TASKS Framework for Personalized Task Implementation

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ABSTRACT

TASKS Framework for Personalized Task Implementation

Jiami Yang

This thesis addresses the complexities of task implementation, focusing on personalized barriers encountered in diverse contexts. It introduces the TASKS framework as a novel deductive approach to analyze and overcome these barriers. The framework, grounded in the interplay between tasks and an implementer's Affect, Skills, Knowledge, and Stress, offers a structured method to identify and address personalized implementation barriers. The thesis validates the framework through three distinct case studies: enhancing designer creativity in design processes, identifying personalized barriers in hypertension self-management, and understanding stakeholder behavior in sustainable product design. Each case study illuminates the framework's efficacy in different scenarios – from creative design practices, healthcare challenges, to environmental sustainability in product design. The findings demonstrate the framework's versatility in categorizing barriers into emotional, logical, knowledge, and resource categories, and its effectiveness in providing tailored solutions. This research contributes to implementation science by offering a comprehensive tool for understanding and tackling personalized barriers in various task implementations, emphasizing the importance of customizing strategies to individual needs and contexts. The thesis not only enriches our understanding of task implementation but also sets the stage for future research directions, including developing tools for streamlined barrier analysis, exploring dynamic problem-solving methods, and team design and healthcare systems, aiming to enhance the practical applicability and scalability of the TASKS framework.

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Contribution of Authors

This thesis is a manuscript-based thesis. Chapter 3 of this thesis was published in Journal of Engineering Design [Publication **4**]. Chapter 4 of this thesis has been submitted to the BMC Research Notes [Publication **1**]. Chapter 5 of this thesis has been submitted to the conference Design Computing and Cognition'24 [Publication **2**]. The author of this thesis was responsible for the development, testing, and application of the methods discussed in this research, along with preparation of manuscripts submitted to peer-reviewed journals.

Dr. Yong Zeng *(Professor, Concordia Institute for Information Systems Engineering, Concordia University),* Dr. Hude Quan *(Professor, Centre for Health Informatics, University of Calgary)*, and Dr. Abdessamad Ben Hamza *(Professor, Concordia Institute for Information Systems Engineering, Concordia University)*, supervised this thesis and provided valuable guidance and advice on various aspects of the research.

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List of publications related to the thesis:

[1] **Yang, J.**, Zeng, Y, Yang, L., Khan, N., Singh, S., Walker, R. L., Eastwood, R., & Quan, H. (2024). Identifying personalized barriers for hypertension self-management from TASKS framework. (Submitted).

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[4] **Yang, J.**, Dou, Y., & Zeng, Y. (2023). Environment-based design (EBD): Using only necessary knowledge for designer creativity. *Proceedings of the Design Society*, *3*, 1675-1684. https://doi.org/10.1017/pds.2023.168

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Chapter 1

1 Introduction

Implementation involves translating plans into action, addressing both the 'how' and 'what'. An implementation problem refers to the challenges encountered in the process of applying planned, intentional activities to transform evidence and ideas into effective practices that function in real-world scenarios (Cline 2000). It encompasses difficulties in ensuring the successful execution of tasks as intended and achieving cooperation among various stakeholders.

Implementation barriers are obstacles or challenges that hinder the successful execution and completion of tasks or actions, preventing individuals or organizations from effectively implementing their intended plans or strategies (Yang *et al.* 2021). The challenge of effective implementation lies in the diversity of personalized barriers individuals face in managing their conditions. These barriers are highly individualized, varying significantly from one person to another based on unique circumstances, beliefs, emotional states, knowledge and skill levels, and access to resources. Recognizing and addressing these unique challenges is pivotal for crafting human-centered strategies, enhancing outcomes by aligning support with each person's specific needs.

This thesis employed the TASKS framework (Yang *et al.* 2021) to analyze implementation problems. TASKS (**T**ask, **A**ffect, **S**kills, **K**nowledge, and **S**tress) framework offers a deductive theory-based approach, considering relationships between tasks and the implementer's affect, skills, and knowledge, based on the inverse U-shaped mental stress-mental effort relation (Nguyen & Zeng 2012). While much of the research in implementation science adopts a bottom-up, inductive evidence-based approach (Bach-Mortensen *et al.* 2018; Waltz *et al.* 2019), the TASKS framework represents a deductive theory-based approach, aiming to model the cause-effect relations between influencing factors and barriers. The framework classifies barriers into emotion, logic, knowledge, and resource categories, with three steps: identifying TASKS components, modeling mental capability, and detecting barriers. Its primary objective is to understand behavior, identify, and overcome implementation barriers. Already applied in education (Ma *et al.* 2022), this thesis explores further applications in design creativity, sustainable product design, and hypertension self-management.

1.1 Objective

This thesis aims to validate the TASKS framework through three distinct task implementations:

Task 1: Knowledge in designer creativity

Design is characterized as a highly nonlinear and chaotic dynamic process with multiple potential solutions, some of which may be creative (Yang *et al.* 2023; Zeng & Gu 1999c). The distinction between routine, innovative, and creative designs lies in the range, content, size, and nature of the design space. The nonlinear and chaotic nature of design dynamics can cause mental stress in designers, and creativity emerges when these stresses reach an optimal level (Nguyen & Zeng 2012). This study employs the TASKS framework to deductively analyze the role of knowledge in design, addressing research questions related to design creativity, designer creativity, and the utilization of knowledge in design.

Task 2: Personalized barriers for hypertension patients

Healthcare is among the most extensively researched areas concerning implementation problems. Hypertension poses a significant global health risk, contributing to cardiovascular diseases and impacting mortality and morbidity rates worldwide (Brunström & Carlberg 2018; Quan *et al.* 2009; Zhou *et al.* 2021a). While self-management plays a crucial role in hypertension management, many patients discontinue treatments and fail to adhere to necessary behavioral changes (Liu *et al.* 2014). Recognizing personalized barriers to hypertension self-management is essential to bridging the evidence-to-practice gap in healthcare. Traditional qualitative methods struggle to capture the diverse and personalized needs of patients. This study aims to employ the TASKS framework to identify personalized barriers to hypertension self-management.

Task 3: Stakeholder behavior pattern in sustainable product design

The Sustainable Development Goals (SDGs) outlined by the United Nations (UN) in 2015 represent a universal call to action to end poverty, protect the planet, and ensure peace and prosperity by 2030 (United Nations 2015). However, progress towards achieving these goals has been limited. Design plays a pivotal role in determining the sustainability impacts of a product, and addressing sustainability concerns at later stages can be challenging and costly. Sustainable product design (SPD) has emerged with the aim of creating products that fulfill functional requirements while minimizing environmental impacts and promoting social and economic well-being. The success of sustainable product design hinges on collaboration with various stakeholders, including customers, suppliers, and local communities. While existing research has focused on sustainable technologies and relevant policies, the role of stakeholders in sustainable design has received limited attention. This study aims to utilize the TASKS framework in modeling stakeholder behavior in sustainable product design from a life cycle perspective, enhancing our understanding of stakeholder behavior patterns.

