determine the novelty and quality scores for each idea, where a score of one denotes the lowest possible rating and a score of seven indicates the highest possible rating (Figure 4.2). For each idea and each evaluation criterion, the average of the two judges' ratings was computed for subsequent data analyses.

Prior to evaluation, the two judges were trained for consistency on their scoring by discussing and reaching common scoring schemes for novelty and quality. Then, they individually performed subjective ratings on the ideation performance measures. Note that they were both blind to the conditions of the experiment and the hypothesis. After completion, the judges identified the ones that did not reach an agreement, and re-evaluated them and reached a consensus through discussion.

Both the Cohen's Kappa coefficient and the percentage of absolute agreement were used to measure inter-rater agreement. The Cohen's Kappa coefficients were determined as .724 for novelty and .775 for quality, both of which were above the acceptable level of agreement (Klenke, 2008). According to Landis and Koch (1977), these kappa coefficients of novelty and quality indicated 'substantial' agreements between two raters. With raters considered to be in agreement when their ratings differed by no more than one point (Diehl & Stroebe, 1987), the two raters agreed in 85.07% of the novelty ratings and 86.57% of the quality ratings. Both the percentages of absolute agreement reached the acceptable level of agreement (Hartmann, 1977; Stemler, 2004).

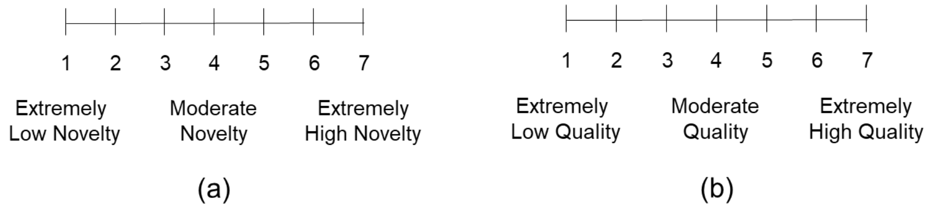


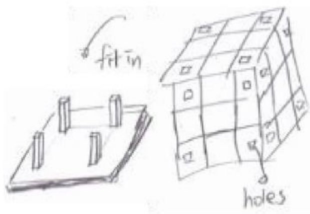
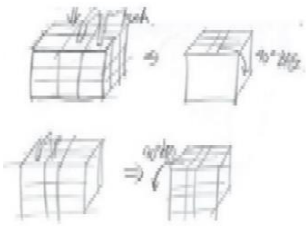

**Figure 4.2** Subjective rating scales for idea novelty and quality evaluations: (a) novelty scale, (b) quality scale

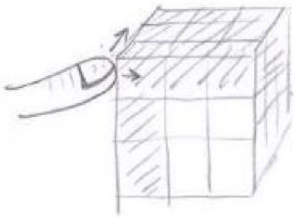
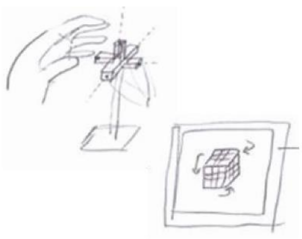
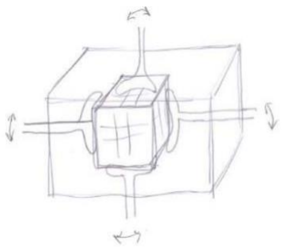
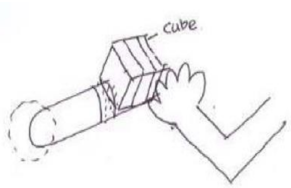
The two participant groups were compared with each other in each of the metrics described above: the total number of distinct ideas within an idea set, the average number of ideas per participant, the variety for each participant group, the novelty score based on the experts' subjective ratings, the novelty (rarity) score proposed by Viswanathan and Linsey (2011), the quality score based on the experts' subjective ratings, the fixation score, the good ideas count and the good ideas proportion. A series of *t*-tests were conducted to statistically compare the means of the two idea sets (two participant groups) in the following metrics: the average number of ideas per participant, the variety for each participant group, the two novelty scores, the quality score, and the fixation score. The assumption for homogeneity of variance was validated for all the analyses. The levene's test was conducted to examine the homogeneity of variance. Also, a chi-square test was conducted to statistically compare the good ideas proportions of the two idea sets.

### 4.1.3 Results

For illustration purposes, Table 4.1 provides some example ideas (new Rubik's cube product concepts) generated from the ideation experiment. The six examples were described with the DH(s) used as well as the sketch and text description of the idea provided by the participants in Group DH.

**Table 4.1** Example ideas generated from the ideation experiment

| No. | Design heuristic(s) used | Idea sketch | Text description |
|---|---|---|---|
| 1 | • Fix the product using a holding or support aid |   | When the cube is placed on the bottom frame, the cube is fixed in position, and thus, can be manipulated with a single hand. |
| 2 | • Replace bi-manual motions with a single hand's pressing/pushing |  | The cube rotates 90 degrees when two pieces (cubelets) on the top face are pressed. |

| | | | |
|---|---|---|---|
| 3 | • Integrate one-hand gesture control to the product |  | The faces of the cube are color changing touch screens. The layer of a cube does not rotate; instead, color patterns on the faces change by a finger touch or a touch gesture. |
| 4 | • Integrate one-hand gesture control to the product |  | A virtual reality Rubik's cube can be manipulated by a single hand through the use of gesture control. |
| 5 | • Fix the product using a holding or support aid<br>• Provide a mechanical extension along with the product |  | The cube is located inside a box. The cube is manipulated by the use of the sticks extending through the box. |
| 6 | • Attach the product to a body part(s)<br>• Fix the product using a holding or |  | The cube fixed on a body part of the user can be manipulated with a single hand. |

| | support aid | | |
|---|---|---|---|
| | | | |

Table 4.2 shows descriptive statistics for means and standard deviations of ideation performance measures for each participant.

**Table 4.2** Descriptive statistics of ideation performance measures for each participant

| Measure | Group SB (n=16) | | Group DH (n=16) | |
|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** |
| Quantity | 7.25 | 2.32 | 9.63 | 3.07 |
| Variety | .30 | .081 | .23 | .043 |
| Novelty | 4.11 | .67 | 4.34 | .41 |
| Quality | 3.83 | .39 | 3.86 | .51 |
| Rarity | .88 | .020 | .91 | .023 |
| Fixation | .23 | .23 | .26 | .27 |

Group SB generated an idea set consisting of 53 distinct ideas. Group DH, on the other hand, produced 68 distinct ideas. In addition, the average number of ideas per participant were compared across the groups by using the *t*-test. The *t*-test results showed that on average, the participants in Group DH ($M$ = 9.63, $SD$ = 3.07) individually generated more ideas than those in Group SB ($M$ = 7.25, $SD$ = 2.23), $t(30) = -2.465$, $p = .020$ (Table 4.3).

The total bins ideas generated from Group SB and Group DH were 20 and 33 bins, respectively. The mean variety scores were also compared between the two groups by using the *t*-test. As shown in Table 4.3, the *t*-

test results showed that on average, the participants in Group SB (*M* = .30, *SD* = .081) individually generated more diverse ideas than those in Group DH (*M* = .23, *SD* = .043), $t(22.806) = 2.975$, $p = .007$. The current study finding indicated that for the individual level, the use of the DHSf_P might not be helpful for exploring diverse solution space; however, overall idea exploration performed by the DHSf_P was greater than standard brainstorming.

The results of the *t*-tests conducted to compare the two participant groups in the experts' mean novelty and quality ratings are also summarized in Table 4.3. The *t*-test for mean novelty did not reveal any statistically significant difference between Group SB (*M* = 4.11, *SD* = .67) and Group DH (*M* = 4.34, *SD* = .41), $t(30) = -1.131$, $p = .267$. In addition, the *t*-test for mean quality did not reveal any statistically significant difference between Group SB (*M* = 3.83, *SD* = .39) and Group DH (*M* = 3.86, *SD* = .51), $t(30) = .164$, $p = .871$.

This study conducted another novelty comparison between the two participant groups by using the t-test. The *t*-test conducted to compare the two participant groups in the mean novelty based on the rarity metric of Viswanathan and Linsey (2011) identified a statistically significant between-group mean difference. Group DH (*M* = .91, *SD* = .023) significantly generate more novel ideas than Group SB (*M* = .88, *SD* = .020), $t(30) = -3.916$, $p < .001$ (Table 4.3).

As shown in Table 4.3, the result of the *t*-test conducted to test the mean difference between the two participant groups in the design fixation score did not show any statistically significant between-group difference, $t(30) = -.386$, $p = .702$.

**Table 4.3** Levene's tests and independent *t*-tests for ideation performance measures

| Measure | Test for Equality of Variances | | *t*-test for Equality of Means | |
|---|---|---|---|---|
| | ***F*** | **Sig.** | ***t*** | **Sig.** |
| Quantity | 1.051 | .314 | -2.465 | .020* |
| Variety | 6.512 | .016* | 2.975 | .007** |
| Novelty | 4.005 | .054 | -1.131 | .267 |
| Quality | 1.490 | .232 | .164 | .871 |
| Rarity | .296 | .591 | -3.916 | <.001*** |
| Fixation | .062 | .805 | -.386 | .702 |

*Note*. * $p < .05$, ** $p < .01$, *** $p < .001$.

The additional analyses for comparing the sets of distinct ideas generated from the two participant groups in terms of mean novelty and quality scores were conducted. Table 4.4 shows descriptive statistics for means and standard deviations of novelty and quality between the two participant groups. The *t*-test results for the mean novelty and quality ratings are summarized in Table 4.5. Accordingly, the *t*-test for mean novelty did not reveal any statistically significant difference between Group SB ($M = 4.36$, $SD = 1.14$) and Group DH ($M = 4.74$, $SD = 1.04$), $t(119) = -1.902$, $p = .060$. Also, the *t*-test for mean quality did not reveal any statistically significant difference between Group SB ($M = 3.80$, $SD = .62$) and Group DH ($M = 3.88$, $SD = .92$), $t(116.772) = -.580$, $p = .563$.

**Table 4.4** Descriptive statistics for novelty and quality by condition

| Measure | Group SB (n=53) | Group DH (n=68) |
|---|---|---|

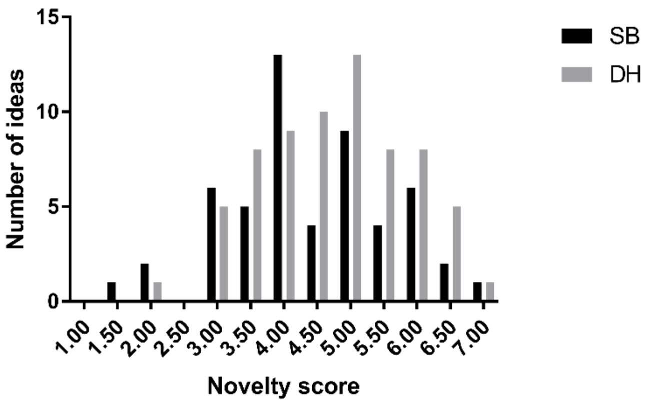
| | Mean | SD | Mean | SD |
|---|---|---|---|---|
| Novelty | 4.36 | 1.14 | 4.74 | 1.04 |
| Quality | 3.80 | .62 | 3.88 | .92 |

**Table 4.5** The Levene's tests and independent *t*-tests for novelty and quality of distinct ideas

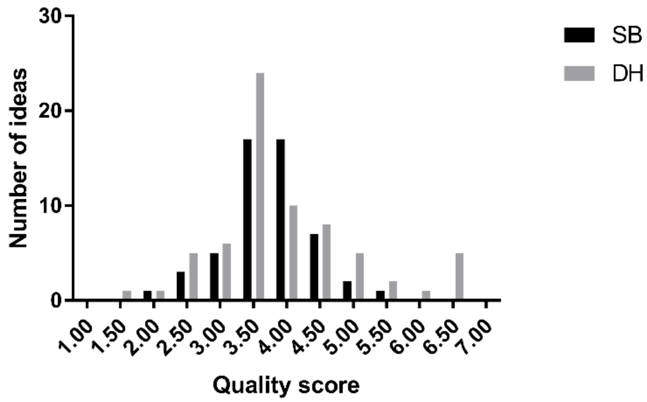
| **Measure** | **Test for Equality of Variances** | | ***t*-test for Equality of Means** | |
|---|---|---|---|---|
| | ***F*** | **Sig.** | ***t*** | **Sig.** |
| Novelty | .495 | .483 | -1.902 | .060 |
| Quality | 4.381 | .038* | -.580 | .563 |

*Note*. * $p < .05$.

Figure 4.3(a) graphically presents the idea novelty score distributions (based on the experts' subjective ratings) of Groups SB and DH using frequency bar graphs; and, Figure 4.3(b), the idea quality score distribution in a similar manner. Group DH produced more high-novelty ideas (novelty score > 4) than Group SB (Figure 4.3(a)). Also, Group DH generated more high-quality ideas (quality score > 4) than Group SB (Figure 4.3(b)).



(a)




(b)

**Figure 4.3** Frequency bar graphs presenting idea novelty and quality score distributions of Groups SB and DH: (a) novelty, (b) quality

Figure 4.4 presents the idea score distributions of the two participant groups in the novelty-quality space, and Figure 4.5 presents only the good ideas (the ideas with novelty and quality scores both greater than 4) in the novelty-quality space. Accordingly, Groups SB and DH were found to have the good ideas counts of six and fifteen, respectively. This indicated that Group DH tend to generate more good ideas than Group SB. This study finding may show that ideas generated from Group DH are more likely to be selected as an optimal solution than those from Group SB.

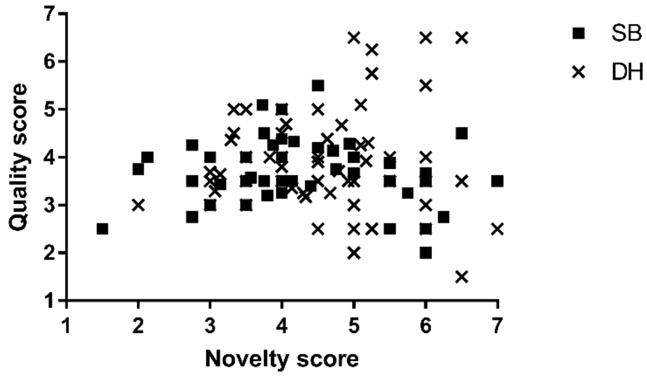



**Figure 4.4** Idea distributions of Groups SB and DH in the novelty-quality space

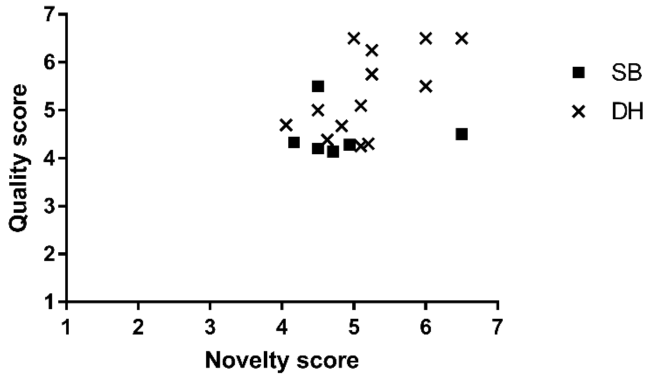



**Figure 4.5** The good ideas (novelty score > 4 and quality score > 4) presented in the novelty-quality space

The corresponding good ideas proportion of Group DH was .22 whereas that of Group SB was only .11. As shown in Table 4.6, the difference in proportions was significant, $\chi^2$ (1, n = 21) = 3.84, $p < .05$. The result of the chi-square test revealed that good ideas were not equally distributed between groups. This indicated that Group DH generated proportionately more good ideas than Group SB. This result gave another evidence that

DHSf_P indeed helped designers generate more good ideas than standard brainstorming.

**Table 4.6** Results of Chi-square goodness-of-fit test for good ideas count

| | Group | |
|---|---|---|
| | **Standard brainstorming** | **DHSf_LHM** |
| Observed frequency | 6 | 15 |
| Expected frequency | 9.2 (.44) | 11.8 (.56) |

*Note.* $\chi^2 = 3.84$*, $df = 1$. Numbers in parentheses are expected proportions.
* $p < .05$

### 4.1.4 Discussion

In this study, an experiment was conducted to empirically evaluate the utility of the DHSf_LHM for assistive product concept generation. Two groups of participants, Groups SB and DH, performed individual brainstorming to create new Rubik's cube product concepts for one-handed users. The participants in Group SB performed standard brainstorming without using any CGTs. Those in Group DH performed brainstorming utilizing the DHSf_LHM as a brainstorming aid. The solution concepts produced by the two participant groups were comparatively evaluated in terms of the quantity, novelty, quality, good ideas count, good ideas proportion and design fixation severity measures. The main findings were as follows:

- Group DH produced the more total number of distinct ideas within an idea set than Group SB. The idea sets SB and DH contained 53 and 68 distinct ideas, respectively. In terms of the average number of ideas per participant, the participants in Group DH also produced significantly more ideas (9.63 ideas) than those in Group SB (7.25 ideas).
- Group DH produced more variety of ideas than Group SB. The idea sets SB and DH contained 20 and 33 bins, respectively. In terms of the mean variety scores, however, the participants in Group SB produced significantly more diverse ideas (.30) than those in Group DH (.23).
- Groups SB and DH did not significantly differ in the mean novelty score based on the experts' subjective ratings. However, the additional analysis using the novelty metric proposed by Viswanathan and Linsey (2011) found that Group DH had a significantly larger mean novelty score than Group SB indicating

the advantage of using the DHSf_LHM. Also, Group DH generated more high-novelty (novelty score greater than four ['moderate']) ideas than Group SB as depicted in Figures 4.3(a) and 4.4. The number of high-novelty ideas for Group SB and Group DH were 26 and 45, respectively.

- Groups SB and DH did not show a significant between-group mean difference in the quality score. Nevertheless, Group DH generated more high-quality (quality score greater than four ["moderate"]) ideas than Group SB as depicted in Figures 4.3(b) and 4.4. The number of high-quality ideas for Group SB and Group DH were 10 and 21, respectively.
- Group DH produced more 'good' (both novelty and quality scores greater than four ["moderate"]) ideas than Group SB (Figure 4.5). The idea sets of Groups SB and DH contained six and fifteen 'good' ideas, respectively. The corresponding good ideas proportions were 11% and 22%. The difference between the good ideas proportions was statistically significant.
- Groups SB and DH did not show a significant difference in the mean design fixation score.

Overall, the DHSf_LHM was found to positively affect the ideation outcome for assistive product concept generation – it increased the total number of distinct ideas within an idea set, the average number of ideas per participant, the counts of high-novelty, high-quality and 'good' ideas, and the 'good' ideas proportion.

The lack of statistical significances in the results of the *t*-tests on the mean novelty and quality scores based on experts' subjective ratings (indicated in Table 4.2) needs to be interpreted with caution. It does not signify that the example DHSfX provided no benefits compared with standard brainstorming; but, rather, it reflects the fact that the use of the DHSf_LHM resulted in generating a variety of solution concepts varying much (from very low to very high) in each of the two metrics (Figure 4.4). In other words, the ideas resulting from using the DHSf_LHM covered the entire range of value for each metric. The benefits of using the DHSf_LHM are clear in the total number of distinct ideas within an idea set, the average number of ideas per participant, the counts of high-novelty, high-quality and 'good' ideas, and the 'good' ideas proportion (Figures 4.3-4.5). Also, the use of the DHSf_LHM did not increase the severity of design fixation compared with that of standard brainstorming.