1.2 Contribution

The principal contributions of this thesis are outlined as follows:

1. A deductive analysis is provided that employs the TASKS framework to explore the role of knowledge in design. Three effective ways to properly use knowledge in design, based on its roles in the design process, are recommended.
2. An inductive analysis is presented, using the TASKS framework to identify personalized barriers faced by patients self-managing hypertension. This analysis draws on personalized mental capabilities discerned from interview transcripts and requirements extracted from global hypertension guidelines.
3. A retrospective exploration explores stakeholder behavior patterns in sustainable product design, emphasizing the integration of natural and cognitive resources within design methodologies to enhance environmental stewardship and user satisfaction through the TASKS framework.

1.3 Thesis organization

This thesis is organized as follows: Chapter 2 proposes the background and literature review. Chapter 3 discusses the role of knowledge and the ways for designer creativity. Chapter 4 identifies personalized barriers for hypertension self-management from TASKS framework. Chapter 5 unearths stakeholder behavior patterns in sustainable product design. Finally, conclusions and future works are presented in Chapter 6.

Chapter 2

2 Background and Literature Review

Implementation is ubiquitous. The word "implement" comes from the Latin "implore", meaning to fulfil or carry into effect (Murray 1971). Implementation science is defined as "the scientific study of methods to promote the systematic uptake of research findings and other evidence-based practices into routine practice" (Albers *et al.* 2020). Hence, implementation science needs to solve a wide range of implementation problems (Peters *et al.* 2013). Identifying and overcoming implementation barriers can be seen in *Education* (Ali *et al.* 2018; Berge 2013; Milic Babic & Dowling 2015), *Sustainability* (Bianchini *et al.* 2019; Karji *et al.* 2020; Kirchherr *et al.* 2018), *Software Development* (Nelson *et al.* 2019; Vassallo *et al.* 2018), *Organization Management* (Oliva & Kotabe 2019; Othman *et al.* 2021), and *Health* (Albers *et al.* 2020; Bach-Mortensen *et al.* 2018; Fischer *et al.* 2016; Waltz *et al.* 2019).

Implementation is an action. Action has its implementer and action object and requires resources. During the implementation process, the implementer is an individual or an organization (implementors), and the action object is a task. Thus, the implementation relies on implicit and tacit resources, implementer capabilities and the task context. An implementation aims to optimize the effectiveness and efficiency of actions within a specific context by overcoming barriers. To overcome implementation barriers, one would ask the following five questions:

- What is to be implemented?
- Who implements?
- What are the barriers to implementation?
- How to identify implementation barriers? and
- How to overcome implementation barriers?

This thesis uses a **TASKS** (**T**ask, **A**ffect, **S**kills, **K**nowledge, and **S**tress) framework to address the first four questions related to implementation barriers. The TASKS framework is based on two premises: first, humans perform the best when their mental stresses are at an optimal level (Yerkes & Dodson 1908)**;** and second, human mental stresses depend on workload and mental capability that is defined by affect, skills, and knowledge (Nguyen & Zeng 2012, 2017a). The last question, overcoming implementation barriers, is the goal of behavior changes, which will be discussed in future.

2.1 What is to be implemented: Task

The implementation object is a task, namely a piece of work to be accomplished (Locke *et al.* 1981). Completing a task is similar to a problem-solving process, which involves four steps: understanding the task, producing candidate solutions to accomplishing the task, making decisions to select a good solution, and taking actions to deliver the selected solution (Zoller *et al.* 1987). Nearly all human activities can be considered tasks. Understanding a task formulates what needs to be implemented, which can mostly take the form of questions. Good questions can open up the opportunity of obtaining important information and digging deeper into a task (Flammer 1981; Vale 2013). Therefore, asking questions is a fundamental prerequisite to incorporating knowledge transfer priorities into task planning (Koch & Sauer 2010). That is to say, asking questions is a vehicle to start a process of generating solutions that can lead to action (Vale 2013). Hence, fundamentally, a task is to ask.

2.2 Who implements: "ASK" constitutes the implementer's mental capability

TASKS framework defines all human activities as tasks and an individual or an organization who accomplishes the task as the task implementer (Yang *et al.* 2021). Knowledge, skill, and affect are fundamental determinants in tackling a perceived workload related to a given task (Nguyen & Zeng 2012). Based on the Yerkes-Dodson law (Yerkes & Dodson 1908), which states an inverse U-shaped relationship between mental stress and performance, Nguyen and Zeng (Nguyen & Zeng 2012, 2017a) qualitatively defined human mental stress ($\boldsymbol{\sigma}$) as the ratio of perceived workload over mental capability, as described in Equation (1).

$$\boldsymbol{Mental\ Stress\ (\sigma)} = \frac{\boldsymbol{Perceived\ Task\ Workload}}{\boldsymbol{Human\ Mental\ Capability}} = \frac{\boldsymbol{Perceived\ Task\ Workload}}{(\boldsymbol{Knowledge+Skill})*\boldsymbol{Affect}},\ \mathbf{A} \in (\mathbf{0}, \mathbf{1}), \quad \textbf{(2-1)}$$

where knowledge (K), skill (S), and affect (A) are three key factors determining the human mental capability (C_p) to tackle a perceived workload (T) related to a given task. The workload is an external load exerted on an individual. This workload can be associated with the complexity of the task. The amount of external workload is the most direct source of mental stress. Both knowledge and skills form human rationality. Knowledge (K) includes the facts and cause-effect relationships related to the workload (T). Skills (S) can be categorized into cognitive and affective, for which logic is a critical part. The activated knowledge and skills lead to the complementation of workload, yet the activation level may vary. Affect (A) refers to any experience of feeling or emotion, ranging from suffering to elation. Affect, which falls between 0 and 1, could determine how much of an implementer's knowledge and skills can be activated and harnessed to complete a given task.

TASKS framework is a generic model that is closely related to existing discipline-specific causal models. The Theory of Planned Behavior (TPB) (Ajzen, Icek 1985) emphasizes the co-functioning of attitudes, subjective norms, and perceived behavioral control on individual behavioral intentions in specific contexts (Ajzen, Icek 1985). Fogg Behavior Model (FBM) (Fogg 2009a) is to find the functional relation of behavior. It proposed three essentials for forming human behavior: Motivation, Ability, and Prompt. In other words, the behavior performer needs to be sufficiently motivated, have the ability, and be prompted to perform the behavior. Besides, timing is a subcomponent of influencing behavior. Michie proposed a behavior system called COM-B (Michie 2015) involving the interaction of Capability, Opportunity, and Motivation to produce behavior. Wan et al. (Wan 2021; Wan *et al.* 2017) proposed the KMAP-O casual framework for the behavioral system that constitutes Knowledge, Motivation, Attitude, Practice, and Outcome. KMAP-O framework suggests that health education or behavioral intervention(s) may directly affect knowledge, motivation, attitude, and practice to influence the outcome. Meanwhiles, suboptimal knowledge, motivation, attitude, and practice could become barriers that mediate the effect of health education or behavioral interventions on desired outcomes.