The results from the empirical evaluation of the DHSf_LHM may be accounted for in terms of possible impacts of the DHSf_LHM on cognitive subtasks involved in product concept generation. Some possible roles of the DHSf_LHM are suggested in the following: first, the DHSf_LHM would help address the difficulties associated with the memory search for acquiring knowledge for concept generation. Some well-known models of the human creative process, such as the geneplore model (Finke, Ward, & Smith, 1992) and the search for ideas in associative memory (SIAM) model (Nijstad & Stroebe, 2006), claim that human concept generation requires first acquiring knowledge that serve as seeds of ideas and then processing it to generate concrete solutions. Such 'seeds of ideas' are referred to as 'preinventive structures' in the geneplore model and as 'images' in the SIAM model, respectively. Without external help, an ideator has to repeatedly search the long-term memory (LTM) to obtain seeds of ideas, using cues from the problem statement/definition. Such memory search is not an effortless task; each attempt could take a long time or even fail. The DHSf_LHM would reduce/eliminate the mental burden and processing time for the memory search by providing a well-organized set of seeds of ideas, that is, DHs and example inventions. The savings in cognitive resources and time, in combination with a rich set of readily available knowledge, would improve productivity in concept generation and result in an increase in the total number of distinct ideas within an idea set and the total number of bins. This in turn would proportionally increase the counts of high-novelty, high-quality, and good ideas according to the maxim 'quantity breeds quality' (Diehl & Stroebe, 1987; Parnes & Meadow, 1959).

Second, the DHSf_LHM would function as an aid for working memory (WM) tasks, particularly, information retention. The WM is a temporary storage system and is limited in capacity – it can hold only about seven items at a time, and, without rehearsal, the information content is quickly lost (Atkinson & Shiffrin, 1968). Without external aids, a designer (or individuals in a design team) must rely mostly on the WM system to maintain all the information given and produced during ideation, including the problem statement, seeds of ideas retrieved from the LTM, intermediate ideation results, etc. Due to the limited capacity and volatility of the WM, some of the information may be lost and may not be recovered. This can adversely affect the productivity of ideation. The DHSf_LHM in the form of a booklet functions as the 'knowledge in the world' (Norman, 1988; 1993) and keeps various seeds of ideas intact and available, relieving the burden of information retention in the WM. The ideator can focus on a DH or an example invention one at a time without having to rehearse other information to retain it. Also, any items in the DHSf_LHM can be revisited when necessary at any point during an ideation session. These characteristics of the DHSf_LHM would result in increased quantity of ideas, and, naturally an increase in the counts of high-novelty, high-quality and good ideas.

Third, the DHSf_LHM provides only 'relevant' knowledge for a given design problem, which would enhance the efficiency and quality of the cognitive process. The term 'relevant' here indicates that the DHs and example inventions in the DHSf_LHM have been proven to be useful for accomplishing the design goal X where X is to create assistive products for individuals with limited hand mobility. Such specificity would help an ideator preclude wasting time and cognitive efforts on irrelevant (useless) information. Utilizing previously proven knowledge (knowledge from inventions commercially successful or available in the market) may also increase the probability of producing desirable ideas. This was indeed evidenced in the current study results – the DH group had a good ideas proportion (22%) twice larger than that of the SB group (11%).

Fourth, the DHSf_LHM presents design knowledge in a manner supportive of analogical reasoning. As a promising avenue for fostering innovation, analogical transfer has brought a lot of success (Chan et al., 2011; Dahl & Moreau, 2002; Linsey, Markman, & Wood, 2012; Linsey, Wood, & Markman, 2008; Moreno et al., 2014). The DHSf_LHM offers the sources of analogical transfer at multiple levels of abstraction in the form of a hierarchical DH-tree structure (Figure 3.3) and concrete example inventions (Figure 3.4 and 3.5). Previous research studies (Ball, Ormerad, & Morley, 2004; Lawson, 2004) showed that different individuals prefer and perform better with different levels of abstraction when utilizing analogies for ideation. According to Ball, Ormerad, and Morley (2004), experts tend to use more schema-driven, that is, more general design solutions derived from a number of examples whilst novices tend to use case-driven analogies, that is, analogies where a specific concrete example was used, to develop a new solution. In line with this, Lawson (2004) suggested that when utilizing analogies, novices tend to focus on more superficial characteristics, whereas experts tend to focus on underlying solution principles. The hierarchical, multi-level DH-tree structure of the DHSf_LHM would likely facilitate making source-target connections for ideators with different knowledge and experience levels by providing design knowledge in a hierarchically organized manner.

Overall, the results from the empirical evaluation of the DHSf_LHM support that DHSfXs are promising design aids for assistive product concept generation – they could help assistive product design teams explore solution spaces efficiently and effectively by providing relevant knowledge for meeting specific design goals.

The DHSfXs could be a practical solution to the current lack of specialized CGTs and the low R & D investment typical of assistive product development, and, may play an important role in supporting real-world assistive product design activities. In order for the DHSfXs approach to have a real impact, a large set of DHSfXs covering the wide variety of human disability types will need to be developed and disseminated. This may require collaborative efforts from a large number of people. Also, further empirical validation employing diverse DHSfXs and design problems is warranted to fully establish the utility of DHSfXs. Currently, several DHSfXs for assistive product design are being developed by the authors' research group.

## 4.2 A case study on the effect of DHSfX in portable product domain

### 4.2.1 Introduction

The portable products which are widely used in the various contexts bring about a better quality of life. With the advancement of technology, designers seem to have more opportunities to use new technology such as mobile technology, wearable technology and long-life battery technology into new portable products. Since the initial design of a new product does not appear immediately with the available technology, product designers have to create something that they have never seen before. Also, the typical portable products so far have a unified structure which is noticeable in wearable devices and smartphones; thus, creating new portable product designs deviated from the typical portable designs would be a challenging task for designers.

Despite these challenges, CGTs that support portable product design seem currently lacking. The authors are not aware of such CGTs. Very few CGTs appear to be useful for creating new portable designs for existing products. Effective CGTs that are capable of supporting portable product design will greatly assist individuals and enterprises in converting abundant design knowledge into portable products, and, thereby, creating new values for themselves and for our society.

As an effort to support product concept generation for portable products, the current study proposes the example DHSfX where the design goal X is creating new product concepts for realizing portability (DHSf_P).

This study empirically evaluates the utility of the DHSf_P in the human performance of new product concept generation and compares its effect on creative ideation performance as compared with existing CGTs.

### 4.2.2 Method

The DHSf_P was empirically evaluated in its ability to improve the ideation performance for new portable product concept generation. The empirical evaluation was conducted through comparing the outcomes of two ideation sessions: a brainstorming session without any CGT, and a brainstorming session with the use of the DHSf_P.

#### 4.2.2.1 Study participants

Forty Seoul National University undergraduate and graduate students (25 males and 15 females; mean age 23.4 (*SD*: 2.36) years) majoring in industrial engineering participated. For the purpose of minimizing the variability in prior experience across groups, participants who had previously taken a course on engineering design and had studied some of the widely used CGTs, including standard brainstorming were chosen.

The participants were randomly divided into two groups, one with sixteen and the other with twenty-four. One group, named the standard brainstorming group (Group SB), was to perform brainstorming with no aid, and the other group, named the design heuristic group (Group DH), was to perform brainstorming with the DHSf_P.

#### 4.2.2.2 Experiment task

The experiment task was to generate as many new product concepts as possible for a given concept design problem within a limited time – each participant conducted concept generation individually. The product concept design problem was to redesign instant cup noodles. The problem statement used was as follows: *"Currently, the instant cup noodles are already portable compared with the noodle soups served at restaurants. A food company wishes to improve its cup noodles' portability to the next level so that their next products can have major competitive advantages in the market. The new portable cup noodle design must enable customers to safely and comfortably carry as many units as possible while traveling and use them in any conditions/situations. The new design solution should be inexpensive and convenient to use. The new design solution should not compromise the product quality in terms of appearance and flavor."*

The participants were instructed to use sketches and/or written words to clearly describe their ideas, and, also generate as many ideas as possible during the one-hour time limit.

#### 4.2.2.3 Experimental protocol

Prior to the experiment trials, each participant group was provided a lecture on the corresponding CGT (the standard brainstorming or the DHSf_P). The duration of each lecture was approximately 60 min. The experiment protocol is graphically illustrated in Figure 4.6. The experiment was approved by the Institutional Review Board of Seoul National University.

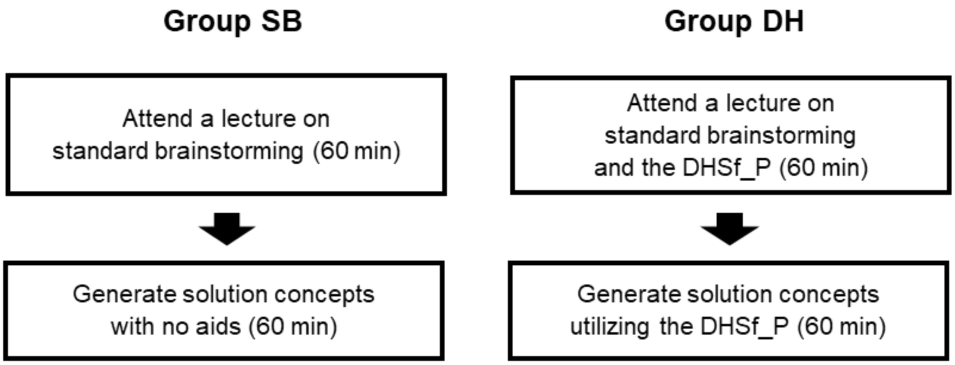



**Figure 4.6** The experiment protocol

The experimenter lectured the background information on standard brainstorming, brainstorming rules and idea-recording procedure. In addition to that, a brief description of the DHSf_P and the procedure of utilizing the booklet describing all DHs given with the corresponding example inventions were introduced to Group DH only.

### 4.2.2.4 Metrics for evaluation

The ideation outcomes generated by the two participant groups were evaluated employing seven evaluation criteria: quantity (the total number of distinct ideas within an idea set and the average number of ideas per participant), variety, three idea evaluation metrics (novelty, workability and relevance), the fixation severity measure, and good-idea criteria (good ideas count and good ideas proportion). For each idea evaluation metric, both the average and maximum values were evaluated. The details of the evaluation criteria were described in Section 4.1.2.4.

An idea's novelty and quality were quantified through experts' subjective ratings. As for novelty, both the average and maximum novelty scores were considered. Note that the average novelty score was computed by calculating the sum of novelty scores of all ideas within the participant divided by the total number of distinct ideas per participant, and the maximum novelty score was determined by selecting the highest novelty score among all ideas within the participant.

The quality metric as proposed by Dean et al. (2006) encompasses dimensions as workability, relevance and specificity. According to Dean et al. (2006), workability expresses how well an idea can be applied from a technical perspective. Relevance refers to the degree to which the concept applies to the problem at hand. An idea's workability and relevance can be quantified through experts' subjective ratings. In this study, specificity was excluded because specificity did not show a strong relationship with the quality measure in the previous studies, and is often discarded as quality measures (Dean et al., 2006). For each quality metric, both the average and the maximum scores were considered. The average workability scores were computed by calculating the sum of workability scores of all ideas within the participant divided by the total number of distinct ideas within an idea set, and the average relevance scores were computed in the same way with the average workability. The maximum workability scores were determined by selecting the highest workability score among all ideas within the participant, and the maximum relevance scores were computed the same way.

In this study, the concept of 'good' idea was suggested as an idea that scores above an arbitrary cutoff point on novelty, workability and relevance. For each participant group, the good idea count was determined by counting the number of ideas whose novelty, workability and relevance scores all exceed a predetermined threshold – in the current study, the threshold is set at the midst of the rating scale (i.e., four on the seven-point rating scale).

#### 4.2.2.5 Evaluation process

Two judges subjectively evaluated all of the ideas without eliminating duplicates within each participant group by using the three idea evaluation metrics; novelty, workability and relevance. Both judges had a bachelor's degree in engineering and a master's degree in a product design-related discipline. The subjective idea evaluation utilized a seven-point Likert scale (Figure 4.7) for each of the three evaluation criteria. For each idea and each evaluation criterion, the average of the two judges' ratings was computed for subsequent data analyses.

Prior to evaluation, the two judges were trained for consistency on their scoring by discussing and reaching common scoring schemes for novelty, workability and relevance. Then, they individually performed subjective ratings on the ideation performance measures. Note that they were both blind to the conditions of the experiment and the hypothesis. After completion, the judges identified the ones that did not reach an agreement, and re-evaluated them and reached a consensus through discussion.

Inter-rater agreements (Cohen's Kappa) for novelty, workability, and relevance were found to be .947, .703 and .875, respectively. According to Landis and Koch (1977), kappa coefficients of novelty and relevance were found to be almost perfectly agreed and that of workability was found to be substantially agreed, assuming that the inter-rater reliability of the subjective ratings was strongly agreed. With raters considered to be in agreement when their ratings differed by no more than one point (Diehl & Stroebe, 1987), the two raters agreed in 96.52% of the novelty ratings, 96.75% of the workability ratings and 98.61% of the relevance ratings. These percentages of absolute agreement reached the acceptable level of agreement (Hartmann, 1977; Stemler, 2004).

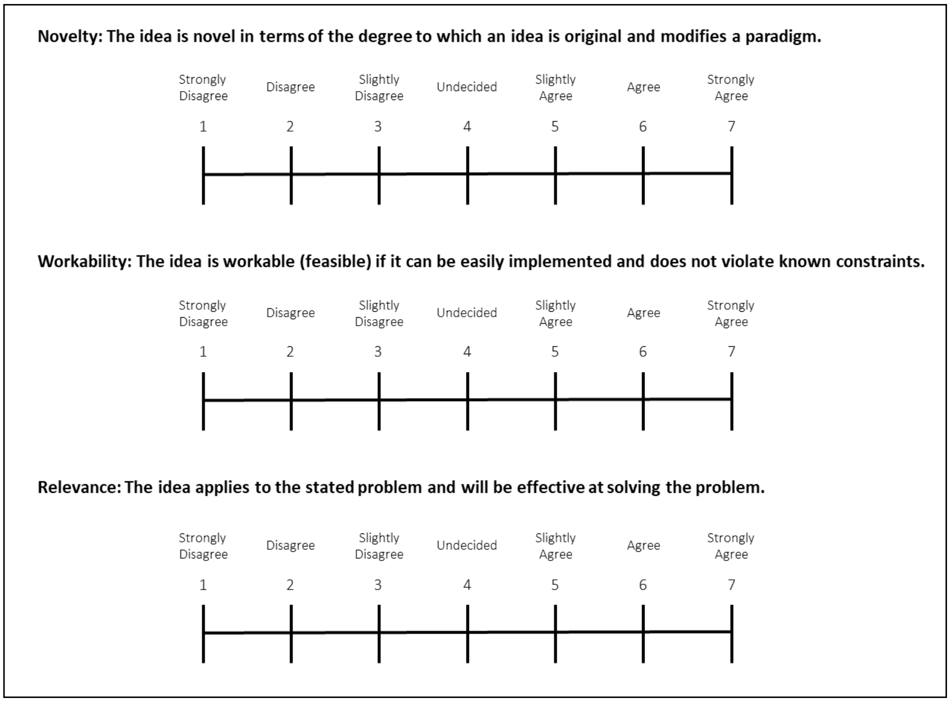


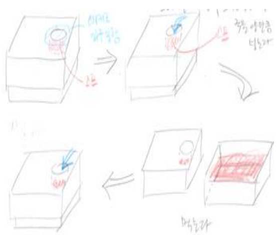
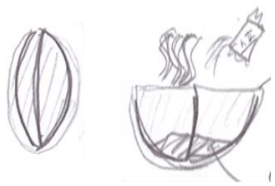

**Figure 4.7** The seven-point Likert scales used for idea evaluation

The two participant groups were compared with each other in each of the metrics described above: the average and maximum novelty scores, the average and maximum workability scores, the average and maximum relevance scores, the total number of distinct ideas within an idea set, the average number of ideas per participant, the variety for each participant group, the fixation score, the good ideas count, and the good ideas proportion. A series of univariate ANOVAs was conducted to statistically compare the means of the two participant groups in the following metrics: the average and maximum novelty scores, the average and maximum workability scores, the average and maximum relevance scores, the average number of ideas per participant, the variety for each participant group, the fixation and the good ideas count. The assumption for homogeneity of variance was validated for all the analyses. The levene's test was conducted to examine the homogeneity of variance. In cases when the homogeneity of variance was violated, we refer to the Welch statistics. In addition to that, a chi-square test was conducted to compare the good ideas proportions of the two participant groups. All statistical tests were conducted at an alpha level of 0.05.

### 4.2.3 Results

For illustration purposes, Table 4.7 provides some example ideas (new noodle cup concepts) generated from the ideation experiment. The six examples were produced by a participant in Group DH. For each example, Table 4.7 presents the design heuristic(s) used as well as the sketch and text description of the idea provided by the participant.

**Table 4.7** Example ideas generated from the ideation experiment

| No. | Design heuristic(s) used | Idea sketch | Text description |
|---|---|---|---|
| 1 | • Shape a product as a container<br>• Make a product fixed to a certain position<br>• Combine multiple products into one |  | Make the container smaller and attach noodle's soup powder beneath the lid. |
| 2 | • Make a product that can transform its shape for easy carriage |  | The noodle cup consists of a plastic skeleton that can be shaped into a bowl and all the ingredients can be placed inside the noodle cup. |

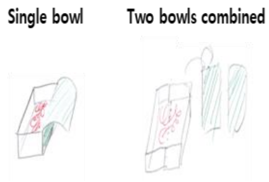
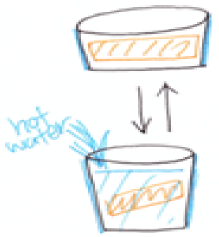
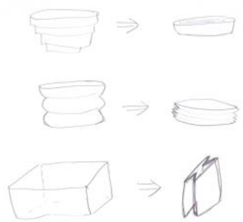
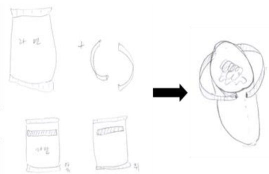
| | | | |
|---|---|---|---|
| 3 | • Divide all components of a product into independent parts<br>• Standardize components of a product |  | The noodle cup is a half-sized cup and rectangular. When combined, two noodle cups become a full-sized cup. |
| 4 | • Make a product that can transform its shape for easy carriage |  | The noodle cup was made up of new materials that keep the original shape in normal temperature but expand its cup when it meets with hot water. |
| 5 | • Place a product inside another product |  | The noodle cup which is a foldable container can be nested inside. |
| 6 | • Provide a product with grips or handles |  | With a frame attached, the noodle can be held with one hand and eat. |

Table 4.8 shows descriptive statistics for means and standard deviations of ten ideation performance measures. Table 4.9 shows summary of one-way analysis of variance for ideation performance measures.