2.3 What are the barriers to implementation: inappropriate mental stress "Sigma (σ)" leads to barriers

Implementation barriers prevent humans from completing tasks (USAID 2014). A direct consequence of implementation barriers is poor performance in completing a task. Yerkes and Dodson related performance to stresses (Yerkes & Dodson 1908). In implementation science, the poor performance of the implementer is often associated with a lack of necessary effort. Nguyen and Zeng adapted the Yerkes-Dodson Law to address the relationship between mental stress and mental effort (Nguyen & Zeng 2012), implying that an appropriate range of mental stresses will lead to optimal mental efforts. Low- and high-level mental stresses would produce low-level mental efforts, whereas medium-level mental stress results in optimal-level mental efforts (Figure 2-1)**Error! Reference source not found.**.

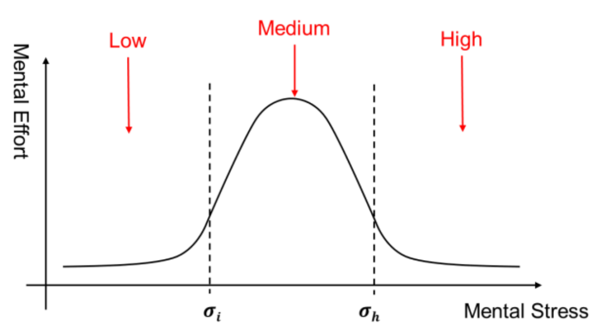

Figure 2-1 Mental Stress-Effort Model

Suboptimal effort and its associated level of mental stress can generate implementation barriers. An implementation task is stated by the statement "Implementers implement a task". We can look for the sources of implementation barriers from the mental stress model presented in Equation (1) and other external resources such as time or cost. Then the statement is formed into "Implementers implement a task with their affect, skill, knowledge, and resources", as illustrated in Figure 2-2. We can then identify implementation barriers through identifying gaps between the actual and ideal human mental capability and resources to complete a task.

Each of the affect, skills, knowledge, and resources gap between actual implementors and ideal scenarios could generate barriers to implementation. Accordingly, implementation barriers can be categorized into four sub-types: 1) emotion barriers related to the awareness associated with motivation, attitudes (such as cognitive/awareness, expectation, and value) (Rosenstock *et al.* 1988; Wan 2021), belief (such as acceptance, optimism), feelings (such as anxiety, pressure, fear), or ethics; 2) logic barriers related to thinking styles (such as synthesists, idealists, pragmatists, analysts, and realists), thinking strategies and reasoning abilities; 3) knowledge barriers, including knowledge and actionability to accomplish a task; and 4) resource barriers related to all required implicit and tacit resources around the task environment. The classification is shown in Table 2-1.

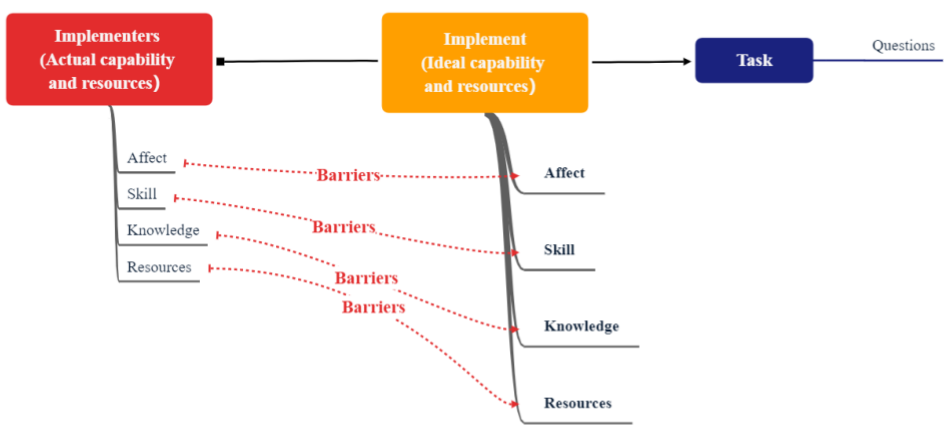

Figure 2-2 The Implementation Barriers

Table 2-1 Classification of Barriers

Categories	Content
Emotion Barriers	Motivation, attitudes (such as cognitive/awareness, expectation, value), belief (such as acceptance, optimism), feelings (such as anxiety, pressure, fear), or ethics
Logic Barriers	Thinking styles, thinking strategies, or reasoning methods
Knowledge Barriers	Knowledge and actionability

Resource Barriers	All environment components (such as time, money and cognitive capacity)

Other researchers have also defined various categories of barriers. Cochrane et al. (Cochrane *et al.* 2007) defined seven categories of barriers: cognitive-behavioral barriers, attitudinal or rational-emotional barriers, professional barriers, barriers embedded in the guidelines or evidence, patient barriers, support/resource barriers, and system/process barriers. Cognitive-behavioral barriers include lack of knowledge, awareness, professional skill, or appraisal skills. Attitudinal or rational-emotional barriers include lack of efficacy, lack of confidence, lack of sense of authority, lack of outcome expectancy, and inaccurate self-assessment. Professional barriers include the influence of invariants such as age, experience, gender, lack of motivation, the influence of individual characteristics, concern for legal issues, rigidity of professional boundaries, lack of appropriate peer influences or models. Barriers embedded in the guidelines or evidence include lack of practical access, lack of comprehensible structure, lack of utility, lack of local applicability, lack of convincing evidence. Patient barriers include conflicting culture, educational, cognitive, attitudinal behaviors, and lack of adherent or concordant behavior. Likewise, Fischer *et al.* (Fischer *et al.* 2016) organized and summarized three main barriers: 1) personal factors related to physicians' knowledge and attitudes; 2) guideline-related factors related to the task and its instructions of the process; 3) external factors related to organizational constraints, tasks required resources, and interactions among other professionals.

2.4 How to identify implementation barriers

Traditionally, thematic analysis, a qualitative method, has been used to identify these barriers (Kirk *et al.* 2016; Ndejjo *et al.* 2020; Tong *et al.* 2017). This method begins with interviews, letting themes emerge organically through deductive or inductive reasoning. Thematic analysis usually involves the process of constant comparison (Strauss & Corbin 1998) to construct themes based on a taxonomy of codes (Nowell *et al.* 2017). Various frameworks like Consolidating Framework for Research Implementation (CFIR) (Damschroder *et al.* 2009a) and Theoretical Domains Framework (TDF) (Michie *et al.* 2005) have provided predefined coding schemes. Michie et al. proposed the Theoretical Domains Framework (TDF) of behavior change at the implementer level to investigate implementation problems (Cane *et al.* 2012; Michie *et al.* 2005). TDF defined 14 domains of theoretical constructs that are related to behavior change: 1) knowledge, 2) skills, 3) social/professional role and identity, 4) beliefs about capabilities, 5) optimism, 6) beliefs about consequences. 7) reinforcement, 8) intentions, 9) goals, 10) memory, attention and decision processes, 11) environmental context and resources, 12) social influences, 13) emotions, and 14) behavioral regulation (Atkins *et al.* 2017). TDF-related domains could act as barriers in the COM-B model to mediate the effect of behavior interventions on behavior change outcomes. At the organizational level, Damschroder and colleagues (Damschroder *et al.* 2009a) proposed the Consolidated Framework for Implementation Research (CFIR) containing five major domains: 1) intervention characteristics, 2) outer setting, 3) inner setting, 4) characteristics of the individuals involved that might influence implementation, and 5) the process of implementation. Several domains in CFIR involve humans, therefore, human activities or tasks. In particular, the fourth CFIR domain is specific to the characteristic of implementers, which echoes the TDF domains and resembles the mental capability in the TASKS framework.