**Table 4.8** Summary of ideation performance measures

| Measure | Participant group | |
|---|---|---|
| | SB (n=16) | DH (n=24) |
| Average Quantity | 6.69 (2.85) | 9.25 (3.64) |
| Average Variety | .20 (.087) | .23 (.092) |
| Fixation | .27 (.20) | .22 (.18) |
| Good ideas count | .56 (.63) | 1.29 (1.20) |
| Average Novelty | 3.04 (.63) | 3.43 (.52) |
| Average Workability | 5.59 (.83) | 5.32 (.65) |
| Average Relevance | 4.67 (.50) | 4.86 (.34) |
| Maximum Novelty | 4.50 (1.07) | 5.46 (.87) |
| Maximum Workability | 6.67 (.54) | 6.65 (.50) |
| Maximum Relevance | 5.41 (.52) | 5.75 (.28) |

*Note.* Standard deviations are in parentheses.

**Table 4.9** One-way analysis of variance for ideation performance measures

| Measure | Source | *df* | *SS* | *MS* | *F* | Sig. |
|---|---|---|---|---|---|---|
| Quantity | Between groups | 63.038 | 1 | 63.038 | 5.624 | .023* |
| | Within groups | 425.937 | 38 | 11.209 | | |
| | Total | 488.975 | 39 | | | |
| Variety | Between groups | .008 | 1 | .008 | .945 | .337 |
| | Within groups | .307 | 38 | .008 | | |
| | Total | .314 | 39 | | | |
| Fixation | Between groups | .029 | 1 | .029 | .796 | .378 |
| | Within groups | 1.370 | 38 | .036 | | |
| | Total | 1.398 | 39 | | | |
| Good-idea-count | Between groups | 5.104 | 1 | 5.104 | 4.987 | .032* |
| | Within groups | 38.896 | 38 | 1.024 | | |
| | Total | 44.000 | 39 | | | |
| Average | Between groups | 1.505 | 1 | 1.505 | 4.749 | .036* |

| | | | | | | |
|---|---|---|---|---|---|---|
| novelty | Within groups | 12.044 | 38 | .317 | | |
| | Total | 13.549 | 39 | | | |
| Average workability | Between groups | .703 | 1 | .703 | 1.329 | .256 |
| | Within groups | 20.105 | 38 | .529 | | |
| | Total | 20.809 | 39 | | | |
| Average relevance | Between groups | .320 | 1 | .320 | 1.895 | .177 |
| | Within groups | 6.412 | 38 | .169 | | |
| | Total | 6.731 | 39 | | | |
| Maximum novelty | Between groups | 8.817 | 1 | 8.817 | 9.723 | .003** |
| | Within groups | 34.458 | 38 | .907 | | |
| | Total | 43.275 | 39 | | | |
| Maximum workability | Between groups | .001 | 1 | .001 | .004 | .950 |
| | Within groups | 10.099 | 38 | .266 | | |
| | Total | 10.100 | 39 | | | |
| Maximum relevance | Between groups | 1.134 | 1 | 1.134 | 4.264 | .046* |
| | Within groups | 10.109 | 38 | .266 | | |
| | Total | 11.244 | 39 | | | |

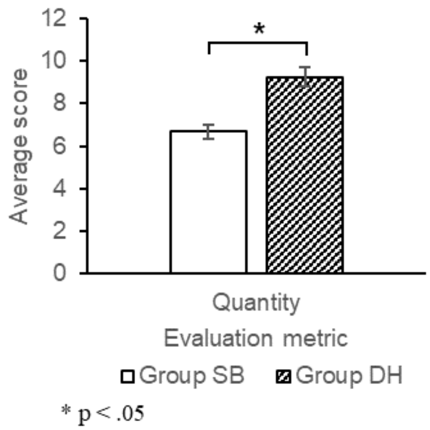
*Note*. * $p < .05$, ** $p < .01$.

The total number of distinct ideas within an idea set of Group SB and Group DH were 44 and 55, respectively. The average number of ideas per participant was compared between the two groups by using the ANOVA (Figure 4.8(a)). The ANOVA results showed that the average number of ideas per participant was significantly different between the two groups, with $F(1, 38) = 5.624$, $p = .023$, and $\eta_p^2 = .129$. This result indicated that the average number of ideas per participant was significantly higher in Group DH ($M = 9.25$, $SD = 3.64$) than SB ($M = 6.69$, $SD = 2.85$, $p < .05$).

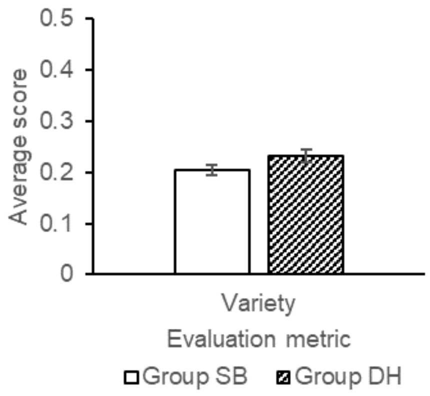
The total bins ideas generated from Group SB and Group DH were 23 and 30 bins, respectively. The mean variety scores were compared between the two groups by using the ANOVA (Figure 4.8(b)). The ANOVA results did not show that the effect of variety was significant, with $F(1, 38) = .945$, $p = .337$, and $\eta_p^2 = .024$.

As shown in Figure 4.8(c), the ANOVA conducted to test the mean difference between the two participant groups in the design fixation severity score did not show any statistically significant between-group difference, with $F(1, 38) = .796$, $p = .378$, and $\eta_p^2 = .021$.

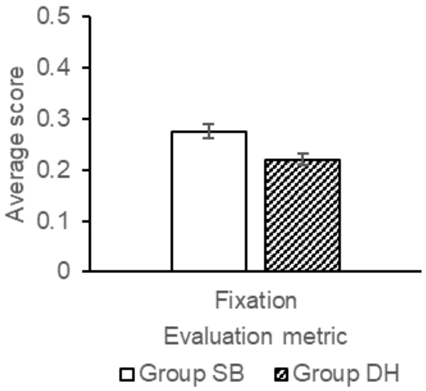
The ANOVA test conducted to compare the two participant groups in the mean good-idea-count showed a statistically significant between-group mean difference, with $F(1, 38) = 4.987$, $p = .032$, and $\eta_p^2 = .116$ (Figure 4.8(d)). This result indicated that the good-idea-count was significantly greater in Group DH ($M = 1.29$, $SD = 1.20$) than SB ($M = .56$, $SD = .63$, $p < .05$).



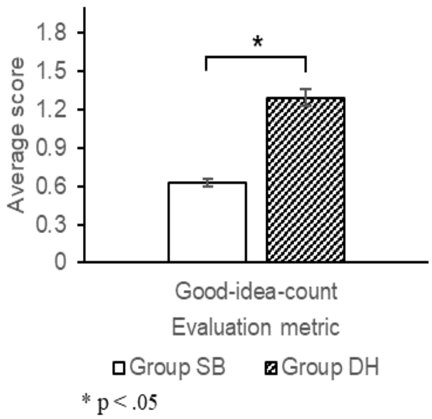

(a)




(b)




(c)




(d)

**Figure 4.8** Mean scores of Groups SB and DH for ideation performance measures: (a) quantity, (b) variety, (c) fixation and (d) good ideas count

Separate univariate ANOVAs on the ratings revealed that a significant difference between the two groups was observed in average novelty: $F(1, 38) = 4.749$, $p = .036$, $\eta_p^2 = .111$; maximum novelty: $F(1, 38) = 9.723$, $p = .003$, $\eta_p^2 = .204$; and maximum relevance, $F(1, 38) = 4.264$, $p = .046$, $\eta_p^2 = .101$. The results indicated that the average novelty was significantly greater in Group DH ($M = 3.43$, $SD = .52$) than Group SB ($M = 3.04$, $SD = .63$, $p < .05$), and maximum novelty was significantly greater in Group DH ($M = 5.46$, $SD = .87$) than Group SB ($M = 4.50$, $SD = 1.06$, $p < .05$). For the maximum relevance scores, Group DH ($M = 5.75$, $SD = .28$) had greater scores than Group SB ($M = 5.41$, $SD = .52$, $p < .05$).

Figure 4.9 presents all the group rating scores for each of the six idea evaluation metrics – Group DH had significantly larger rating scores than Group SB in terms of average novelty, maximum novelty and maximum relevance.

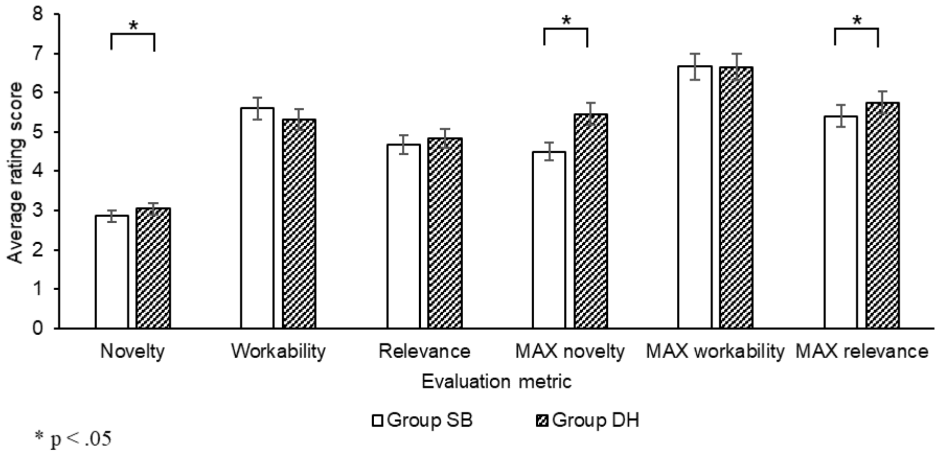



**Figure 4.9** Group mean scores for each of the six evaluation criteria

Figure 4.10 presents only the good ideas (the ideas with two of novelty, workability and relevance scores greater than 4) in the two-dimensional space. Figure 4.10(a) shows the good ideas in the novelty-workability space, Figure 4.10(b) shows the good ideas in the novelty-relevance space and Figure 4.10(c) shows the good ideas in the workability-relevance space. As for the number of good ideas for the novelty-workability space, Groups SB and DH were found to have the good ideas counts of five and fifteen, respectively. As for the number of good ideas for the novelty-relevance space, Groups SB and DH were found to have the good ideas counts of six and sixteen, respectively. Also, for the workability-relevance space, Groups SB and DH were found to have the good ideas counts of thirty-two and forty-one, respectively. In the three-dimensional space (novelty-workability-relevance space), the count number of good ideas for groups SB and DH were found to be five and fourteen, respectively. Overall, Group DH tend to generate more good ideas than Group SB as shown in every two-dimensional solution space. These results showed that ideas generated from Group DH were more likely to be selected as an optimal solution than those from Group SB.

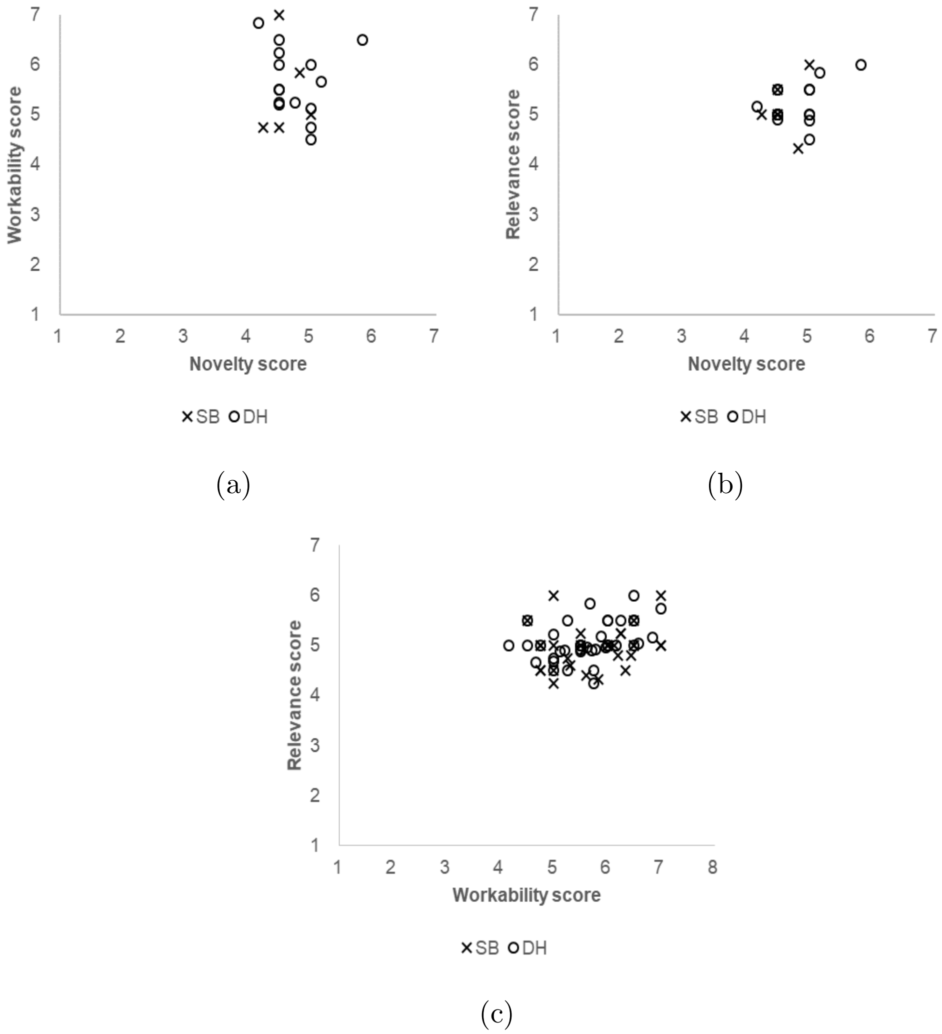



**Figure 4.10** The good ideas presented in (a) the novelty-workability space, (b) the novelty-relevance space, and (c) the workability-relevance space

The corresponding good ideas proportion of Group DH was .25 whereas that of Group SB was only .11. As shown in Table 4.10, the difference in proportions was significant, with $\chi^2$ (1, n = 19) = 4.263, and $p < .05$. The result of the chi-square test revealed that good ideas were not equally distributed between the groups. This indicated that Group DH generated proportionately more good ideas than Group SB. This result gave another evidence that DHSf_P indeed helped designers generate more good ideas than standard brainstorming.

**Table 4.10** Result of Chi-square goodness-of-fit test for good ideas count

| | **Group** | |
|---|---|---|
| | **Standard brainstorming** | **DHSf_P** |
| Observed frequency | 5 | 14 |
| Expected frequency | 8.4 (.44) | 10.6 (.56) |

*Note.* $\chi^2 = 4.263^*$, $df = 1$. Numbers in parentheses are expected proportions.
* $p < .05$

### 4.2.4 Discussion

This study conducted an experiment to empirically evaluate the utility of the DHSf_P against standard brainstorming for portable product concept generation. Two participant groups, Groups SB and DH, performed standard brainstorming to create new noodle cup product concepts. The participants in Group DH performed brainstorming utilizing the DHSf_P while those in Group SB only performed brainstorming. The solution concepts produced by the two participant groups were comparatively evaluated in terms of the average and maximum idea evaluation metrics (novelty, workability and relevance) based on the experts' subjective ratings, the total number of distinct ideas within an idea set, the average number of ideas per participant, the variety for each participant group, the design fixation severity measure, the good ideas count, and the good ideas proportion. Overall, the example DHSf_P was found to positively affect the ideation outcome for product concept generation – as compared with the standard brainstorming it increased the total number of distinct ideas within an idea set, the average number of ideas per participant, the average novelty, the maximum novelty, the maximum relevance, the counts of 'good' ideas, and the good ideas proportion.

The current results demonstrated that the DHSf_P impacted more on quantity measure than standard brainstorming. Group DH produced the higher (total) number of distinct ideas within an idea set than SB. The idea sets SB and DH contained 44 and 55 distinct ideas, respectively. In terms of the average number of ideas per participant (Figure 4.8), the participants in Group DH also produced significantly more ideas (9.25 ideas) than those in Group SB (5.10 ideas). This finding can be explained by the fact that the DHSf_P provided the ideators readily applicable design knowledge for solving the portable product design problem. The more accessibility of design knowledge would likely improve productivity of ideation performance. Ideators were able to associate the closely related design knowledge (DHs) to the given design problem, leading to the increase in productivity. The DHs were known to be helpful for increasing the ideation performance in terms of quantity. According to Yilmaz et al. (2015), having an arsenal of design heuristics as tools led to improvement in the ideation productivity. It was indeed found that the use of the DHSf_P resulted in an increase in the total number of distinct ideas within an idea set and the number of ideas per participant.

The DHSf_P influenced more impact on ideation performance in terms of novelty measure than standard brainstorming. Group DH produced more novel ideas than Group SB (Figure 4.9). The mean novelty in Group DH (3.43) was significantly larger than Group SB (3.04). The significant difference in maximum novelty between groups did not exist. One possible explanation is that the DHSf_P would allow the ideators to facilitate divergent thinking by using the readily accessible DHs with standard brainstorming. Thirteen DHs offered by the DHSf_P, which are closely related to the portability problem, would inform the ideators with various different ways of realizing portability. Exposure to such diverse and relevant design knowledge would allow the ideators to explore a wide solution space and, more likely, to identify the novel solution alternatives. Additionally, the DHs offered by the DHSf_P may help draw analogies which are inspiration sources of creative thinking. Such likelihood of analogical transfer may affect novelty of ideation performance. Prior research provides ample evidence on the impact of analogy on creative concept generation (Dahl & Moreau, 2002; Chan et al., 2011; Linsey, Markman, & Wood, 2012; Linsey, Wood, & Markman, 2008; Moreno et al., 2014). Moreover, the DHSf_P may help the ideators overcome impasse. The DHs may be much helpful especially when ideators have exhausted to generate any more ideas and confronted with impasse. Gray et al. (2015) found that the use of DHs allowed more productive outcomes when the ideators were exhausted to get out first and obvious ideas. It was indeed evidenced in the results of the current study – the average novelty and the maximum novelty measures were reported significantly higher in Group DH than Group SB.

The observed effect of the DHSf_P on workability was not significant; however, as for relevance (usefulness) measure, the DHSf_P impacted more than standard brainstorming. Group DH significantly produced ideas with higher relevance than Group SB (Figure 4.9). Group DH produced ideas with significantly higher maximum relevance (5.75) than Group SB (5.41). This finding can be attributed to the fact that the DHSf_P provides the ideators design knowledge (DHs) which is pre-established as relevant design knowledge for addressing a specific design goal, that is, the creation of portable products. Such relevance or specific design knowledge has been shown to influence concept generation (Mumford et al., 1998; Vincent, Decker, & Mumford, 2002). On the other hand, brainstorming is limited to the ideators' own experience and knowledge, so that it may be difficult to generate useful ideas if the ideators do not have any tacit knowledge or experience on realizing portability.

The participant groups did not show a significant between-group mean difference in the fixation score. This indicated that the external stimuli offered by the DHSf_P have not affected the redundancy of generating similar ideation outcomes. This finding can be inferred that rather than fixated to one feature or a specific example, the ideators utilizing the

DHSf_P were exposed to various inspiration sources which could help avoid fixation. In line with this, previous studies also found that the exposure to various design knowledge improved the variety of ideation outcomes and reduced the fixation effect (Jansson & Smith, 1991; Shah, Kulkarni & Hernandez, 2000; Shah, Smith & Hernandez, 2003; Viswanathan & Linsey, 2011).

Overall, the current study findings showed that the example DHSfX (DHSf_P) in concept generation activities may play an important role especially for portable product designs; therefore, designers can inspire new ways of realizing portability so as to develop various, new creative portable products. In order to have a real impact of the DHSf_P on creative portable product designs, the utility of the DHSf_P will need to be validated in the various contexts of design problems. Further empirical validation employing various design problems for creating portable products is warranted to fully establish the utility of the DHSf_P.

# Chapter 5. A comparative content analysis of the DHSfX and CDHSs

## 5.1 Introduction

Successful problem solving may require to identify useful design knowledge (DHs) among many. As compared with the DHs offered by the DHSfX, the identification of useful DHs from the CDHS for addressing a specific design problem is more challenging. In the case for TRIZ, excessive mental effort and time were required in order to identify technical contradictions. Depending on how to transform a given design problem into technical contradictions, the resulting inventive principles may vary. Also, the 77 Design Heuristics allow designers to select and apply DHs without any pre-determined procedure; however, there exists too many DHs to be selected from, which makes it difficult and effortful to use. It may bring about the possibility of finding different DHs among the ideators, most of which are dependent on their own perception when identifying the relevant DHs for the given design problem.

Despite the challenges on utilizing the CDHS for solving a particular design problem with the design goal X, however, a question remains about whether the relevant DHs identified from the CDHS are able to cover all the potential solution space explored by the DHs of the DHSfX. Currently, few studies were conducted to compare similarities and differences observed in the DHs between the CDHSs and DHSfXs. By addressing the aforementioned question, the more thorough understanding on how different design knowledge can be offered by both DHSs, and how they would influence differently on ideation performance. Also, the distinct characteristics underlying in the DHs offered by the DHSfX and the CDHS would be identified.

As an effort to address this question, the current study performed content analyses between the DHSs to present how much the DHs or design strategies offered by the DHSs are similar or different from one another. This study conducted a comparative content analysis between the example DHSfX and two CDHSs, that is, the TRIZ 40 inventive principles (Altshuller, 1996) and the 77 Design Heuristics (Daly et al., 2012; Yilmaz et al., 2012; Yilmaz et al., 2014; Yilmaz & Seifert, 2011; Yilmaz, Seifert, & Gonzalez, 2010). In this study, the comparison was conducted between the DHSf_LHM and other CDHSs. The objective of this current study was to examine the extent to which the DHSf_LHM differs from the CDHSs in the information content (the DHs) on the basis of the perception of product designers.

## 5.2 Method

A group of 20 designers participated in this study (see Appendix F.1). At the time of participation, each participant had a master's degree in a design discipline and had prior experience in assistive and/or ergonomic product design.

Each participant was instructed to examine all 40 DHs in the TRIZ 40 inventive principles and all 77 DHs in the 77 Design Heuristics, and identify the one he/she thought was semantically equivalent or similar enough to be considered semantically equivalent to each of the DHs in the DHSf_LHM. Such similarity or equivalence detection task was referred to as 'examine and identify the equivalent' task. The participants were asked to perform two 'examine and identify the equivalent' tasks for both the TRIZ 40 inventive principles and the 77 Design Heuristics.

## 5.3 Results

The results of the 'examine and identify the equivalent' tasks were summarized in Table 5.1. In Table 5.1, for each DH of the DHSf_LHM, the DH in each of the two CDHSs for which the largest number of participants responded 'equivalent' was presented, along with the percentage and number of the participants.

Table 5.1 showed that very few DHs in the TRIZ 40 inventive principles or the 77 Design Heuristics were perceived as equivalent to a DH in the DHSf_LHM by a majority of the 20 participants. In fact, only two cases were found that had a percentage value greater than 50% (10 out of the 20 participants):

- 'Merge two products into one' (DHSf_LHM) and 'Merging' (TRIZ 40 inventive principles) with 65% (13 participants out of 20), and
- 'Attach the product to a body part(s)' (DHSf_LHM) and 'Attach product to user' (77 Design Heuristics) with 55% (11 participants out of 20).

**Table 5.1** Comparison of the DHSf_LHM and two existing CDHSs (the TRIZ 40 inventive principles and the 77 Design Heuristics)

| **DHSf_LHM** | **TRIZ 40 Inventive Principles** | **77 Design Heuristics** |
|---|---|---|
| Attach the product to a body part(s) | Merging | Attach product to user |
| | 40% (8/20) | 55% (11/20) |
| Design the product operable with one hand | Segmentation | Adjust function through movement |

| | | |
|---|---|---|
| and a non-hand body part | 20% (4/20) | 20% (4/20) |
| Fix the product using a holding or support aid | Preliminary action | Use common base to hold components |
| | 15% (3/20) | 30% (6/20) |
| Integrate one-hand gesture control to the product | Merging | Incorporate user input |
| | 25% (5/20) | 20% (4/20) |
| Merge two products into one | Merging | Add to existing product |
| | 65% (13/20) | 35% (7/20) |
| Offer an attachable accessory for the product | Intermediary | Offer optional components |
| | 25% (5/20) | 35% (7/20) |
| Permanently integrate hand/finger rings into the product | Preliminary action | Attach independent functional components |
| | 15% (3/20) | 25% (5/20) |
| Place controls/grips of the product within the hand's functional range | Preliminary action | Align components around center |
| | 30% (6/20) | 25% (5/20) |
| Provide a mechanical extension along with the product | Intermediary | Expand or collapse |
| | 15% (3/20) | 25% (5/20) |
| Provide a shape maintaining aid along with the product | Preliminary action | Offer optional components |
| | 20% (4/20) | 15% (3/20) |
| Replace bi-manual | Merging | Apply existing |

| | | |
|---|---|---|
| motions with a single hand's gripping/squeezing | | mechanism in new way |
| | 20% (4/20) | 15% (3/20) |
| Replace bi-manual motions with a single hand's pressing/pushing | The other way round | Apply existing mechanism in new way |
| | 20% (4/20) | 15% (3/20) |
| Turn the product into a motion-activated one | Dynamics | Add motion |
| | 20% (4/20) | 50% (10/20) |

## 5.4 Discussion

In this study, the DH content of the DHSfX, especially DHSf_LHM, was compared with other CDHSs (77 Design Heuristics and TRIZ 40 inventive principles). The rationale for basing the comparison of DHSs on the designers' perception was as follows:

- It was the users of DHs who should decide whether or not DHs presented in different DHSs were semantically equivalent (or similar enough to be considered semantically equivalent),
- If designers perceived two DHs as equivalent, then only one of them can be provided to designers without any loss of information; on the other hand, if designers perceived two DHs as not equivalent, then one cannot replace the other as they convey different information, and
- Different designers would interpret a DH differently due to inherent individual differences, and, hence, different designers could have different opinions as to the equivalence of two DHs; therefore, the view shared by the majority of designers should become the basis for the final judgment as to whether or not two DHs were semantically equivalent.

An interesting observation of this current study was that the DHSf_LHM was found to significantly differ from two available CDHSs (the TRIZ 40 inventive principles and the 77 Design Heuristics) in the information content (Table 5.1) – Table 5.1 showed that very few DHs in the TRIZ 40 inventive principles or the 77 Design Heuristics were perceived as equivalent to a DH in the DHSf_LHM by a majority of 20 designers. The observed difference showed that 1) a DHSf_LHM provided design knowledge that designers did not perceive as equivalent to that in the existing CDHSs and 2) a DHSf_LHM indeed had specificity (providing only the knowledge relevant to the given design goal X), which was not supported by the CDHSs. The difference between the DHSf_LHM and the CDHSs suggested that DHSfXs were unique and could make additional contributions to product concept generation problems.

It should be noted that DHSfXs by no means replaced the existing CDHSs – DHSfXs and the existing CDHSs were intended to address different design needs. If a designer wanted to work with a large, general set of DHs that were derived from numerous patents in engineering or many excellent industrial design examples, they should consider utilizing the TRIZ 40 inventive principles or the 77 Design Heuristics because a DHSfX for a particular design goal X would not provide enough needed information.

Another observation was that the TRIZ 40 inventive principles were often evaluated as similar to multiple DHs in DHSfX. This finding can be explained by the fact that the DH, which was considered by a wide and vast amount of patents in the case of TRIZ, provided meanings that contained specific DHs of the DHSfX in various viewpoints.

# Chapter 6. A comparison of the DHSfX against TRIZ

## 6.1 Introduction

An approach of utilizing the DHs has been used for enhancing designers' abilities for creative concept generation activities. Multiple previous studies demonstrated that the DHs offered by CDHSs have shown positive influence on ideation performance (Birdi, Leach, & Wissam, 2012; Chang et al., 2016; Chulvi et al., 2013; Daly et al., 2012; Dumas & Schmidt, 2015; Hernandez et al., 2014; Hernandez, Schmidt, & Okudan, 2013; Hernandez et al., 2010; Ogot & Okudan, 2007; Okudan, Ogot, & Shirwaiker, 2006; Yilmaz et al., 2012; Yilmaz et al., 2014). Overall, DHSs offering DHs are currently known to be effective for creative concept generation activities in comparison with a brainstorming technique or rather than even without any aids.

With a new classification scheme of the DHSs, however, 'comprehensive' and 'goal-directed' DHSs may have different influence on the ideation performance. It seems that developing and utilizing the DHSfX for innovative product design offers some obvious advantages over the CDHS. First, the DHSfX for addressing a specific design goal will be more likely to be applied to a given problem and help generate many diverse ideas. The closer the relationship between external stimuli and the given design problem, the more likely they are to be associated with the problem (Cheong & Shu, 2013; Tseng et al., 2008). The likelihood of generating solutions may lead to creative solutions of the design problem at hand.

Second, the DHSfX offers readily applicable DHs, so that it does not require cognitive effort to find appropriate and useful DHs, and apply them to the given design problem. On the contrary, as the CDHS includes a vast amount of design knowledge (DHs), designers need to identify which of the DHs would be appropriate to apply to the given design problem. For example, TRIZ requires extensive training for the designers to effectively utilize the inventive principles for generating solutions (Ilevbare, Probert, & phaal, 2013). In addition, the CDHS contains a few DHs that may not be related to the given problem. Consequently, the ideators may have irrelevant information for their concept generation which could act as a distractor, that is, a hindrance to generating creative ideas.

Despite the aforementioned benefits of the DHSfX over the CDHS, however, few studies seem to have examined the effect of the DHSfX over the CDHS on an empirical basis. Therefore, this study aimed to investigate the effect of an example DHSfX against one of the well-known CDHSs, that is, the TRIZ 40 inventive principles. In this study, the effect of the DHSfX was validated by using the DHSf_P, and the design problem of creating portable products was considered. The design problem of creating portable product seems to be an intriguing problem because integrating portability requires great advanced technology into the current product domain, and such innovative portable products are not currently existing in various product domains except mobile devices and wearables. This is a typical open-ended design problem in which designers try to maximize their abilities to create new, varied concepts.

## 6.2 Method

The DHSf_P was empirically evaluated in its ability to improve the ideation performance for new portable product concept generation. The empirical evaluation was conducted through comparing the outcomes of two ideation sessions: a brainstorming session with the use of the DHSf_P and a brainstorming session with TRIZ 40 inventive principles and the contradiction matrix.

### 6.2.1 Study participants

Forty-four Seoul National University undergraduate and graduate students (26 males and 18 females; mean age 25.1 (*SD*: 3.70) years) majoring in industrial engineering participated. All of the participants had previously taken a course on engineering design and had studied some widely used CGTs, including brainstorming and mind mapping.

The participants were randomly divided into two groups, one with twenty-four students and the other with twenty. One group, named the DHs group (Group DH), was to perform brainstorming with the DHSf_P, and the other group, named the TRIZ group (Group TRIZ), was to perform brainstorming with the TRIZ 40 inventive principles and the contradiction matrix.

### 6.2.2 Experiment task

The experiment task was to generate as many new product concepts as possible for a given concept design problem within limited time – each participant conducted idea generation individually. The product concept design problem was to redesign instant cup noodles. The same problem statement described in Section 4.2.2.2 was used.

The participants were instructed to use sketches and/or written words to clearly describe their ideas, and, also generate as many ideas as possible. The time limit was one-hour. As mentioned earlier, the participants in Group DH were allowed to freely use the DHs and example inventions in the DHSf_P booklet while brainstorming. Those in Group TRIZ were instructed to follow the general procedure of the TRIZ methodology.

### 6.2.3 Experimental protocol

Before each experiment, there was a lecture elucidating and detailing one of the DHSs (the DHSf_P and the TRIZ 40 inventive principles). The duration of each lecture was approximately 60 minutes. The experiment protocol is graphically illustrated in Figure 6.1. The experiment was approved by the Institutional Review Board of Seoul National University.

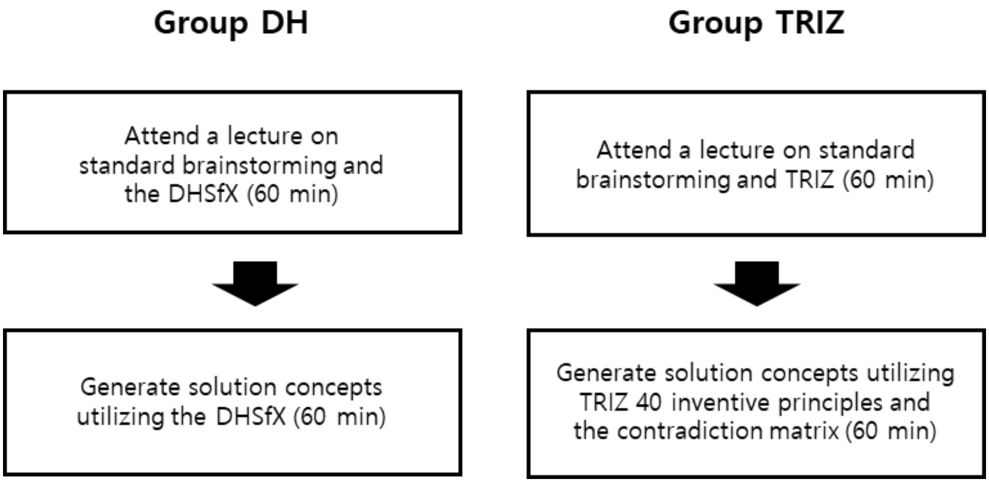



**Figure 6.1** The experiment protocol

The lecture included background information on brainstorming, brainstorming rules, and idea-recording procedure. Additionally, for Group DH, a brief description of the DHSfX and the procedure of utilizing the booklet describing all DHs given with the corresponding example inventions were introduced. For Group TRIZ, the lecture focused on the concept of the TRIZ 40 inventive principles and the procedure of how to use them with the contradiction matrix. Hardcopies of the 40 inventive principles and the contradiction matrix were provided during the lecture and the design experiment.

### 6.2.4 Metrics for evaluation

The ideation outcomes generated by the two participant groups were evaluated employing seven evaluation criteria: quantity (the total number of distinct ideas within an idea set and the average number of ideas per participant), variety, three idea evaluation metrics (novelty, workability and relevance), the fixation severity measure, and good-idea criteria (good ideas count and good ideas proportion). For each idea evaluation metric, both the average and maximum values were evaluated. The details of the evaluation criteria were described in Section 4.1.2.4.

### 6.2.5 Evaluation process

The evaluation process employing the evaluation criteria was also described in Section 4.2.2.5. Inter-rater agreements (Cohen's Kappa) for novelty, workability, and relevance were found to be .935, .892 and .957, respectively. According to Landis and Koch (1977), kappa coefficients of novelty, workability and relevance were found to be almost perfectly agreed, assuming that the inter-rater reliability of the subjective ratings was strongly agreed. With raters considered to be in agreement when their ratings differed by no more than one point (Diehl & Stroebe, 1987), the two raters agreed in 97.53% of the novelty ratings, 96.60% of the workability ratings and 98.46% of the relevance ratings. These percentages of absolute agreement reached the acceptable level of agreement (Hartmann, 1977; Stemler, 2004).

The two participant groups were compared with each other in each of the metrics described above: the average and maximum novelty scores, the average and maximum workability scores, the average and maximum relevance scores, the total number of distinct ideas within an idea set, the average number of ideas per participant, the variety for each participant group, the fixation, the good ideas count, and the good ideas proportion. A series of univariate ANOVAs was conducted to statistically compare the means of the two participant groups in the following metrics: the average and maximum novelty scores, the average and maximum workability scores, the average and maximum relevance scores, the average number of ideas per participant, the variety for each participant group, the fixation and the good ideas count. The assumption for homogeneity of variance was validated for all the analyses. The levene's test was conducted to examine the homogeneity of variance. In cases when the homogeneity of variance was violated, we refer to the Welch statistics. In addition to that, a chi-square test was conducted to compare the good ideas proportions of the two participant groups. All statistical tests were conducted at an alpha level of .05.

## 6.3 Results

As for the TRIZ 40 inventive principles, the ideators identified a few technical contradictions underlying in the portability design problem and further utilized the resulting inventive principles. As a result, the ideators identified on average 2.05 contradictions which may be offered with 8 or less resulting inventive principles. The number of inventive principles the ideators have adopted during concept generation was on average 5.35. While using the DHSf_P, the ideators were provided with the entire set of DHs (25 DHs), and the DHs were applied to the given design problem for about 9.92 times on average.

Table 6.1 shows descriptive statistics for means and standard deviations of ten ideation performance measures. Table 6.2 shows summary of one-way analysis of variance for ideation performance measures.

**Table 6.1** Descriptive statistics of ideation performance measures by condition

| Measure | Participant group | |
|---|---|---|
| | **TRIZ (n=20)** | **DH (n=24)** |
| Average Quantity | 5.10 (2.38) | 9.25 (3.64) |
| Average Variety | .16 (.072) | .23 (.092) |
| Fixation | .13 (.18) | .22 (.18) |
| Good ideas count | .35 (.67) | 1.29 (1.20) |
| Average Novelty | 2.96 (.65) | 3.43 (.52) |
| Maximum Novelty | 4.28 (1.43) | 5.46 (.87) |
| Average Workability | 4.90 (.61) | 5.32 (.65) |
| Maximum Workability | 6.00 (.54) | 6.65 (.50) |
| Average Relevance | 4.58 (.23) | 4.86 (.34) |

| | | |
|---|---|---|
| Maximum Relevance | 5.13 (.51) | 5.75 (.28) |

*Note*. Standard deviations are in parentheses.