The TASKS framework provides a systematic approach to identify implementation barriers by following three steps: 1) identifying the required TASKS components, 2) modeling the personalized implementer's mental capability (ASK), and 3) detecting barriers to implementation. The ideal TASKS components are identified by understanding the requirements and expectations of the task. The implementer's mental capability, including their affect, skills, and knowledge, is modeled using various quantitative and qualitative research methods. The detection of implementation barriers involves comparing the implementer's mental stress (ASK) with the ideal TASKS components to analyze any gaps or discrepancies. Notably, the first step is the key to the process, while the other two steps follow and contextually depend on the ideal TASKS components.

2.4.1 Identifying required TASKS components

Identifying the ideal TASKS components, as the foundation for detecting implementation barriers, aims to identify the contextual workload and related knowledge and skills. Based on Equation (1), the required TASKS components can be identified following two steps: 1) workload analysis and 2) affect, skills, and knowledge analysis. Workload analysis aims to determine the critical workload and resources required for each stage of a task's life cycle to be completed. The affect, skills, and knowledge analysis aims to gather the necessary and sufficient information to address questions related to each aspect of the workload.

2.4.1.1 Workload analysis

This step aims to define "who" is "to do what" with "what resources" to complete a task. The input of a workload analysis is a task description, and the output is the necessary resources assigned to the specific task implementer(s). The workload related to a task lies in the interactions between the task implementers, which is a part of task environment components, and the other task environment components throughout the entire life cycle of a task. Therefore, workload analysis can be conducted by analyzing the life cycle of a task, the environment components included in the life cycle, and interactions between task implementers and other task environment components.

The environment of a task is everything except the task itself (Zeng 2011, 2015). Zeng and colleagues (Chen & Zeng 2006; Yang *et al.* 2020; Zeng 2020) define the task environment in three dimensions: life cycle events, life cycle time, and environment types (social, economic, built, and natural environment), as shown in Figure 2-3. In the context of implementation science, life cycle time might depend on the specific task and the task-specific context. A typical life cycle of a task includes the initiation, planning, implementation, monitoring, and closure (Westland 2007).

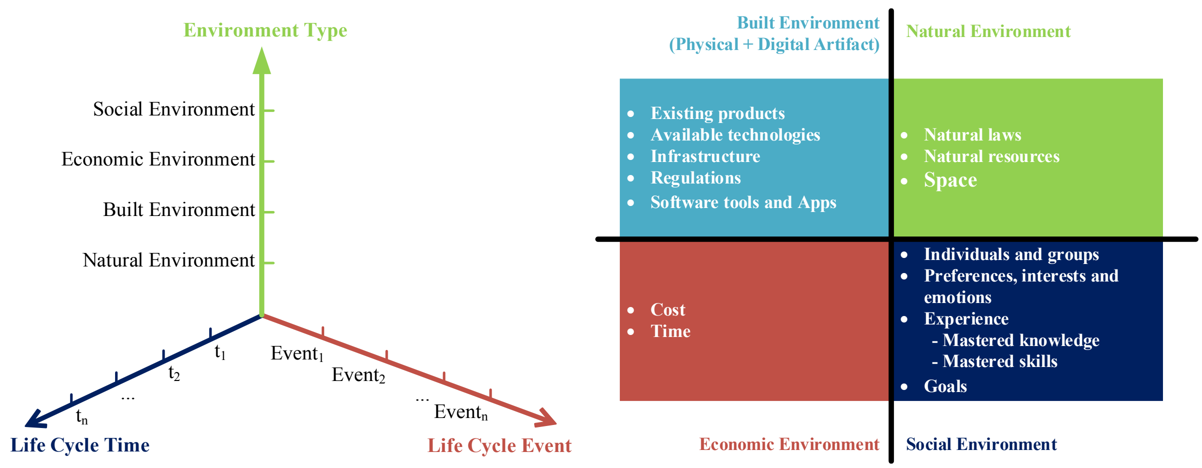

Figure 2-3 Product Environment Structure (Yang *et al.* 2020)

The relationship between sub-life cycle events and their environment components is "who is to do what with what resources to complete a task". The social environment forms the task implementers. Implementers need to detail tasks for each life cycle event. The workloads are analyzed through sub-life cycle events. Other environment components (natural, built, and economic environment) can be viewed as the source of task resources, as shown in Table 2-2.

Table 2-2 Environment Components for Each Life Cycle Event

Task life cycle	Initiation	Planning	Implementation	Monitoring	Closure
Implementer	Who				
Resources	Natual, Built, and Economic environments				
Workload	Verb-Noun phrase				

2.4.1.2 Affect, skills, and knowledge analysis

This step aims to gather the necessary and sufficient information about each aspect of the workload. The analysis takes the workload as input, while the output comprises the affect, skills, and knowledge required to address the workload, as depicted in Table 2-3. For each workload, a set of questions can be posed. Subsequently, after answering these questions, the necessary affect, skills, knowledge and resources associated with each workload can be derived. The detailed definitions are provided in Table 2-4.

Table 2-3 Knowledge and Skills to Questions

Workload	**Questions**	**Required resources**		
		Affect	Skills	Knowledge
Verb-Noun phrase	5W1H	Attitude, etc.	Cognitive and affective skills	Domain knowledge

Table 2-4 Affect, Skills, Knowledge and Resource Definition

Affect (A)	Any experience of feeling or emotion, ranging from suffering to elation. Such as attitudes (such as cognitive/awareness, expectation, value), beliefs (such as acceptance, optimism), feelings (such as anxiety, pressure, fear), or ethics
Skills (S)	Cognitive and affective, for which logic is a critical part. (such as thinking styles, thinking strategies, or reasoning methods)
Knowledge (K)	Facts and cause-effect relationships related to the workload (T); Cognitive resources that are persons' past knowledge.
Resource	External environmental components (such as time, money, and physical devices)

2.4.2 Modelling personalized implementer's mental capability

The second step aims to model the personalized implementer's mental capability to complete the implementation task. The input can consist of any type of actual data, and the outcome is the personalized implementer's affect, skills, knowledge, and resources for each workload. The fundamental challenge in effectively modeling the implementer's mental capability is to extract a structured model from often unstructured implementer behavior data.

Therefore, an implementer's TASKS components can be identified through three steps: data acquisition, data segmentation and coding, and data analysis, as illustrated in Figure 2-4. Data acquisition aims to gather data related to the implementer's task. Data segmentation and coding aim to structure and quantify the qualitative data, typically unstructured text. Data analysis aims to model the personalized implementer's mental capability related to a given task from the data."

2.4.3 Detecting of implementation barriers

This step aims to identify the four categories of barriers (Table 2-1) related to a task workload. The inputs are the required TASKS components (from Step 1) and the actual TASKS components (from Step 2), respectively. The output consists of knowledge barriers, logic barriers, emotion barriers, and resource barriers, which represent the gaps between the required and actual TASKS components. The process of identifying implementation barriers is depicted in Figure 2-5.