**Table 6.2** One-way analysis of variance for ideation performance measures

| Measure | Source | *df* | *SS* | *MS* | *F* | Sig. |
|---|---|---|---|---|---|---|
| Quantity | Between groups | 1 | 187.882 | 187.882 | 19.139 | <.001*** |
| | Within groups | 42 | 412.300 | 9.817 | | |
| | Total | 43 | 600.182 | | | |
| Variety | Between groups | 1 | .058 | .058 | 8.277 | .006** |
| | Within groups | 42 | .293 | .007 | | |
| | Total | 43 | .351 | | | |
| Fixation | Between groups | 1 | .097 | .097 | 2.980 | .092 |
| | Within groups | 42 | 1.369 | .033 | | |
| | Total | 43 | 1.466 | | | |
| Good idea count | Between groups | 1 | 9.763 | 9.763 | 9.788 | .003** |
| | Within groups | 42 | 41.508 | .988 | | |
| | Total | 43 | 51.182 | | | |
| Average novelty | Between groups | 1 | 2.439 | 2.439 | 7.218 | .010* |
| | Within groups | 42 | 14.194 | .338 | | |
| | Total | 43 | 16.633 | | | |
| Average workability | Between groups | 1 | 1.988 | 1.988 | 4.951 | .031* |
| | Within groups | 42 | 16.861 | .401 | | |
| | Total | 43 | 18.849 | | | |
| Average relevance | Between groups | 1 | .841 | .841 | 9.619 | .003** |
| | Within groups | 42 | 3.673 | .087 | | |
| | Total | 43 | 4.515 | | | |
| Maximum novelty | Between groups | 1 | 15.276 | 15.276 | 11.417 | .002** |
| | Within groups | 42 | 56.196 | 1.338 | | |
| | Total | 43 | 71.471 | | | |
| Maximum | Between groups | 1 | 4.550 | 4.550 | 17.003 | <.001*** |

| | | | | | | |
|---|---|---|---|---|---|---|
| workability | Within groups | 42 | 11.240 | .268 | | |
| | Total | 43 | 15.790 | | | |
| Maximum relevance | Between groups | 1 | 4.261 | 4.261 | 24.064 | <.001*** |
| | Within groups | 42 | 7.438 | .177 | | |
| | Total | 43 | 11.699 | | | |

*Note*. * $p < .05$, ** $p < .01$, *** $p < .001$.

The total number of distinct ideas generated by Group DH and Group TRIZ were 55 and 45, respectively. Figure 6.2(a) presented the average number of ideas per participant for Groups DH and TRIZ. The ANOVA results showed that the average number of ideas per participant was significantly different between the two groups, with $F(1, 42) = 19.139$, $p < .001$, and $\eta_p^2 = .313$. This result indicated that the average number of ideas per participant was significantly higher in Group DH ($M = 9.25$, $SD = 3.64$) than TRIZ ($M = 5.10$, $SD = 2.38$, $p < .001$).

The total bins of ideas generated from Group DH and Group TRIZ were 30 and 27 bins, respectively. The ANOVA results showed that the effect on the variety was significant, with $F(1, 42) = 8.277$, $p = .006$, and $\eta_p^2 = .165$. As shown in Figure 6.2(b), this result indicated that Group DH ($M = .23$, $SD = .092$) produced the more variety of ideas than Group TRIZ ($M = .16$, $SD = .072$, $p < .01$).

As shown in Figure 6.2(c), the ANOVA conducted to test the mean difference between the two participant groups in the design fixation score did not show any statistically significant between-group difference, with $F(1, 42) = 2.980$, $p = .092$, and $\eta_p^2 = .066$.

The ANOVA test conducted to compare the two participant groups in the mean good-idea-count identified a statistically significant between-group mean difference (Figure 6.2(d)), with $F(1, 37.205) = 10.787$, $p = .002$, and $\eta_p^2 = .189$. This result indicated that significantly more number of good ideas were generated by Group DH ($M = 1.29$, $SD = 1.20$) than Group TRIZ ($M = .35$, $SD = .67$, $p < .01$).

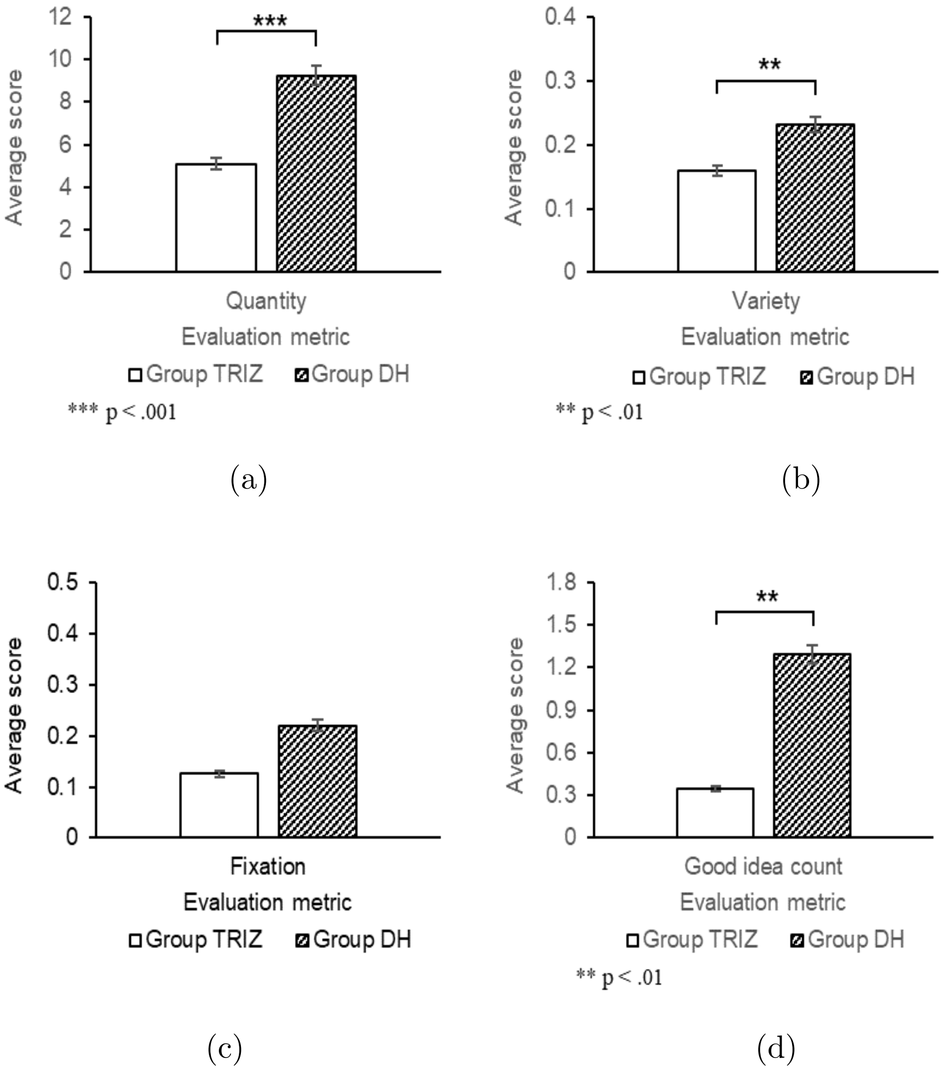



**Figure 6.2** Mean scores of Groups DH and TRIZ for ideation performance

measures: (a) quantity, (b) variety, (c) fixation and (d) good ideas count

Separate univariate ANOVAs on the ratings revealed that a significant difference between the two groups was observed in average novelty: $F(1, 42) = 7.218$, $p = .010$, $\eta_p^2 = .147$; maximum novelty: $F(1, 30.216) = 10.484$, $p = .003$, $\eta_p^2 = .214$; average workability: $F(1, 42) = 4.951$, $p = .031$, $\eta_p^2 = .105$; maximum workability: $F(1, 42) = 17.003$, $p < .001$, $\eta_p^2 = .288$; average relevance: $F(1, 42) = 9.619$, $p = .003$, $\eta_p^2 = .186$, and maximum relevance, $F(1, 36.451) = 26.659$, $p < .001$, $\eta_p^2 = .364$. The results indicated that the average novelty was significantly greater in Group DH ($M = 3.43$, $SD = .52$) than Group TRIZ ($M = 2.96$, $SD = .65$, p $< .05$), and maximum novelty was significantly greater in Group DH ($M = 5.46$, $SD = .87$) than Group TRIZ ($M = 4.28$, $SD = 1.43$, $p < .001$). As for workability, both average and maximum workability were greater in Group DH than Group TRIZ. Accordingly, the average workability was significantly greater in Group DH ($M = 5.32$, $SD = .65$) than Group TRIZ ($M = 4.90$, $SD = .61$, p $< .05$), and the maximum workability was also greater in Group DH ($M = 6.65$, $SD = .50$) than Group TRIZ ($M = 6.00$, $SD = .54$, $p < .001$). For the average relevance scores, Group DH ($M = 4.86$, $SD = .34$) had greater scores than Group TRIZ ($M = 4.58$, $SD = .23$, $p < .01$); and for the maximum relevance scores, Group DH ($M = 5.75$, $SD = .28$) had greater scores than Group TRIZ ($M = 5.13$, $SD = .51$, $p < .001$).

Figure 6.3 presents all the group rating scores for each of the six idea evaluation metrics – Group DH had significantly larger rating scores than Group TRIZ.


**Figure 6.3** Group mean scores for each of the three evaluation criteria

Figure 6.4 presents only the good ideas in the solution space. Figure 6.4(a) shows the good ideas (the ideas with both novelty and workability scores greater than 4) in the novelty-workability space, Figure 6.4(b) shows the good ideas (the ideas with both novelty and relevance scores greater than 4) in the novelty-relevance space, and Figure 6.4(c) shows the good ideas (the ideas with both workability and relevance scores greater than 4) in the workability-relevance space. As for the number of good ideas for the novelty-workability space, Groups TRIZ and DH were found to have the good ideas counts of three and fifteen, respectively. As for the number of good ideas for the novelty-relevance space, Groups TRIZ and DH were found to have the good ideas counts of three and sixteen, respectively. As for the number of good ideas for the workability-relevance space, Groups TRIZ and DH were found to have the good ideas counts of thirty-one and forty-one, respectively. In the three-dimensional space (novelty-workability-relevance space), the count number of good ideas for groups TRIZ and DH were found to be two and fourteen, respectively. Overall, Group DH tend to generate more good ideas than Group TRIZ as shown in every two-dimensional solution space. These results showed that ideas generated from Group DH were more likely to be selected as an optimal solution than those from Group TRIZ.

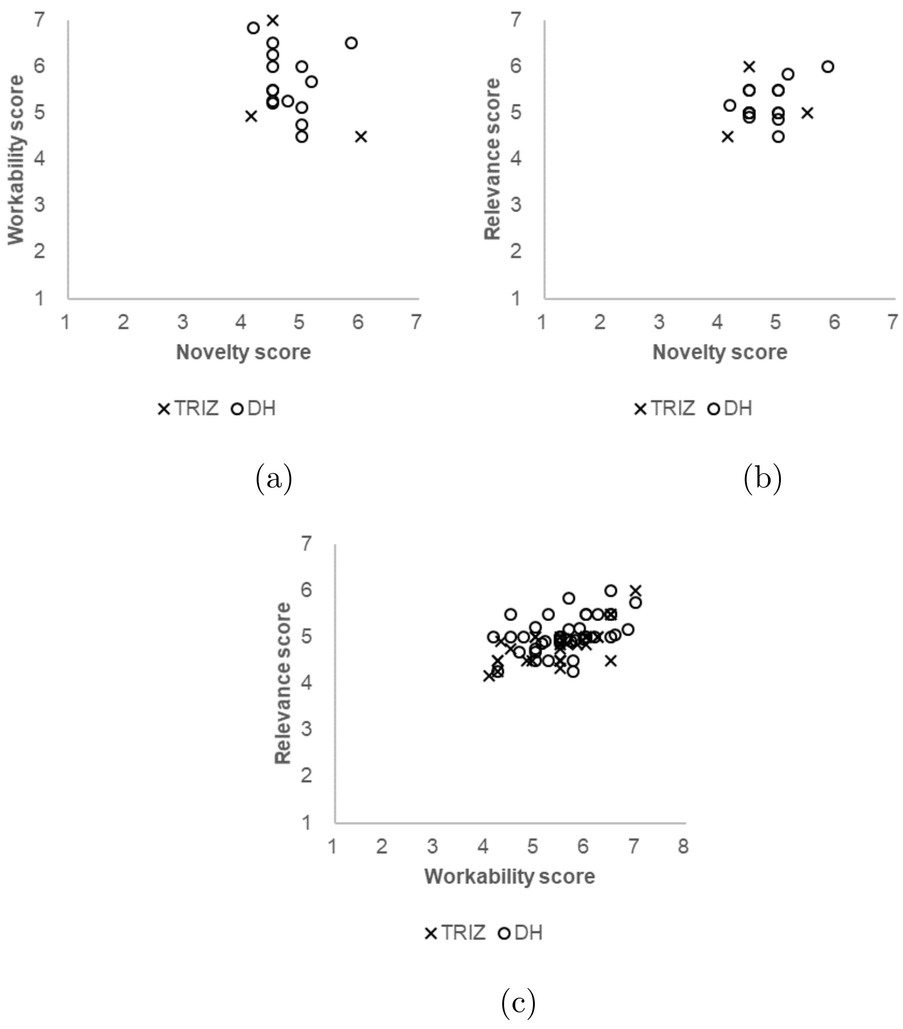



**Figure 6.4** The good ideas presented in (a) the novelty-workability space, (b) the novelty-relevance space, and (c) the workability-relevance space

The corresponding good ideas proportion of Group DH was .25 whereas that of Group TRIZ was only .04. As shown in Table 6.3, the difference in proportions was significant, with $\chi^2$ (1, n = 16) = 6.828, and $p < .01$. The result of the chi-square test revealed that good ideas were not equally distributed between the groups. This indicated that Group DH generated proportionately more good ideas than Group TRIZ. This result gave another evidence that DHSf_P indeed help designers generate more good ideas than TRIZ.

**Table 6.3** Result of Chi-square goodness-of-fit test for good ideas count

| | **Group** | |
|---|---|---|
| | **TRIZ** | **DHSf_P** |
| Observed frequency | 2 | 14 |
| Expected frequency | 7.2 (.45) | 8.8 (.55) |

*Note.* $\chi^2 = 6.828^{**}$, $df = 1$. Numbers in parentheses are expected proportions.
** $p < .01$

## 6.4 Discussion

This current study examined the effect of the DHSf_P against the TRIZ 40 inventive principles. Two participant groups, Groups DH and TRIZ, performed individual brainstorming to create new noodle cup product concepts. The participants in Group DH performed brainstorming utilizing the DHSf_P while those in Group TRIZ performed brainstorming utilizing the TRIZ 40 inventive principles with the contradiction matrix. The solutions produced by the two participant groups were comparatively evaluated in terms of the average number of ideas per participant, the variety for each participant group, the fixation score, the good ideas count and the average and maximum idea evaluation metrics (novelty, workability and relevance) based on the experts' subjective ratings. Overall, the DHSf_P was found to improve the ideation performance for product concept generation as compared with TRIZ – the DHSf_P was superior to TRIZ across all of the ideation performance measures except the fixation score.

The DHSf_P had more impact on ideation performance in terms of quantity measure than the TRIZ 40 inventive principles and the contradiction matrix. Group DH produced more ideas than Group TRIZ. The total number of distinct ideas within an idea set generated by the Groups DH and TRIZ contained 55 and 45 ideas, respectively. In terms of the average number of ideas per participant, the participants in Group DH also produced significantly more ideas (9.25 ideas) than those in Group TRIZ (5.10 ideas) as shown in Figure 6.2(a). This finding can be explained by the effect of mental burden associated with the concept generation process. TRIZ required the identification of technical contradictions prior to obtaining the suggested inventive principles based on the contradiction.

Such preparatory task may demand mental workload; each attempt can take a long time and designers may fail to identify appropriate contradiction related to the design problem even after such attempts. As for the DHSf_P, the ideators can strictly manipulate well-organized, readily applicable design knowledge (DHs) without performing any preparatory task – the ideators may reduce/eliminate the mental burden and directly generate idea alternatives. This finding broadly supports the work of De Dreu et al. (2012), stating that significant mental burden on individuals negatively affect creative ideation performance. In line with this, it was also found that the increased mental workload can decrease creative human performance (Drews et al., 2009; Wickens & Hollands, 2000). Therefore, the savings in mental burden and time by the use of the DHSf_P would improve productivity in concept generation. Additionally, a richer set of readily available knowledge offered by the DHSf_P would improve productivity more so than TRIZ. The current study results showed that on average, 9.92 DHs of the DHSf_P were applied to the design problem whereas 5.35 inventive principles followed by the identification of technical contradictions and contradiction matrix were applied to the problem. The high accessibility of design knowledge for the DHSf_P would likely facilitate generation of many solution ideas. It was indeed found that the use of the DHSf_P resulted in an increase in the total number of distinct ideas within an idea set and the number of ideas per participant as compared with TRIZ.

The current study results also demonstrated that the DHSf_P caused more impact on the variety measure than the TRIZ 40 inventive principles. Group DH produced more diverse ideas than Group TRIZ. The idea sets DH and TRIZ contained 30 and 27 bins, respectively. As shown in Figure 6.2(b), the participants in Group DH also produced significantly more varieties of ideas (.23) on average than those in Group TRIZ (.16). This finding can be accounted for by the exposure to various design knowledge. The study results showed that the ideators were exposed to eight different branches of DH categories (second-order DHs) followed by twenty-five DHs while the ideators were exposed to less than eight inventive principles resulting from only two technical contradictions on average. Previous studies have demonstrated that participants tend to generate more diverse ideas if exposed to ideas from a wide range of semantic categories (Amabile, 1998; Kurtoglu, Campbell, & Linsey, 2009; Liikkanen & Perttula, 2010; Nijstad, Stroebe, & Lodewijkx, 2002; Valacich et al., 1995). Additionally, the DHSf_P would facilitate divergent thinking by using the readily accessible DHs with standard brainstorming. On the contrary, the ideators using TRIZ may not be able to identify all possible technical contradictions underlying in the portable product design problem. If all possible technical contradictions are not fully constructed, search for solutions would be limited. As the more limited the quantity and possible manipulations are, the lower the achievable solution diversity and quality will be (Birkhofer, 2011).

As a result of this study, Group DH produced more novel ideas than Group TRIZ (Figure 6.3). The mean novelty in Group DH (3.43) was significantly greater than Group TRIZ (2.96). Also, Group DH produced ideas with higher maximum novelty (5.46) than Group TRIZ (4.28). The relatively higher novelty scores observed in Group DH may be explained by the fact that design knowledge offered by the DHSf_P is closely related to the design problem. Perhaps, the ideators in Group DH may have been encouraged to generate solution alternatives with knowing that the DHs were derived from the analyses of useful inventions for addressing the given design problem. Such encouragement facilitated more frequent analogical transfer of knowledge, and thus, it helped generate more novel solution alternatives (Chan et al., 2011; Dahl & Moreau, 2002; Linsey, Markman & Wood, 2012; Linsey, Wood, & Markman, 2008; Moreno et al., 2014). On the other hand, the TRIZ 40 inventive principles and the corresponding examples did not appear to be readily applicable to the portable product design problem because the inventive principles (DHs) were only general suggestions that have proven fruitful in previous engineering problems. From the analogical transfer standpoint, the corresponding examples offered by TRIZ may be irrelevant to the portability design problem; thus, TRIZ required excessive mental effort for associating examples to the portability design problem. Such barrier could demand more mental effort and thus reduce analogical transfer, which may bring about the generation of low novelty ideas.