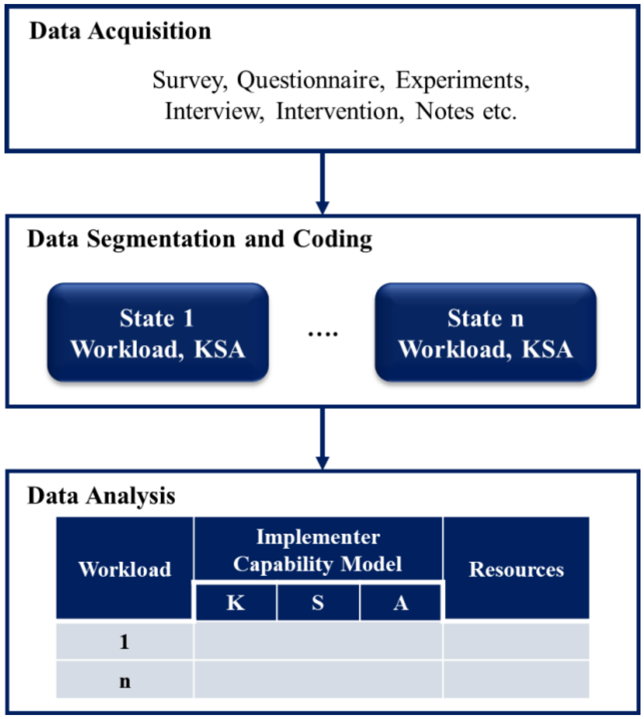

Figure 2-4 Process to Model Implementer's Mental Capability

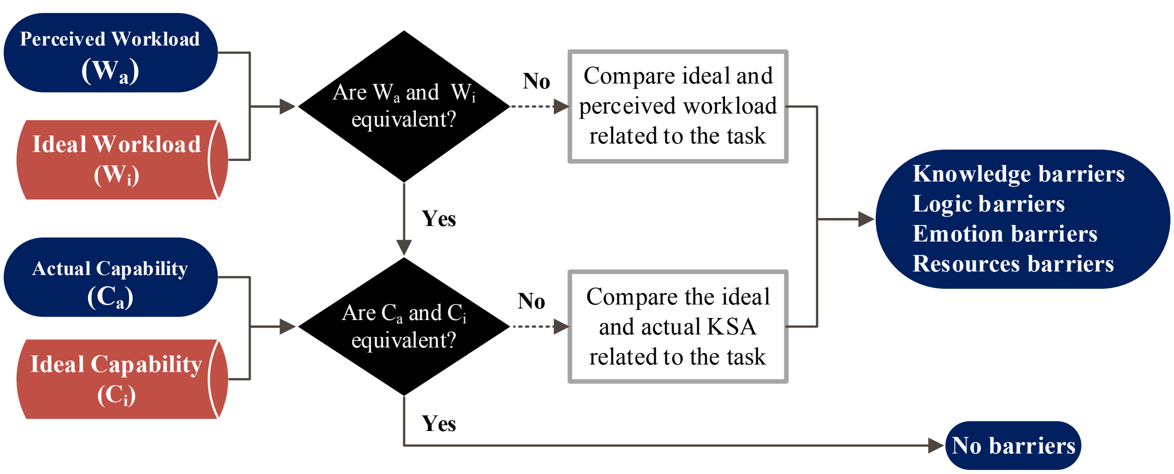

Figure 2-5 Process of Detecting Implementation Barriers

Chapter 3

3 Knowledge: The Good, the Bad, and the Ways for Designer Creativity

Abstract

Design is a highly nonlinear chaotic dynamic process with many possible solutions, some of which can be creative. The chaotic nonlinearity of design dynamics triggers mental stresses in designers, whose creativity happens only when their mental stresses are at an optimal level. Following a deductive approach, this paper investigates how knowledge can contribute to designer creativity by uncovering knowledge's (good and bad) roles in the design process, based on which three ways are recommended to use knowledge properly in design. The assumption is that all designs follow one governing equation, which is a recursive integration of three basic design activities: formulation, evaluation and synthesis. The difference between designs of various fields and different kinds (routine, innovative and creative) lies in the range, content, size and nature of the design space in which the design governing equation works. The design governing equation implies a nonlinear chaotic design dynamics, whose solutions are sensitive to its initial conditions and can be routine, innovative or creative. The design governing equation is solved and reformulated by the designer's creativity capability. Therefore, design researchers, practitioners and educators should cohesively look at both designer's knowledge/experience and the designer's creative thinking process.

***Keywords**:* knowledge; designer creativity; design dynamics; creativity; mental stress; chaotic dynamics

The role of a designer's knowledge in the design process has long been an important research topic, which has been used as one of the determinants to distinguish novice and expert designers (Ahmed *et al.* 2003; Cross 2004; Ho 2001; Ozkan & Dogan 2013; Wu *et al.* 2019). Some believe that a designer's knowledge is the core of a creative design process (Christensen & Ball 2016; Kunrath *et al.* 2020; Li *et al.* 2007). Without knowledge, it would be impossible to create anything that could meet the design requirements. Knowledge plays a good role for designers to deeply and differently understand design problems (Grauberger *et al.* 2022; Lee *et al.* 2021). Some believe that a good design process and methodology are the foundation of creative design (Liu *et al.* 2011; Thoring & Müller 2011). Some others believe that both design methodology and design knowledge are important to creative design (Jiao *et al.* 2022; Su *et al.* 2022). The variety of understandings and perspectives has many implications for design computing (Lee *et al.* 2021), design practices (Buker *et al.* 2022; Lindwall *et al.* 2022; Madhusudanan *et al.* 2019), design management (Du & Jiao 2022; Shafqat *et al.* 2022), and design education (Borgianni *et al.* 2022; Prabhu *et al.* 2022).

The present paper aims to provide a theoretical, deductive and perspective analysis of the role of knowledge in design by answering the following four research questions:

Q1: What is design creativity?
Q2: What is designer creativity?
Q3: What is the role of knowledge in design/designer creativity?
Q4: When and how to use knowledge in design?

The rest of the present paper is organized as follows: Section 1 answers Q1 by employing a mathematical theory of design. Section 2 answers Q2 and Q3 by analyzing the dual roles (the good and the bad) of knowledge in design by using a TASKS framework. Section 3 answers Q4 by providing three ways enabling designers to effectively and efficiently use knowledge in creative design. Finally, section 4 summarises the paper and briefly discusses implications of the perspectives offered in the paper. To facilitate the reading of the present paper, we have made the headings and subheadings self-explainable showing the logic of the arguments made in the paper.

3.1 Design creativity: Knowledge drives a design process to creative designs

Design creativity generally refers to the situation that the created product is creative. Three standard criteria of design creativity are originality (or novelty), effectiveness (or utility and usefulness) (Sternberg & Lubart 1999), and surprise (Boden 2004; Runco & Jaeger 2012; Simonton 2012). Furthermore, Simonton (2012) proposed a quantitative three-criterion equation to describe design creativity in terms of novelty, utility, and surprise.

3.1.1 Different designs fundamentally follow the same mechanism

As Herbert Simon described, design is an action aimed at changing existing situations into preferred ones (Simon 1981). We are all designers since the intelligent activity that produces an engineering product is fundamentally no different from the one that prescribes interventions for a patient, the one that proposes a healthcare act for a country, the one that creates a plan for career success, or the one that arranges a vacation for a family. Design is the core of all professional and everyday thinking dealing with various situations (Norman 2013; Simon 1981). The situation is where a design product is to work.

Zeng defined the situation as a part of the environment in which the product is expected to function (Zeng 2002, 2015). Therefore, the design process can be viewed as an environment-changing process, as illustrated in Figure 3-1, where the product comes from the environment, serves the environment and evolves the environment.

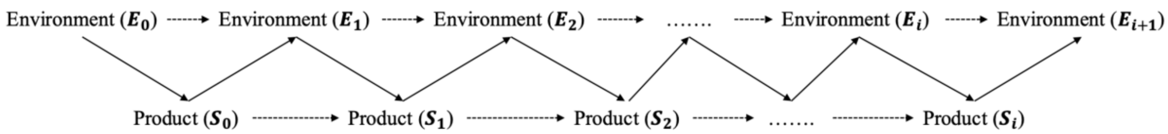

Figure 3-1 Design: environment changing process

The environment evolution can be represented in Eq. (3-1), where $\oplus$, the structure operation defined in (Zeng 2002), represents the union of an object and the relation to the object itself. When a new product (S_i) is created into its environment (E_i), the structure of the original environment ($\oplus E_i$) will be changed into a new structure ($\oplus E_{i+1}$), which has four components: the structure of the original environment ($\oplus E_i$), the structure of the new product ($\oplus S_i$), and the mutual interactions between the original environment and the new product ($E_i \otimes S_i$ and $S_i \otimes E_i$). The environment structure of the initial state ($\oplus \boldsymbol{E_i}$) includes the description of the design solution at the design stage i, the design requirements for the design stage (i+1), the related design knowledge, and other relevant design information (Zeng 2004). It was shown that environment structure embodies everything appearing in design activities, including design requirements, knowledge, and solutions (Zeng 2004).

$$\oplus \boldsymbol{E_{i+1}} = \oplus(\boldsymbol{E_i} + \boldsymbol{S_i}) \qquad \textbf{(3-1)}$$

A design process indeed governs the environment-changing shown in Figure 3-1. Formulation, synthesis and evaluation are three primary phases in the design process (Jones 1963). First, design formulation aims to collect and formulate the design problem, which corresponds to the structuring of the environment $\oplus \boldsymbol{E_i}$ in Eq. (3-1). Secondly, design evaluation, corresponding to $\boldsymbol{K_i^e}(\oplus \boldsymbol{E_i})$ in Eq. (3-2), is the process to identify the gap of the existing product descriptions with the design requirements formulated in design analysis. In most cases, design evaluation would take causal knowledge to assess the product performance (Kim & Kim 2011). Finally, design synthesis is a process that generates new product descriptions according to the identified gap from design evaluation. Zeng and Cheng (1991) integrate the three operations into the recursive logic of design, based on which Zeng and Gu (1999b) developed a mathematical theory to formally represent the recursive formulation, evaluation and synthesis processes. Zeng (2004) further formalized the process into the recursive evolution of the environment structure, which is called the design governing equation (Zeng 2002, 2004; Zeng & Yao 2009), as shown in Eq. (3-2).

$$\oplus \boldsymbol{E_{i+1}} = \boldsymbol{K_i^s}(\boldsymbol{K_i^e}(\oplus \boldsymbol{E_i})) \qquad \textbf{(3-2)}$$

where a design problem is formulated by analyzing the current design state (environment $\oplus \boldsymbol{E_i}$) through $\boldsymbol{K_i^e}(\oplus\boldsymbol{E_i})$ using the evaluation operation $\boldsymbol{K_i^e}$. Then a new design state (i+1) (environment $\oplus$ $\boldsymbol{E_{i+1}}$) results from the application of the synthesis operation $\boldsymbol{K_i^s}$ to the formulated design problem $\boldsymbol{K_i^e}(\oplus\boldsymbol{E_i})$**.** Combining Eq. (3-1) and (3-) with Figure 3-1, we can get an updated design process, as shown in Figure 3-2.

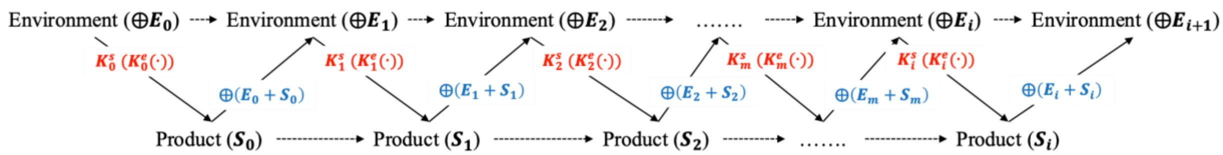

Figure 3-2 Design: evolution from E_i to E_{i+1}

In the design governing equation Eq. (3-2), the design requirements and solutions define a design space through the structure operation $\oplus$, which will be stretched by the synthesis operation and shrunk by the evaluation operation, as shown in Figure 3-3. The final design solutions are the result of balancing the stretching and shrinking operations. Design is such an ill-defined problem where designers will continuously define and redefine the design problem/requirements, constraints, and context (Simon 1973).

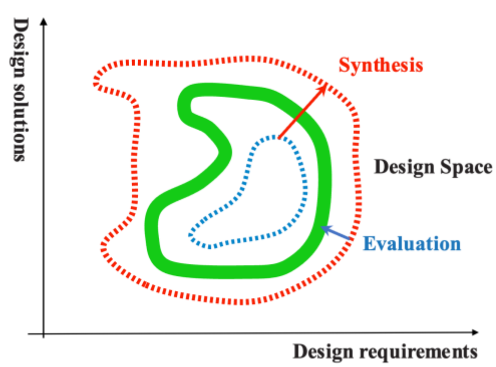

Figure 3-3 Design space under synthesis and evaluation

3.1.2 The fundamental design mechanism is a recursive, nonlinear, and chaotic dynamics

It was proposed that the design governing equation, Eq. (3-2), implies recursive nonlinear chaotic dynamics (Zeng 1992, 2001), under which a slight difference in initial conditions could lead to chaotic fluctuations during the time course with the synthesis and evaluation as stretching and folding operations. The same observation was made by Richards (1996, 2001, 2021) in that creativity follows a nonlinear dynamics (chaotic), demonstrating the Butterfly Effect. Chaotic does not mean randomness or disorder, chaotic dynamics is a well-established scientific discipline.

The design mechanism is recursive in the following two aspects:

1) Design problem, solutions, and knowledge evolve simultaneously and recursively during the design process. This recursion was mathematically and logically identified as the recursive logic of design (Zeng & Cheng 1991). As a confirmation, Roozenburg associated the recursive logic of design with Charles Pierce's innovative abduction (Roozenburg 1993). Furthermore, Dixon and French further studied this phenomenon in the context of Deweyan logic (Dixon & French 2020). At a different level, Maher *et al.* (1996) and Dorst & Cross (2001) claim that the design problem space and design solution space follow co-evolution during the design process. The co-evolution process is driven by a reaction to a surprise (change in environment) (Dorst & Cross 2001). The same can be found in Campell's evolutionary theory (Campbell 1965) and Simonton's evolutionary model (Simonton 1999).
2) Evaluation knowledge, synthesis knowledge and structure operation recursively interact in the design process. This recursive interaction between the three design subprocesses was formulated and formalized in (Zeng & Jing 1996) and (Zeng & Gu 1999a, 1999b).