Group DH produced ideas with higher workability than Group TRIZ (Figure 6.3). The mean workability in Group DH (5.32) was significantly greater than Group TRIZ (4.90). In addition, Group DH produced ideas with higher maximum workability (6.65) than Group TRIZ (6.00). One possibility for the greater impact of the DHSf_P on workability scores against the TRIZ 40 inventive principles may be due to the possible failures when utilizing prior cases or previous design strategies offered by TRIZ for the given portable product design context. The ideators using TRIZ may not be able to identify all possible technical contradictions underlying in the portable product design problem. The current study results showed that in 8 cases out of 48 technical contradictions, the ideators failed to identify the relevant technical contradictions for realizing portability. Such failures on the identification of technical contradictions may lead to suggesting irrelevant design knowledge; in these cases, the ideators may have suffered cognitive barriers in associating irrelevant knowledge with the given design problem, and have failed to detect potential associations. Such irrelevant examples may serve as distractors for resolving the given design problem, and thus, negatively impact the workability measure. On the contrary, the previously proven knowledge (knowledge from inventions commercially successful or available in the market) offered by the DHSf_P may help the ideators generate feasible solution ideas. The example inventions that satisfy a specific design goal X, that is, to realize portability, may be closely related to the typical portable products in terms of structural and/or behavioral similarities. It can, therefore, be assumed that as compared with the TRIZ 40 inventive principles, the DHSf_P influenced more on the workability scores.

The current study also demonstrated that the DHSf_P helped generate more relevant (useful) ideas than the TRIZ 40 inventive principles. Group DH produced ideas with higher relevance than Group TRIZ (Figure 6.3). The mean relevance in Group DH (4.86) was significantly greater than Group TRIZ (4.58). Group DH produced ideas with higher maximum relevance (5.75) than Group TRIZ (5.12). One way to interpret this finding is that the DHSf_P provides relevant knowledge and experience on how to realize portability for the creation of portable products to the ideators. Such relevance of design knowledge has been shown to positively influence creative ideation performance (Mumford et al., 1998; Schwartz, Bransford, & Sears, 2005; Vincent, Decker, & Mumford, 2002). On the other hand, the TRIZ 40 inventive principles do not offer the extensive design knowledge specifically for addressing portability, but for solving a technical contradiction. There may exist some knowledge gaps between the technical contradiction and the portability problem. Perhaps, the direct association of design knowledge for addressing a technical contradiction to the portable product design problem may have been difficult, and thus, the fewer number of useful ideas could be observed. It was indeed evidenced in the results of the current study – the relevance and further good ideas count measures were reported significantly higher in Group DH than Group TRIZ.

Significant difference on the fixation metric was not observed between the participant groups. This indicated that either of the ideators utilizing the DHSf_P and TRIZ have not shown any tendency of focusing on a specific feature of the examples and/or abstract stimuli, that is, the DHs or the inventive principles. One explanation could be that offering various, readily accessible inspiration sources may help the ideators avoid fixation. Even though the DHs and the corresponding inventions seem to offer closely related design knowledge for resolving the portability problem, exposure to the variety of the DHs and examples which can be easily transferred into the given problem may help the ideators not to be focused on one feature or a specific example. Previous research also supported that exposure to a variety of design knowledge could improve the variety of the ideation outcomes, and further avoid the fixation effect (Jansson & Smith, 1991; Shah, Kulkarni, & Hernandez, 2000; Shah, Smith, & Hernandez, 2003; Viswanathan & Linsey, 2011).

One interesting observation of this study was that the DHSf_P facilitated the ideators to combine multiple DHs more frequently than the TRIZ 40 inventive principles – about 45.9% of the solution ideas generated from the DHSf_P were combined with multiple DHs whereas only 4.9% of the solution ideas from the TRIZ 40 inventive principles and the contradiction matrix were generated with multiple inventive principles. It may be explained by the fact that some example inventions were collected for the construction of DHs in multiple times, meaning that they share more than one commonality in their underlying design features. Such duplicate example inventions utilized for the extraction of DHs may affect ideators' concept generation behaviors. If a specific example invention utilized for the multiple DHs, the possibility of combining multiple DHs while designers generate solution alternatives would increase, and thus, it is likely that the more solution alternatives may have been originated from the combination of multiple DHs. On the contrary, the TRIZ 40 inventive principles seem to be mutually exclusive, which may account for the small percentage of ideas generated through combination of inventive principles.

Overall, the results from the comparative empirical investigation of the DHSf_P and TRIZ supported that the effect of the DHSf_P had more impact on ideation outcomes than the TRIZ 40 inventive principles – the DHSf_P could help product design teams explore solution spaces efficiently and effectively, and also cost less information access effort than TRIZ.

The current study results should be interpreted with caution in that the utility of each DHS may be different from one another. The DHSfX may be well-suited for situations where designers facilitate convergent and divergent thinking skills to generate new design alternatives for achieving a particular design goal X, especially during the concept generation phase of the design process. On the other hand, TRIZ does not seem to be appropriate for resolving a specific design problem because its capability is widely variable depending on the type of problems being solved. According to Mann (2000), the likelihood of contradiction matrix recommending 'correct' inventive principles decreases when the contradiction refers to complex mechanical or electrical related issues. From this reason, designers may have to examine all 40 of the inventive principles, trying to make connections with the problem at hand. Therefore, this finding could be contributed to designers who need to select the most effective CGT on their product concept generation project. It may also contribute to maximizing the designers' creative thinking abilities.

# Chapter 7. Conclusion

## 7.1 Summary

The objective of the current study was to introduce a DHSfX as an approach to product design concept generation, and to empirically investigate the effect of the DHSfX on ideation performance. The dissertation consisted of four major research studies in relation to the research objectives.

In research 1 (Chapter 3), the generic process of constructing the DHSfX was introduced. This process consists of keyword search for describing a design goal X, data collection of relevant inventions, and extraction of the underlying design idea. In this study, two example DHSfXs, DHSf_LHM and DHSf_P, were developed. As a result, a total of 13 DHs for DHSf_LHM and 25 DHs for DHSf_P have been extracted for creating assistive products and portable products, respectively.

In research 2 (Chapter 4), the effects of example DHSfXs (i.e., DHSf_LHM and DHSf_P) on the ideation performance were examined against standard brainstorming. The design briefs were to create new Rubik's cube for one handed people and to redesign the current cup noodle into the more portable product. The results of data analyses showed that the DHSfXs influenced more impact on the ideation performance than standard brainstorming.

In research 3 (Chapter 5), a comparative analysis of information content across the example DHSfX (DHSf_LHM), the TRIZ 40 inventive principles and the 77 Design Heuristics was conducted. The analysis was to evaluate practitioners' similarity judgments between the DHs offered by different DHSs. The results of the data analysis showed that the DHs offered by the DHSf_LHM seem to be differentiated with the TRIZ 40 inventive principles or the 77 Design Heuristics on many occasions. This indicated that the development of the DHSfX added unique value to the existing DHSs such as the TRIZ 40 inventive principles and the 77 Design Heuristics, as DHs offered by DHSfXs were perceived as different with other DHs of CDHSs based on the subjective similarity judgment.

In research 4 (Chapter 6), the effect of the example DHSfX (DHSf_P) on the ideation performance were examined against the TRIZ 40 inventive principles. The data analyses revealed significant difference between the DHSfX and the TRIZ 40 inventive principles.

## 7.2 Implications of the research

This study demonstrated that the DHSfXs can help enhance designers' abilities to create new product concept designs of existing products. While the use of DHs for design itself is not a new idea (Altshuller, 1996; Daly et al., 2012; Eberle, 1996; Hwang & Park, 2015; Singh et al., 2007; Weaver et al., 2010; Yilmaz et al., 2012), the approach of developing and utilizing DHSfXs specific to design goals Xs for product concept generation represents a new contribution to product design.

The current study suggested a new classification scheme of DHSs into two large categories: DHSfXs and CDHSs. It was the first to compare the DHSfX and the CDHS with regard to their impact on ideation performance. This study also showed that DHSfXs could make unique contributions to product design concept generation in addition to the existing CDHSs, such as the TRIZ 40 inventive principles and the 77 Design Heuristics. The study results provided valuable information that it was worth deriving such goal specific design knowledge that was not fully discovered by existing CDHSs. Such results may contribute to the future efforts for systematically producing more DHSfXs for important design goals, and further, constructing a system of a DHSfX.

In this study, a generic process of constructing the DHSfX was established. Throughout the generic construction process, two example DHSfXs, DHSf_LHM and DHSf_P, were developed. The empirical evidence showed that the example DHSfXs indeed helped the ideators to gain new, relevant product design knowledge for solving real world design problems in the domains of assistive products and portable products. The current study findings may help understand and predict the impacts of

DHSfXs on ideation performance in a variety of situations where the designers need to generate practical product concept solutions in various product domains.

The DHSfXs could be a practical solution to the lack of previous design knowledge on addressing a specific design goal and may play a central role in supporting new design activities for existing products. This approach of utilizing the DHSfX on the new product design activities may also be effective at other product domains by setting up various design goal Xs. The current study findings may contribute as an intermediate step towards establishing possibilities of developing systems of the DHSfXs. It would provide great value if the designers or design teams are able to find useful design knowledge to solve problems in their ongoing design projects at hand.

In this study, the effects of the DHSfX were discussed from various viewpoints such as the geneplore model, the SIAM model, and the human mental process; this enabled an in-depth understanding of which the DHs helped design practitioners on achieving their creative performance while concept generation.

## 7.3 Limitations and future works

Limitations of the current study are recognized along with some future research directions: first, the current study presented only few empirical evidence for supporting the utility of the DHSfX concept – only two design goal Xs (i.e., creating products for one-handed persons and creating new portable products) were considered in the empirical evaluation study. In order to further generalize the utility of the DHSfX concept, more empirical studies with different design goals (Xs) will need to be conducted.

Second, it should be noted that the KJ method utilized to construct a DHSfX is costly in that it is time-consuming and requires much human efforts. This limitation can hinder developing DHSfXs in a timely manner. Thus, a more automated process for constructing DHSfXs will need to be developed.

Third, the current study was conducted with undergraduate and graduate engineering students. From the education standpoint, the DHSfX would provide benefits for novice designers who can learn from the DHs offered by the DHSfX and use them in their own design projects. On the other hand, it needs to be addressed whether expert designers who already have tacit knowledge and experience can also benefit from the DHSfX when dealing with their real world product design problems. Future work should explore the generalizability of these findings for different expertise levels and across different backgrounds.

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# Appendix A. A DHS for creating products for individuals with limited hand mobility

## Design principles for accommodating individuals with limited hand mobility

Version 2.0

Dongwook Hwang and Woojin Park

Life Enhancing Technology Lab
Seoul National University


## Attach the product to a body part(s)

- A product can be manipulated with one hand by attaching the product to a body part(s) using additional components (i.e., straps, holders, etc.).

## Design the product operable with one hand and a non-hand body part

- A product can be manipulated using one hand with the help of a non-hand body part.


## Fix the product using a holding or support aid

- Fixed in position, a product can be manipulated to perform tasks with one hand

# Integrate one-hand gesture control to the product

- A product can be manipulated with one hand by integrating one-hand gesture control to the product.

**Design Problem**

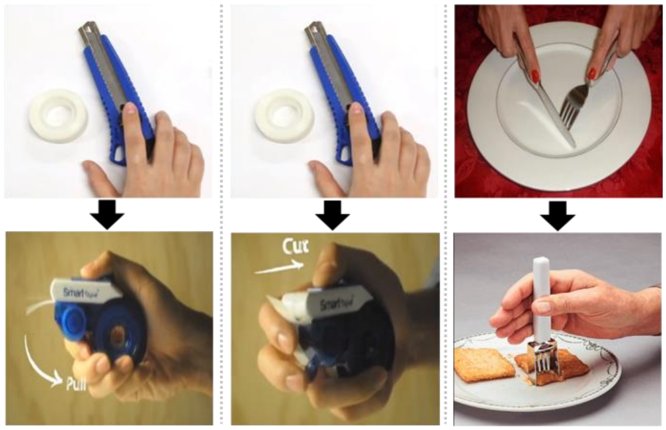
**Design Solution**

# Merge two products into one

- A product can be manipulated with one hand by integrating multiple functions originally accomplished by separate products into the product.

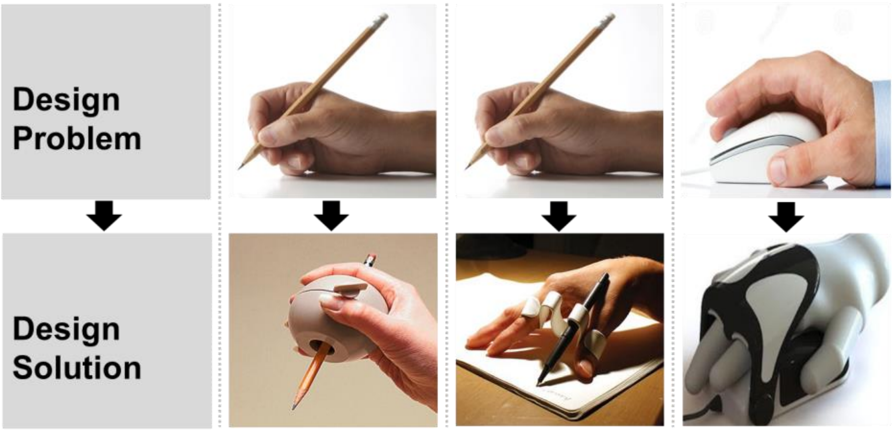
**Design Problem**

**Design Solution**



## Offer an attachable accessory for the product

- A product can be manipulated with one hand by offering an attachable accessory for the product.




## Permanently integrate hand/finger rings into the product

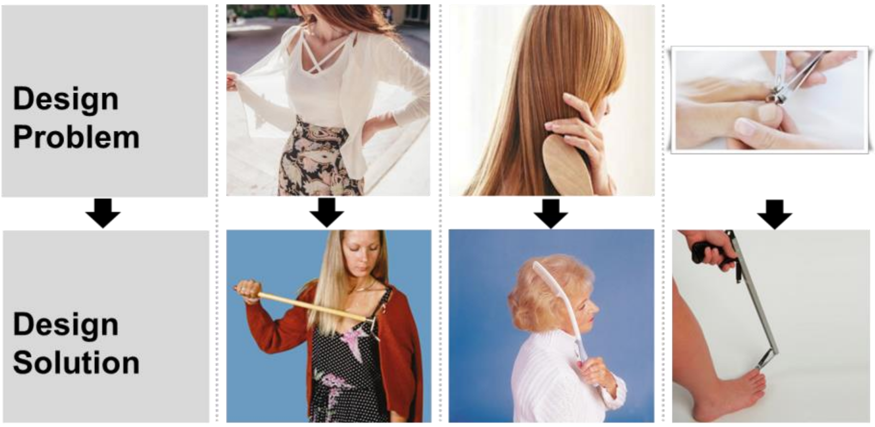
- A product can be manipulated with one hand by integrating hand/finger rings into the product.

## Place controls/grips of the product within the hand's functional range

- A product can be manipulated with one hand by placing controls or grips within the hand's functional range.


## Provide a mechanical extension along with the product

- A product can be manipulated with one hand by providing a mechanical extension (i.e., a reacher grabber, a button hook, etc.) to extend the user's hand reach and manipulation abilities.



## Provide a shape maintaining aid along with the product

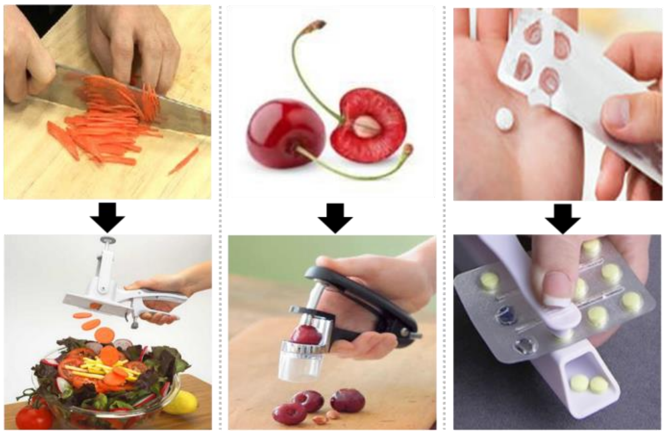
- A product can be manipulated with one hand using a shape maintaining aid (i.e., a shell, a frame, etc.).

**Design Problem** ↓ **Design Solution**

## Replace bi-manual motions with a single hand's gripping/squeezing

- Operate devices with gripping/squeezing motion
- Turn two hands operation into single hand gripping/squeezing motion

**Design Problem** ↓ **Design Solution**

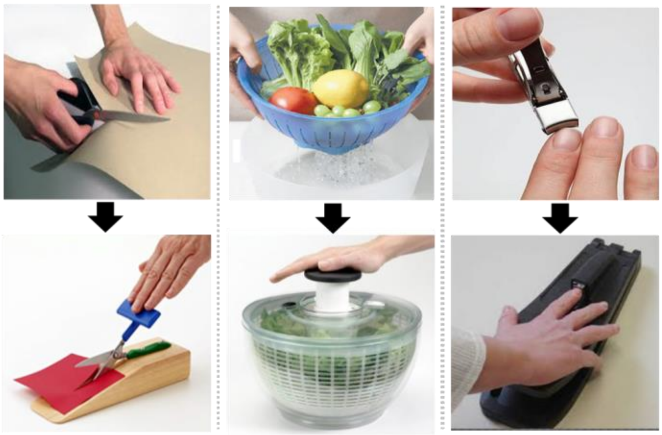


## Replace bi-manual motions with a single hand's pressing/pushing

- Change necessary movement type
- A product can be manipulated using one-hand motions (i.e., pressing or pushing).

**Design Problem**

**Design Solution**



## Turn the product into a motion-activated one

- A product can be manipulated with one hand if its operation is fully or partially automated with sensors and actuators.

**Design Problem**

**Design Solution**

# Appendix B. A DHS for creating portable products

## Design principles for creating portable products

Version 2.0

Dongwook Hwang and Woojin Park

Life Enhancing Technology Lab
Seoul National University


## Make a product that can transform its shape for easy carriage

- A product can be turned into a portable product by transforming its shape for easy carriage (e.g. fold, roll, etc.)

## Divide all components of a product into independent parts

- A product can be reduced in size by dividing it into independent parts or making it sectional.

| | | | |
|---|---|---|---|
| **Design Problem** |  |  |  |
| **Design Solution** |  |  |  |

## Place a product inside another product

- A product can be reduced in size by placing it inside another product.

| | | | |
|---|---|---|---|
| **Design Problem** |  |  |  |
| **Design Solution** |  |  |  |

## Use elastic materials in product

- A product can be turned into a portable product by utilizing elasticity.

Design Problem

Design Solution

## Use waterproof materials in product

- A product can be turned into a portable product by adopting waterproof materials.

Design Problem

Design Solution

## Use flexible materials in product

- A product can be turned into a portable product by adopting flexible materials to the product.


## Use light materials in product

- A product can be turned into a portable product by using light materials to be able to hold with hand(s) only.

## Use a rigid outer protection on a product

- A product can be turned into a portable product by using a rigid outer protection on the product.


## Shape a product as a container

- A product can be turned into a portable product by making the product shaped like a container.

## Utilize a product with what is already portable

- A product can be turned into a portable product by utilizing what is already portable for the use of the product.

**Design Problem**

↓

**Design Solution**

## Extract essential parts from a product

- A product can be turned into a portable product by extracting only essential parts of the product.

**Design Problem**

↓

**Design Solution**

## Standardize components of a product

- A product can be turned into a portable product by standardizing its components and interfaces, making the product adaptable with others.

**Design Problem**

**Design Solution**


## Utilize an intermediary or connector for the use of a product

- A product can be turned into a portable product by utilizing an intermediary or a connector when two or more products are not standardized.

**Design Problem**

**Design Solution**

## Integrate a battery into a product

- A product can be turned into a portable product by integrating a battery into the product.

**Design Problem**



**Design Solution**



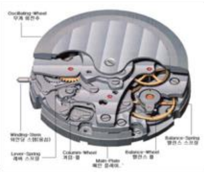
## Make an energy-harvesting product

- A product can be turned into a portable product by making the product harvest energy by itself and utilize the energy during its use.

**Design Problem**



**Design Solution**


## Attach an energy conversion device on a product

- A product can be turned into a portable product by making the product self-generate the energy necessary for its use via an energy conversion device.


## Organize/unclutter all the components of a product

- A product can be turned into a portable product by grouping related components to perform functions of the product.

## Combine multiple products into one

- A product can be turned into a portable product by combining multiple entities with different functions into one entity.

**Design Problem** ↓ **Design Solution**

## Add multiple functions to a product

- A product can be turned into a portable product by adding multiple functions to the product.

**Design Problem** ↓ **Design Solution**

## Make a product less stressful on human body

- A product can be turned into a portable product by making it inflict less stress on the human body.


## Provide a product with grips or handles

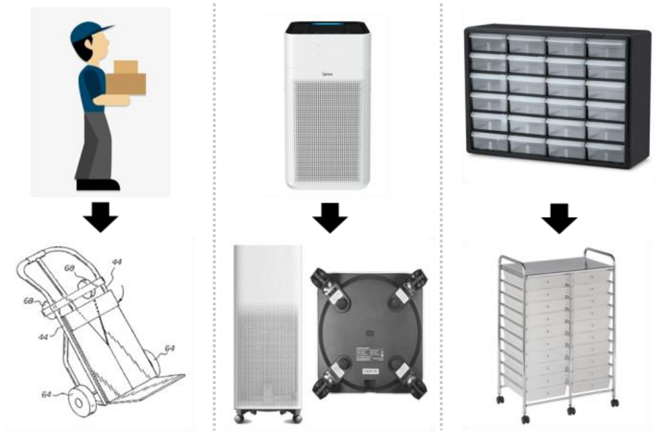
- A product can be turned into a portable product by providing a product with grips or handles.

## Attach wheels to a product

- A product can be turned into a portable product by attaching wheels to an object.

**Design Problem**

**Design Solution**



## Provide a product with adjustable components

- A product can be turned into a portable product by providing a product adjustability to enhance flexibility.

**Design Problem**

**Design Solution**

## Make a product fixed to a certain position

- A product can be turned into a portable product by fixing it to a certain position, preventing it from falling down and getting damaged.


## Attach a product to other body parts

- A product can be turned into a portable product by designing the product to be wearable.

# Appendix C. The design brief for redesigning a Rubik's Cube

<u>Design Problem Description (Time Limit: 60 minutes)</u>
CubeWorld Co. Ltd., a toy company that produces educational toys, wants to solve a difficult design problem. They have hired you for design problem solving as you are a world-renown expert of innovative product design who took Dr. Park's course on creative thinking ☺

The design problem pertains to their existing product "Rubik's cube" (See Exhibit 1).

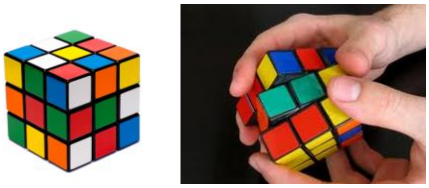


Exhibit 1. Rubik's cube

The product has been a great success in the market. However, CubeWorld wishes to improve their market share even more by creating a new innovative product that even people with limited hand mobility, especially one-handed individuals, can use (See Exhibit 2). Currently, one-handed individuals find it difficult to play with the original Rubik's cube.

Exhibit 2. Potential one-handed customers

The design requirements for the new product are as follows:

- One-handed customers should be able to easily and efficiently play with the product
- **While the new product does not have to resemble the original Rubik's cube in the mechanism design and other aspects, the new product should allow playing the very same 3D puzzle game. In other words, the new product should be identical to the original one in terms of the product functions.**
- The new product should be inexpensive and easy to carry.

**Develop as many solution concepts as possible. Use the individual brainstorming technique.** Clearly describe them in the following blank pages – provide sketches and/or verbal descriptions as needed (you can choose to use either English or Korean for verbal descriptions). 10 blank pages are provided. If you need more, then ask the TA.

# Appendix D. The design brief for redesigning an instant noodle cup

<u>Design Problem Description (Time Limit: 60 minutes)</u>
Long Shim Co. Ltd., a food company that produces instant noodles and snacks, wants to solve a difficult design problem. They have hired you for problem-solving as you are a world-renown expert of portable product design who took Dr. Park's course on creative thinking ☺

The design problem pertains to the portability of their product "Bowl Noodle Soup." It is a typical instant cup noodle as shown in Exhibit 1.


Exhibit 1. Long Shim Bowl Noodle Soup

The product is already portable (compared with the noodle soups served at restaurants). However, Long Shim wishes to improve its portability to the next level so that their next-generation noodle soup product can have major competitive advantages over the competitors' products. Especially, they want the customers to be able to:

- Safely carry as many units as possible while traveling, and
- Use the product in any conditions/situations.

Also, the new design solutions should be inexpensive and convenient to use. Finally, the new design solutions should not compromise the product quality (content and taste).

# Appendix E. Tests of homogeneity of variances for a comparison between standard brainstorming and DHSf_P

Table E.1 Test of homogeneity of variances for ideation performance measures

| **Measure** | **Levene Statistic** | ***df1*** | ***df2*** | **Sig.** |
|---|---|---|---|---|
| Quantity | .813 | 1 | 38 | .373 |
| Variety | .333 | 1 | 38 | .567 |
| Fixation | .130 | 1 | 38 | .721 |
| Good-idea-count | 5.493 | 1 | 38 | .024 |
| Average Novelty | 1.250 | 1 | 38 | .271 |
| Maximum Novelty | .304 | 1 | 38 | .585 |
| Average Workability | 3.298 | 1 | 38 | .077 |
| Maximum Workability | .033 | 1 | 38 | .858 |
| Average Relevance | 1.371 | 1 | 38 | .249 |
| Maximum Relevance | .064 | 1 | 38 | .802 |

# Appendix F. Background information of designers for a comparative content analysis between DHSf_P and TRIZ

Table F.1 Background information about 20 designers participated in Research 3

| Designer | Age | Major | Degree |
|---|---|---|---|
| Designer 1 | 24 | Mechanical Engineering | Master's |
| Designer 2 | 24 | Industrial Engineering | Master's |
| Designer 3 | 26 | Industrial Engineering | Master's |
| Designer 4 | 27 | Industrial Engineering | Master's |
| Designer 5 | 27 | Industrial Engineering | Master's |
| Designer 6 | 27 | Industrial Engineering | Master's |
| Designer 7 | 28 | Industrial Engineering | Master's |
| Designer 8 | 28 | Industrial Engineering | Master's |
| Designer 9 | 36 | Psychology | Ph.D. candidate |
| Designer 10 | 25 | Industrial Engineering | Ph.D. candidate |
| Designer 11 | 27 | Industrial Engineering | Ph.D. candidate |
| Designer 12 | 28 | Industrial Engineering | Ph.D. candidate |
| Designer 13 | 30 | Industrial Engineering | Ph.D. candidate |
| Designer 14 | 30 | Industrial Engineering | Ph.D. candidate |
| Designer 15 | 31 | Industrial Engineering | Ph.D. candidate |
| Designer 16 | 31 | Industrial Engineering | Ph.D. candidate |
| Designer 17 | 32 | Industrial Engineering | Ph.D. candidate |
| Designer 18 | 34 | Industrial Engineering | Ph.D. candidate |
| Designer 19 | 33 | Industrial Engineering | Ph.D. |
| Designer 20 | 34 | Industrial Engineering | Ph.D. |

# Appendix G. Tests of homogeneity of variances for a comparison between DHSf_P and TRIZ

Table G.1 Tests of homogeneity of variances for ideation performance measures

| Measure | Levene Statistic | *df1* | *df2* | Sig. |
|---|---|---|---|---|
| Quantity | 3.027 | 1 | 42 | .089 |
| Variety | .018 | 1 | 42 | .893 |
| Fixation | .259 | 1 | 42 | .614 |
| Good-idea-count | 6.885 | 1 | 42 | .012 |
| Average Novelty | 1.423 | 1 | 42 | .240 |
| Maximum Novelty | 15.648 | 1 | 42 | .000 |
| Average Workability | .217 | 1 | 42 | .644 |
| Maximum Workability | .390 | 1 | 42 | .536 |
| Average Relevance | 1.148 | 1 | 42 | .290 |
| Maximum Relevance | 12.646 | 1 | 42 | .001 |

# Appendix H. Raw data for ideation performance measures between standard brainstorming and DHSf_LHM

Table H.1 Summary of ideation performance for a group comparison

| Group | Quantity | Bins | Variety | Novelty | Quality | Good idea count | Good idea proportion | Fixation | Rarity |
|---|---|---|---|---|---|---|---|---|---|
| Brainstorming | 7.00 | 5.00 | 0.25 | 5.21 | 3.93 | 1.00 | 0.14 | 0.40 | 0.88 |
| Brainstorming | 6.00 | 6.00 | 0.30 | 4.58 | 3.83 | 2.00 | 0.33 | 0.00 | 0.88 |
| Brainstorming | 6.00 | 5.00 | 0.25 | 3.33 | 3.83 | 0.00 | 0.00 | 0.20 | 0.85 |
| Brainstorming | 11.00 | 8.00 | 0.40 | 3.23 | 3.73 | 0.00 | 0.00 | 0.38 | 0.87 |
| Brainstorming | 8.00 | 7.00 | 0.35 | 4.88 | 3.38 | 1.00 | 0.13 | 0.14 | 0.92 |
| Brainstorming | 6.00 | 5.00 | 0.25 | 3.83 | 4.58 | 1.00 | 0.17 | 0.20 | 0.88 |
| Brainstorming | 8.00 | 7.00 | 0.35 | 4.13 | 3.50 | 0.00 | 0.00 | 0.14 | 0.88 |
| Brainstorming | 4.00 | 3.00 | 0.15 | 2.88 | 3.13 | 0.00 | 0.00 | 0.33 | 0.86 |
| Brainstorming | 5.00 | 4.00 | 0.20 | 4.90 | 4.30 | 2.00 | 0.40 | 0.25 | 0.90 |
| Brainstorming | 9.00 | 9.00 | 0.45 | 4.22 | 4.11 | 1.00 | 0.11 | 0.00 | 0.90 |
| Brainstorming | 5.00 | 5.00 | 0.25 | 4.10 | 4.10 | 0.00 | 0.00 | 0.00 | 0.88 |
| Brainstorming | 8.00 | 8.00 | 0.40 | 3.83 | 4.33 | 1.00 | 0.13 | 0.00 | 0.85 |
| Brainstorming | 12.00 | 7.00 | 0.35 | 3.83 | 3.79 | 1.00 | 0.08 | 0.71 | 0.86 |
| Brainstorming | 5.00 | 5.00 | 0.25 | 4.70 | 3.50 | 1.00 | 0.20 | 0.00 | 0.88 |
| Brainstorming | 6.00 | 5.00 | 0.25 | 4.58 | 3.50 | 0.00 | 0.00 | 0.20 | 0.91 |
| Brainstorming | 10.00 | 6.00 | 0.30 | 3.60 | 3.75 | 0.00 | 0.00 | 0.67 | 0.89 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| DHSf_LHM | 13.00 | 10.00 | 0.30 | 4.58 | 4.58 | 6.00 | 0.46 | 0.30 | 0.93 |
| DHSf_LHM | 8.00 | 8.00 | 0.24 | 4.38 | 3.75 | 2.00 | 0.25 | 0.00 | 0.91 |
| DHSf_LHM | 7.00 | 6.00 | 0.18 | 3.93 | 3.93 | 0.00 | 0.00 | 0.17 | 0.92 |
| DHSf_LHM | 11.00 | 8.00 | 0.24 | 4.68 | 3.64 | 0.00 | 0.00 | 0.38 | 0.92 |
| DHSf_LHM | 12.00 | 10.00 | 0.30 | 4.32 | 3.27 | 0.00 | 0.00 | 0.20 | 0.93 |
| DHSf_LHM | 8.00 | 8.00 | 0.24 | 4.11 | 3.56 | 0.00 | 0.00 | 0.00 | 0.94 |
| DHSf_LHM | 6.00 | 5.00 | 0.15 | 3.75 | 4.25 | 0.00 | 0.00 | 0.20 | 0.86 |
| DHSf_LHM | 7.00 | 7.00 | 0.21 | 4.71 | 3.50 | 1.00 | 0.14 | 0.00 | 0.91 |
| DHSf_LHM | 15.00 | 9.00 | 0.27 | 4.20 | 5.03 | 7.00 | 0.47 | 0.67 | 0.92 |
| DHSf_LHM | 10.00 | 7.00 | 0.21 | 4.50 | 3.30 | 0.00 | 0.00 | 0.43 | 0.93 |
| DHSf_LHM | 7.00 | 6.00 | 0.18 | 5.07 | 4.21 | 2.00 | 0.29 | 0.17 | 0.91 |
| DHSf_LHM | 6.00 | 6.00 | 0.18 | 4.58 | 3.75 | 0.00 | 0.00 | 0.00 | 0.90 |
| DHSf_LHM | 9.00 | 8.00 | 0.24 | 4.67 | 3.17 | 0.00 | 0.00 | 0.13 | 0.91 |
| DHSf_LHM | 16.00 | 8.00 | 0.24 | 4.09 | 4.22 | 5.00 | 0.31 | 1.00 | 0.88 |
| DHSf_LHM | 9.00 | 7.00 | 0.21 | 3.44 | 4.06 | 0.00 | 0.00 | 0.29 | 0.87 |
| DHSf_LHM | 10.00 | 8.00 | 0.24 | 4.35 | 3.50 | 0.00 | 0.00 | 0.25 | 0.92 |

# Appendix I. Raw data for novelty and quality of distinct idea sets between standard brainstorming and DHSf_LHM

Table I.1 Summary of novelty and quality between standard brainstorming and DHSf_LHM groups

| Group | Novelty | Quality |
|---|---|---|
| Brainstorming | 4.81 | 3.85 |
| Brainstorming | 2.71 | 3.78 |
| Brainstorming | 3.42 | 4.39 |
| Brainstorming | 2.92 | 3.63 |
| Brainstorming | 3.32 | 3.43 |
| Brainstorming | 4.14 | 3.29 |
| Brainstorming | 5.06 | 4.13 |
| Brainstorming | 4.30 | 4.00 |
| Brainstorming | 4.25 | 4.00 |
| Brainstorming | 3.86 | 3.19 |
| Brainstorming | 4.36 | 4.50 |
| Brainstorming | 4.57 | 3.79 |
| Brainstorming | 5.00 | 4.67 |
| Brainstorming | 5.42 | 4.33 |
| Brainstorming | 3.48 | 3.40 |
| Brainstorming | 3.50 | 4.00 |
| Brainstorming | 3.68 | 4.93 |
| Brainstorming | 6.00 | 5.00 |
| Brainstorming | 6.33 | 4.00 |
| Brainstorming | 3.81 | 3.61 |
| Brainstorming | 4.75 | 3.50 |
| Brainstorming | 5.38 | 3.75 |
| Brainstorming | 4.75 | 3.75 |
| Brainstorming | 5.75 | 3.75 |
| Brainstorming | 4.75 | 3.25 |
| Brainstorming | 5.33 | 3.00 |
| Brainstorming | 5.00 | 4.00 |
| Brainstorming | 2.75 | 4.25 |
| Brainstorming | 2.75 | 2.75 |
| Brainstorming | 2.00 | 3.75 |

| | | |
|---|---|---|
| Brainstorming | 6.00 | 2.50 |
| Brainstorming | 4.00 | 4.00 |
| Brainstorming | 3.75 | 4.50 |
| Brainstorming | 5.00 | 3.67 |
| Brainstorming | 5.00 | 4.00 |
| Brainstorming | 4.00 | 3.25 |
| Brainstorming | 5.50 | 2.50 |
| Brainstorming | 7.00 | 3.50 |
| Brainstorming | 4.17 | 4.33 |
| Brainstorming | 6.00 | 3.50 |
| Brainstorming | 1.50 | 2.50 |
| Brainstorming | 4.00 | 3.50 |
| Brainstorming | 3.00 | 4.00 |
| Brainstorming | 3.50 | 4.00 |
| Brainstorming | 5.50 | 3.50 |
| Brainstorming | 4.00 | 4.00 |
| Brainstorming | 5.00 | 4.00 |
| Brainstorming | 4.50 | 5.50 |
| Brainstorming | 5.00 | 4.00 |
| Brainstorming | 3.50 | 3.50 |
| Brainstorming | 3.00 | 3.00 |
| Brainstorming | 4.00 | 5.00 |
| Brainstorming | 6.00 | 3.50 |
| DHSf_LHM | 4.81 | 3.85 |
| DHSf_LHM | 2.71 | 3.78 |
| DHSf_LHM | 3.42 | 4.39 |
| DHSf_LHM | 2.92 | 3.63 |
| DHSf_LHM | 3.32 | 3.43 |
| DHSf_LHM | 4.14 | 3.29 |
| DHSf_LHM | 5.06 | 4.13 |
| DHSf_LHM | 4.30 | 4.00 |
| DHSf_LHM | 4.25 | 4.00 |
| DHSf_LHM | 3.86 | 3.19 |
| DHSf_LHM | 4.36 | 4.50 |
| DHSf_LHM | 4.57 | 3.79 |
| DHSf_LHM | 5.00 | 4.67 |
| DHSf_LHM | 5.42 | 4.33 |
| DHSf_LHM | 3.48 | 3.40 |

| | | |
|---|---|---|
| DHSf_LHM | 3.50 | 4.00 |
| DHSf_LHM | 3.68 | 4.93 |
| DHSf_LHM | 6.00 | 5.00 |
| DHSf_LHM | 6.33 | 4.00 |
| DHSf_LHM | 3.81 | 3.61 |
| DHSf_LHM | 4.75 | 3.50 |
| DHSf_LHM | 5.38 | 3.75 |
| DHSf_LHM | 4.75 | 3.75 |
| DHSf_LHM | 5.75 | 3.75 |
| DHSf_LHM | 4.75 | 3.25 |
| DHSf_LHM | 5.33 | 3.00 |
| DHSf_LHM | 3.50 | 3.50 |
| DHSf_LHM | 6.00 | 3.50 |
| DHSf_LHM | 2.00 | 3.00 |
| DHSf_LHM | 4.00 | 4.00 |
| DHSf_LHM | 6.00 | 4.00 |
| DHSf_LHM | 4.00 | 4.50 |
| DHSf_LHM | 6.00 | 3.00 |
| DHSf_LHM | 4.50 | 4.00 |
| DHSf_LHM | 5.00 | 2.50 |
| DHSf_LHM | 4.50 | 3.90 |
| DHSf_LHM | 5.25 | 2.50 |
| DHSf_LHM | 5.17 | 3.92 |
| DHSf_LHM | 5.50 | 3.50 |
| DHSf_LHM | 4.50 | 3.50 |
| DHSf_LHM | 5.50 | 3.50 |
| DHSf_LHM | 4.67 | 3.25 |
| DHSf_LHM | 6.00 | 2.50 |
| DHSf_LHM | 7.00 | 2.50 |
| DHSf_LHM | 6.50 | 3.50 |
| DHSf_LHM | 5.00 | 2.00 |
| DHSf_LHM | 4.30 | 3.25 |
| DHSf_LHM | 5.50 | 3.50 |
| DHSf_LHM | 6.00 | 3.50 |
| DHSf_LHM | 5.10 | 4.25 |
| DHSf_LHM | 5.50 | 3.50 |
| DHSf_LHM | 5.50 | 4.00 |
| DHSf_LHM | 5.25 | 5.75 |

| | | |
|---|---|---|
| DHSf_LHM | 5.00 | 6.50 |
| DHSf_LHM | 6.00 | 5.50 |
| DHSf_LHM | 5.25 | 6.25 |
| DHSf_LHM | 4.50 | 5.00 |
| DHSf_LHM | 4.00 | 4.00 |
| DHSf_LHM | 4.00 | 5.00 |
| DHSf_LHM | 5.00 | 3.50 |
| DHSf_LHM | 4.50 | 2.50 |
| DHSf_LHM | 5.00 | 6.50 |
| DHSf_LHM | 3.00 | 3.00 |
| DHSf_LHM | 6.00 | 5.50 |
| DHSf_LHM | 6.50 | 3.50 |
| DHSf_LHM | 3.00 | 3.50 |
| DHSf_LHM | 3.50 | 5.00 |
| DHSf_LHM | 3.50 | 3.50 |