Eq. (3) is not a linear equation in that the superimposition rule fails the equation. As a result, multiple design solutions exist, and different initial conditions could lead to different solutions. Furthermore, this nonlinear dynamic design process becomes chaotic since the recursive dependence among evaluation knowledge, synthesis knowledge and structuring operation implies the stretching and folding operations necessary for chaos to emerge in nonlinear design dynamics. Therefore, the design governing equation Eq. (3-2) defines recursive, nonlinear and chaotic dynamics for the design process.

With a similar line of understanding, some scholars have noted the importance of recursion in the sub-phases of creativity (Lubart 2001; Zeng 2011). In describing the design (Gero & Kannengiesser 2004) highlighted that an "agent's view of the world changes depending on what the agent does." In describing the creative process, Corazza (2019) stressed that continued exploration is a primary force driving the creative process, while bidirectional dynamic interaction with the environment influences the recursion underlying the creative process in terms of dynamic assessment and the emergence of unpredictable new functionalities. Lubart (2001) indicated that initial ideas might interact with the developing work in a dynamic and evolving creative process. Lubart also raised several critical questions for future research on creativity, such as "to what extent is the creative processes recursive?"; "how exactly is this recursion organized?"; "what provokes recursion?"; and "what metacognitive functions control the choice of certain subprocesses and their recursive application?"

Though the nonlinear design dynamics appears to be a structured, deterministic, and causal model of design, it accommodates flexibility, uncertainty, unpredictability, and chaos through its sensitivity to initial conditions. Furthermore, the definition of the initial design condition is subjective. Therefore, the nonlinear recursive design process can be naturally viewed as an evolving creative process, and it can be derived that

1) Routine, innovative and creative designs follow the same design governing mechanism; and
2) Designer creativity is the condition leading to routine, innovative and creative designs.

3.1.3 Design creativity crosses routine, innovative and creative design spaces

Creative design is unpredictable; sometimes, it even seems impossible– yet they happen (Boden 2004). Different designers could produce different design solutions for the same design problem, and the same designer could produce different design solutions at different times for the same design problem. Creativity may happen even if one does not mean to conduct a creative design, whereas creative design just may not come out no matter how hard one tries. Thus, a natural question is: does a designer produce routine, innovative and creative designs following one governing mechanism, as shown in Eq. (3-2)?

According to Gero's classification (Gero 1990), a design is routine if it proceeds within a design space of known and ordinary designs; it is innovative if it proceeds within a well-defined state space of potential designs, but produces different designs; and it is creative if new variables and structures are introduced into the design space of potential designs. A good design solution is a result of recursively selecting methods based on related good knowledge. Knowledge is a resource for designers to produce design solutions from design problems. Design can be seen as a knowledge-based problem-solving activity (Chandrasekaran 1990), in which knowledge recursively links to their problem and sub-problem (Chandrasekaran *et al.* 1992). As such, Figure 3-4 defines different types of design, according to which design spaces are described where the design governing equation Eq. (3-2) would apply. Obviously, the knowledge and experience of the designer determines the boundaries of design spaces.

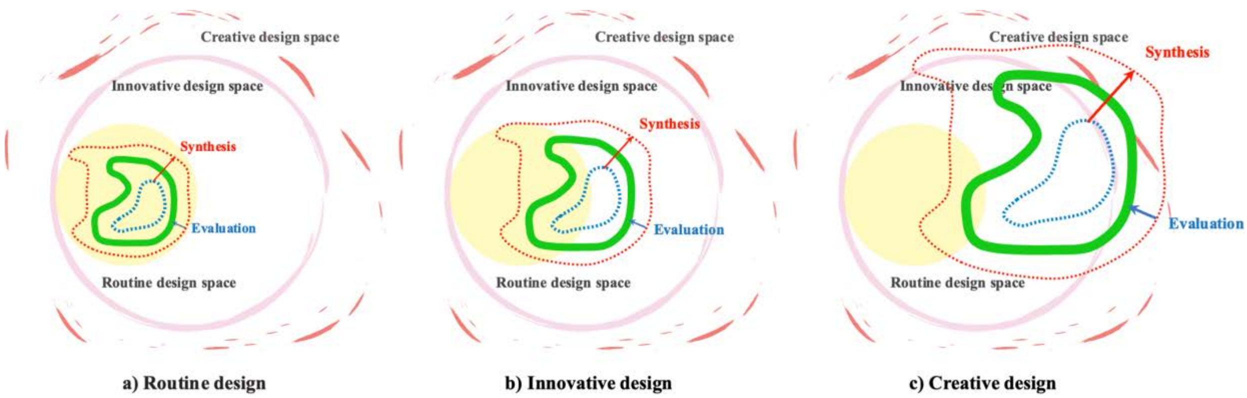

Figure 3-4 Design creativity: a) routine design – synthesis and evaluation operators act only on the routine design space; b) innovative design – synthesis and evaluation operators act on both the routine and innovative design spaces; c) creative design – synthesis and evaluation operators act on the routine, innovative, and creative design spaces.

3.2 Designer creativity: Knowledge-related designer capability is fundamental to creative designs

Designer creativity is the ability to come up with ideas or artifacts that are new, surprising and valuable (Boden 2004). Given a design problem, a designer will identify the relevant knowledge to generate tentative design solutions, improving the designer's understanding of the design problem. This improved understanding might lead to a reformulation of the original design problem. Reformulating the problem will lead the designer to identify new knowledge and change previously generated solutions, leading to another design problem reformulation.

Designer creativity means that the designer is creative, which is the process of design creativity. Designer creativity can be divided into static states related to how the designer's capability influences creativity and dynamic processes related to achieving creativity (Corazza 2016; Zeng & Gu 1999c). The dynamic creative process requires the available flexibility for designers to switch freely among information and idea evaluation, idea generation, and idea evolution (Corazza *et al.* 2022; Jia & Zeng 2021).

It is possible that a designer is not creative but the product is and a designer is creative but the product is not. The Four C model is commonly used to describe individual creativity (Kaufman & Beghetto 2009): mini-c (relevant to the genesis of creative expression), little-c (relevant to non-professional readily creative recognition), pro-c (relevant to professional creative recognition), and big-c (relevant to eminent creativity). Some researchers argued that different factors of capability influence designer creativity, such as intelligence (Gardner 2011; Torrance 1969), knowledge, thinking style (ex. divergent and convergent thinking) (Guilford 1967), personality

(Csikszentmihalyi 2014; Feist 1998; Lebuda *et al.* 2021; Stein 1953) and motivation (Amabile 1983; Sternberg & Lubart 1991). Torrance (Torrance 1969) argued that creativity requires a certain level of intelligence. Gardner (2011) also proposed different types of intelligence and argued that creativity is multiple as intelligence is. Sternberg (2021) argued that intelligence is adaptive, interacting with a person, task, and situation. Tromp & Sternberg (2022) applied Person x Task x Situation interaction framework to explain creativity. Guilford (1950, 1967) proposed a special thinking style, divergent thinking (divergent product), to describe creativity. He argued that it is essential for creativity to the interplay between divergent and convergent production. Recently, exploring the relationship between divergent thinking and ideation has been very often found in creativity studies (Lee & Ostwald 2022; Mastria *et al.* 2021). Amabile (1983) proposed a componential model that assumes three components influencing creativity: domain-relevant skills, creativity-relevant processes and intrinsic task motivation. Sternberg & Lubart (1991) proposed an investment theory where an economist's vision of creativity includes six elements to form creativity: intelligence, knowledge, thinking style, personality, motivation, and circumstances.