# Appendix J. Raw data for ideation performance measures among standard brainstorming, DHSf_P and TRIZ

Table J.1 Summary of ideation performance for group comparisons

| Group | Novelty | Workability | Relevance | Quantity | Variety | Fixation | Good idea count | Novelty MAX | Workability MAX | Relevance MAX |
|---|---|---|---|---|---|---|---|---|---|---|
| Brainstorming | 2.88 | 4.31 | 4.63 | 8.00 | 0.30 | 0.13 | 1.00 | 4.50 | 6.50 | 5.00 |
| Brainstorming | 3.30 | 4.20 | 3.90 | 5.00 | 0.17 | 0.20 | 0.00 | 4.50 | 5.50 | 5.00 |
| Brainstorming | 4.00 | 6.25 | 4.50 | 4.00 | 0.09 | 0.50 | 0.00 | 5.50 | 7.00 | 5.00 |
| Brainstorming | 3.50 | 6.67 | 5.67 | 3.00 | 0.13 | 0.00 | 1.00 | 5.50 | 7.00 | 6.50 |
| Brainstorming | 2.50 | 6.40 | 5.00 | 5.00 | 0.17 | 0.20 | 1.00 | 4.50 | 7.00 | 5.00 |
| Brainstorming | 3.88 | 5.13 | 3.88 | 4.00 | 0.09 | 0.50 | 0.00 | 6.00 | 5.50 | 5.00 |
| Brainstorming | 3.50 | 5.86 | 5.00 | 7.00 | 0.09 | 0.71 | 2.00 | 5.00 | 7.00 | 6.00 |
| Brainstorming | 4.00 | 5.00 | 4.83 | 6.00 | 0.17 | 0.33 | 1.00 | 6.00 | 6.50 | 6.00 |
| Brainstorming | 2.81 | 4.88 | 4.00 | 8.00 | 0.26 | 0.25 | 1.00 | 4.00 | 6.00 | 5.00 |
| Brainstorming | 3.17 | 5.67 | 5.50 | 3.00 | 0.13 | 0.00 | 0.00 | 3.50 | 7.00 | 6.00 |
| Brainstorming | 2.13 | 6.31 | 4.69 | 8.00 | 0.22 | 0.38 | 0.00 | 3.00 | 7.00 | 5.00 |
| Brainstorming | 2.58 | 6.12 | 4.65 | 13.00 | 0.30 | 0.46 | 0.00 | 5.00 | 7.00 | 5.00 |
| Brainstorming | 2.91 | 4.41 | 4.68 | 11.00 | 0.35 | 0.27 | 0.00 | 4.50 | 6.50 | 6.00 |
| Brainstorming | 3.00 | 5.61 | 4.39 | 9.00 | 0.26 | 0.33 | 1.00 | 4.50 | 7.00 | 5.50 |
| Brainstorming | 2.44 | 6.50 | 4.69 | 8.00 | 0.30 | 0.13 | 1.00 | 4.00 | 7.00 | 5.00 |
| Brainstorming | 2.00 | 6.20 | 4.80 | 5.00 | 0.22 | 0.00 | 0.00 | 2.00 | 7.00 | 5.50 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DHSf_P | 3.50 | 5.41 | 4.68 | 11.00 | 0.23 | 0.36 | 1.00 | 5.50 | 7.00 | 5.00 |
| DHSf_P | 3.71 | 5.36 | 5.00 | 7.00 | 0.10 | 0.57 | 0.00 | 7.00 | 6.50 | 6.00 |
| DHSf_P | 3.70 | 5.65 | 4.70 | 10.00 | 0.23 | 0.30 | 2.00 | 6.00 | 6.50 | 6.00 |
| DHSf_P | 3.33 | 5.83 | 5.25 | 12.00 | 0.23 | 0.42 | 2.00 | 6.50 | 7.00 | 6.50 |
| DHSf_P | 3.64 | 4.96 | 4.96 | 11.00 | 0.20 | 0.46 | 3.00 | 5.50 | 6.50 | 6.00 |
| DHSf_P | 3.10 | 5.30 | 4.80 | 5.00 | 0.13 | 0.20 | 0.00 | 5.50 | 6.00 | 5.00 |
| DHSf_P | 4.36 | 4.68 | 4.73 | 11.00 | 0.20 | 0.46 | 1.00 | 6.50 | 6.50 | 5.50 |
| DHSf_P | 3.19 | 5.69 | 4.97 | 18.00 | 0.50 | 0.17 | 3.00 | 6.00 | 7.00 | 6.50 |
| DHSf_P | 3.47 | 5.16 | 4.78 | 16.00 | 0.30 | 0.44 | 4.00 | 5.00 | 7.00 | 5.50 |
| DHSf_P | 3.00 | 5.19 | 4.50 | 8.00 | 0.23 | 0.13 | 1.00 | 5.50 | 7.00 | 5.50 |
| DHSf_P | 4.00 | 6.00 | 5.25 | 4.00 | 0.13 | 0.00 | 0.00 | 6.00 | 7.00 | 5.50 |
| DHSf_P | 4.00 | 5.50 | 4.81 | 8.00 | 0.27 | 0.00 | 1.00 | 5.00 | 7.00 | 5.50 |
| DHSf_P | 3.38 | 5.00 | 4.81 | 8.00 | 0.23 | 0.13 | 0.00 | 6.50 | 6.00 | 6.00 |
| DHSf_P | 2.68 | 5.04 | 4.57 | 14.00 | 0.33 | 0.29 | 1.00 | 4.00 | 7.00 | 6.00 |
| DHSf_P | 3.44 | 5.89 | 5.22 | 9.00 | 0.23 | 0.22 | 2.00 | 5.00 | 7.00 | 6.50 |
| DHSf_P | 3.30 | 5.60 | 4.80 | 5.00 | 0.17 | 0.00 | 0.00 | 6.00 | 7.00 | 5.00 |
| DHSf_P | 3.60 | 5.80 | 5.10 | 5.00 | 0.17 | 0.00 | 1.00 | 5.50 | 7.00 | 6.50 |
| DHSf_P | 2.94 | 5.00 | 4.94 | 8.00 | 0.27 | 0.00 | 1.00 | 5.00 | 7.00 | 6.00 |
| DHSf_P | 3.31 | 4.50 | 4.50 | 8.00 | 0.20 | 0.25 | 1.00 | 4.50 | 5.50 | 5.00 |
| DHSf_P | 2.58 | 5.54 | 4.81 | 13.00 | 0.43 | 0.00 | 0.00 | 5.00 | 7.00 | 6.00 |
| DHSf_P | 4.00 | 5.38 | 5.19 | 8.00 | 0.20 | 0.25 | 3.00 | 6.00 | 6.00 | 6.00 |
| DHSf_P | 3.64 | 3.05 | 3.77 | 11.00 | 0.27 | 0.27 | 1.00 | 5.50 | 5.50 | 5.00 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DHSf_P | 2.25 | 6.25 | 4.94 | 8.00 | 0.17 | 0.38 | 0.00 | 3.00 | 7.00 | 5.50 |
| DHSf_P | 4.25 | 6.00 | 5.50 | 4.00 | 0.13 | 0.00 | 3.00 | 5.00 | 6.50 | 6.00 |
| TRIZ | 3.86 | 4.21 | 4.50 | 7.00 | 0.26 | 0.00 | 0.00 | 5.50 | 7.00 | 6.00 |
| TRIZ | 2.68 | 5.82 | 4.59 | 11.00 | 0.30 | 0.27 | 0.00 | 5.00 | 6.50 | 5.50 |
| TRIZ | 3.25 | 4.92 | 4.50 | 6.00 | 0.22 | 0.00 | 0.00 | 5.50 | 6.00 | 5.00 |
| TRIZ | 4.14 | 4.00 | 4.57 | 7.00 | 0.26 | 0.00 | 2.00 | 6.00 | 6.00 | 5.00 |
| TRIZ | 3.14 | 4.50 | 4.21 | 7.00 | 0.26 | 0.00 | 0.00 | 5.00 | 6.00 | 5.00 |
| TRIZ | 2.25 | 4.75 | 4.25 | 2.00 | 0.07 | 0.00 | 0.00 | 2.50 | 5.00 | 5.00 |
| TRIZ | 2.33 | 5.67 | 5.00 | 3.00 | 0.11 | 0.00 | 0.00 | 3.00 | 6.00 | 5.00 |
| TRIZ | 2.50 | 4.88 | 4.63 | 4.00 | 0.15 | 0.00 | 0.00 | 3.00 | 6.00 | 5.00 |
| TRIZ | 3.36 | 4.64 | 4.29 | 7.00 | 0.19 | 0.29 | 1.00 | 6.00 | 7.00 | 5.50 |
| TRIZ | 4.25 | 5.25 | 4.75 | 2.00 | 0.07 | 0.00 | 1.00 | 6.50 | 5.50 | 5.00 |
| TRIZ | 2.25 | 4.50 | 4.38 | 4.00 | 0.07 | 0.50 | 0.00 | 2.50 | 6.00 | 5.00 |
| TRIZ | 3.00 | 4.20 | 4.20 | 5.00 | 0.19 | 0.00 | 0.00 | 5.00 | 6.00 | 5.00 |
| TRIZ | 3.00 | 5.21 | 4.71 | 7.00 | 0.15 | 0.43 | 0.00 | 5.00 | 6.50 | 5.00 |
| TRIZ | 2.00 | 6.00 | 4.75 | 2.00 | 0.07 | 0.00 | 0.00 | 2.00 | 6.00 | 5.00 |
| TRIZ | 2.25 | 5.25 | 4.75 | 2.00 | 0.07 | 0.00 | 0.00 | 2.50 | 5.50 | 5.00 |
| TRIZ | 3.70 | 3.90 | 4.60 | 5.00 | 0.11 | 0.40 | 1.00 | 5.00 | 5.50 | 5.00 |
| TRIZ | 3.07 | 4.43 | 4.57 | 7.00 | 0.19 | 0.29 | 2.00 | 5.50 | 5.00 | 5.00 |
| TRIZ | 2.50 | 5.50 | 4.83 | 3.00 | 0.11 | 0.00 | 0.00 | 3.00 | 6.00 | 5.00 |
| TRIZ | 2.75 | 5.50 | 4.92 | 6.00 | 0.15 | 0.33 | 0.00 | 3.50 | 6.50 | 5.50 |
| TRIZ | 2.90 | 4.80 | 4.60 | 5.00 | 0.19 | 0.00 | 0.00 | 3.50 | 6.00 | 5.00 |

# 국 문 초 록

혁신적인 제품 디자인을 개발하기 위해서는 설계자의 창의적인 사고와 문제 해결 역량이 필요하다. 제품 디자인의 전 과정, 특히 문제 정의 및 개념 생성 전반에 걸쳐 설계자는 디자이너의 기능을 향상시키는 수단으로 다양한 개념 생성 기법 및 도구를 사용한다. 그 중에서도 디자인 휴리스틱을 제공하는 개념 생성 기법은 혁신적인 제품 디자인 상황에서 장점을 가지고 있다. 기존 연구에 따르면 디자인 휴리스틱은 다른 설계자가 과거의 유사 문제를 해결했던 방법에 대한 설계 통찰력을 얻는 데 효과적이라고 알려져 있다.

개념 생성 기법의 대부분은 도메인 전반에서 활용 가능한 포괄적인 디자인 휴리스틱 정보를 제공한다. 디자인 휴리스틱은 일반적으로 시스템을 만들거나 개선하기 위한 유용한 설계 지식으로 통용되지만, 각 디자인 휴리스틱이 어떤 제품 혹은 시스템의 특정 요소(설계 목표 및 요구 사항)에 특화된 정보를 제공하는 데에 목적을 두고 있는 지 명시적으로 제시되지 않았다.

본 연구에서는 디자인 휴리스틱 개념을 활용한 개념 생성 기법의 새로운 분류 체계를 제안한다. 트리즈 40 가지 발명 원리 및 77 디자인 휴리스틱과 같이 포괄적인 디자인 휴리스틱 정보를 제공하는 개념 생성 기법들을 포괄적인 설계 휴리스틱 세트(CDHS)라고 정의하였고, 특정 목표 지향적 설계 휴리스틱을 제공하는 다른 개념 생성 기술은 설계 휴리스틱 세트(DHSfX)로 정의하였다. 여기서 X 는 특정 설계 목표를 나타낸다. 현재 DHSfX 가 창의성에 미치는 영향은 실증적으로 검증되지 않았으며,

DHSfX 와 CDHS 가 디자이너의 아이디어 생성 능력에 미치는 영향을 비교•분석한 연구도 현재 미비한 실정이다.

따라서 본 연구는 네 가지 주요 연구 활동을 구성하였다. 연구 활동 1 에서는 DHSfX 개발 과정을 (1) 설계 목표 X 를 설명하기 위한 키워드 검색, (2) 추출된 키워드와 관련된 제품 데이터 수집 및 (3) 내재된 설계 아이디어 도출 등 총 3 가지 단계로 구성하였다. 또한, DHSfX 접근 방법을 활용하여 제품 도메인별 DHSf_LHM 와 DHSf_P 를 개발하였고, 이는 각각 장애인 보조기기와 휴대용 제품 등의 두 가지 제품 도메인에 활용 가능한 디자인 휴리스틱 정보들을 제공한다. DHSf_LHM 와 DHSf_P 는 각각 총 13 가지와 25 가지의 디자인 휴리스틱 정보들을 제공하였다.

연구 활동 2 에서는 앞 서 개발된 DHSfXs (DHSf_LHM, DHSf_P)가 실제 아이디어 생성 능력에 미치는 영향을 브레인스토밍 기법과 비교하여 분석하였다. 본 연구 활동에서는 한 손만 활용 가능한 사람들을 위한 새로운 루빅스 큐브 설계 문제와 휴대성을 향상시키는 제품 설계 문제들로 설정하였다. 연구 결과에 따르면 DHSfX 는 브레인스토밍 기법보다 디자이너들의 아이디어 생성 능력에 더 좋은 영향을 미치는 것을 알 수 있었다. 따라서, DHSfX 를 활용한 제품 컨셉 생성 활동은 창의적인 컨셉 생성에 보조 도구로 활용 가능하다는 것을 알 수 있었다.

연구 활동 3 에서는 DHSf_LHM 가 제공하는 컨텐츠 정보와 트리즈 40 가지 발명 원리 및 77 디자인 휴리스틱 기법에서 제공하는 컨텐츠 정보 간의 비교 분석 연구를 수행하였다. 비교 분석을 위해 개념 생성 기법들이 제공하는 정보들 간의 유사성을 실무자들의 주관적인 판단을 바탕으로 한 컨텐츠 정보 평가 방법을 활용하여 분석하였다. 본 연구의 결과,

DHSf_LHM 이 제공하는 디자인 휴리스틱 정보들은 트리즈 40 가지 발명 원리 또는 77 디자인 휴리스틱에서 제공하는 컨텐츠와는 차별화되는 것으로 나타났다. 따라서, 디자인 휴리스틱 간의 주관적인 유사성을 기반으로 DHSfX 가 제공하는 디자인 휴리스틱이 다른 기법들이 제공하는 디자인 가이드라인과 다르다고 인식되었음으로, 기존 개념 생성 기법에 제공하지 않는 새로운 정보들을 제공한다는 측면에서 연구의 의의를 찾아볼 수 있었다.

연구 활동 4 에서는 DHSfX (DHSf_P)와 트리즈 40 가지 발명 원리가 디자이너들의 아이디어 생성 능력에 미치는 효과를 보고자 실험적으로 검증하는 아이디에이션 연구를 수행하였다. 본 연구 결과, DHSfX 가 트리즈 40 가지 발명 원리에 비해 디자이너의 아이디에이션 성능에 더 좋은 효과를 미친다는 것을 알 수 있었다.

본 연구는 제품 개념 생성 설계에 대한 DHSfX 의 효과를 조사하였다. 본 연구 결과, DHSfX 접근 방법이 기존의 다른 개념 생성 기법과 더불어 제품 개념 생성에 효과적이다 라는 새로운 정보 제공에 기여할 뿐만 아니라 특정 목적에 특화된 정보들을 도출함으로써 기존 개념 생성 기법들이 제공하지 않는 새로운 정보들을 제공한다는 실험적 근거를 제공하였다. 이러한 연구 결과는 효과적인 제품 개념 생성을 위해 더 많은 DHSfX 를 체계적으로 도출하고 DHSfX 시스템을 구축하기 위한 향후 노력에 기여할 수 있다.

**주요어**: 창의성, 디자인 휴리스틱, 공학 설계, 아이디에이션, 제품 개념 생성
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