Considering that the recursive nature of the design process leads to unpredictability and uncertainties and that the novelty of creative design would challenge the designer's comfort zone, mental stress is an inevitable outcome during the creative design process. Inspired by Yerkes & Dodson Law (1908), which indicated that people would perform the best under moderate amounts of stress, Zeng and his students proposed that people would be most creative when they are subject to an optimal level of mental stress (Nguyen & Zeng 2012; Zhu *et al.* 2007). Instead of assuming an inversed U-shaped-curve relation between performance and stress, Nguyen and Zeng defined an inversed U-shaped-curve relation between mental stress and mental effort (Nguyen & Zeng 2014). Nguyen and Zeng also defined how mental stress is related to perceived workload, knowledge, skill, and affect (Nguyen & Zeng 2012, 2017a, 2017b).

3.2.1 Designer mental stress: Designer creativity comes from the designer's optimal mental stress

Based on Nguyen & Zeng's work on mental stress and mental effort, Yang *et al.* (2021) proposed TASKS Framework (**T** for Task, **A** for Affect, **S** for Skills, **K** for Knowledge, and **S** for mental Stress-effort relation), which is a theoretical framework to identify implementation facilitators and barriers for human behavior in implementing a task. The underlying reason for a person's behavior is their perceived tasks, knowledge, skill, and affect (Nguyen & Zeng 2012). The creativity behavior is adaptive to their perceived task. The level of mental stress, in turn, affects the designer's creative performance. As for the same question, a designer's knowledge and skills cannot change in a short period. Therefore, a designer's mental effort decides the designer's level of creativity.

Low- and high-level mental stresses produce low-level mental efforts, whereas medium-level mental stress results in optimal mental efforts, which may lead to creativity, as shown in Figure 3-5 (Nguyen & Zeng 2012).

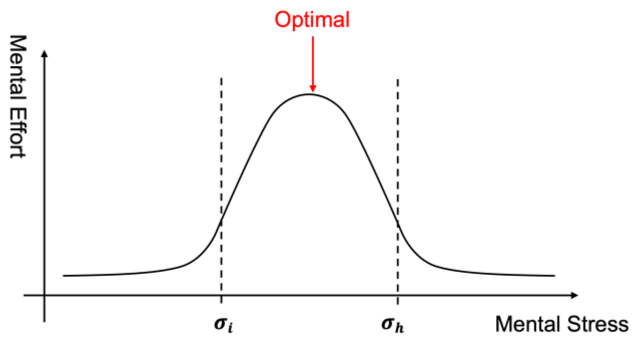

Figure 3-5 Relationship between mental stress and mental effort

Importantly, Nguyen & Zeng (Nguyen & Zeng 2012, 2017a) also formulated the cause-effect relationship of mental stress and perceived task workload, knowledge, skill, and affect, as shown in Eq. (3-3)**.** The perceived task workload is an external load exerted on an individual and can be associated with the complexity of the task. Both knowledge and skills form human cognitive ability and rationality. Depending on the mental capacity, the perceived task workload, which is the workload perceived by an individual, can be higher or smaller than the actual workload. The perceived task workload will then determine the mental stress. Knowledge originates in human cognition and can aid people in making proper decisions (Rowley 2007). Better knowledge could help a better decision about actions (Davenport & Prusak 1998), which can be influenced by different types of knowledge such as experience, judgement, thumb rules, and values and beliefs. Skills can be categorized into cognitive, affective and psychomotor (Bloom 1956), for which logic is critical. Affect refers to any experience of feeling or emotion, ranging from suffering to elation, such as fixation and uncertainty. Affect, which falls between 0 and 1, could determine how much of a designer's knowledge and skills can be activated and harnessed to complete a given design task. Gero also pointed to the interpreted world that is very similar to mental capability and the expected world as perceived task workload (Gero & Kannengiesser 2004).

$$\boldsymbol{Mental\ stress} = \frac{Task\ workload}{Mental\ capability} = \frac{Perceived\ task\ workload}{(Knowledge+Skills)\times Affect},\ A \in (0,1) \qquad \textbf{(3-3)}$$

TASKS framework identifies barriers and facilitators to human behaviors. In the TASKS framework, barriers and facilitators build on the gap between the ideal TASKS components and the implementer's actual mental capability (ASK). Yang et al. (2021) categorized implementation barriers/facilitators into four types: knowledge, logic, emotion, and resource. The good knowledge for designers is the facilitator, whereas the bad is the barrier. In the following session, we will discuss when the designer's knowledge could lead to good (facilitator) and bad (barrier) mental stress.

3.2.2 The good: Proper designer knowledge maintains the designer's mental stress to the right level to trigger the creativity

Designer creativity happens when designers' mental stress is optimal, which means the combination of perceived task workload, knowledge, skills, and affect are optimal. The designer's knowledge and skills can be assumed to be constant during a short design process; thus, the designer's perceived task workload will be mainly influenced by the affect. The perceived task workload in a good affect (close to 1) reflects the actual one more than that in a bad affect (close to 0).

If a designer has the perfect knowledge for a given design problem, then the design solution will be available simultaneously (Yoshikawa 1981). However, because of the limitation in human understanding of the world, designer knowledge is never perfect and always goes with the designer's perception (Zeng 2002). As a result, the design problem becomes open-ended and ill-defined, and the design process becomes recursive, nonlinear and chaotic. Furthermore, the uncertainty can appear in different ways: 1) the design requirements may be unclear, incomplete, or conflicting; 2) the environment and its possible interactions with the product may be unknown due to the lack of knowledge; and 3) the lack of design thinking and capability to deal with the first two situations. Nevertheless, the uncertainty arising from a design task is the condition for a designer to demonstrate creativity (Nguyen & Zeng 2012), and uncertainty makes creativity possible (Beghetto 2021; Runco 2022).

Under an uncertain situation, designers must employ their creative capabilities to find and apply proper knowledge to their design problems. Too much uncertainty could make it difficult for a designer to find the proper knowledge to understand and solve the design problem, which could bring the designer into the over-stress zone and thus defy the designer's effort to perform. Equipped with proper knowledge, certain degrees of uncertainty mean more possibilities that fall under the designer's capability zone. The unknown can be exciting and motivating, prompting designers to experiment with and develop new ideas. Without any uncertainty, there is likely no emotion and stress to drive designers to experiment with and try new things. Both the knowledge and affect factors will regulate the designer's mental stress, according to Eq. (3-3). The knowledge-related skills introduced in Section 3.3 will help designers identify and acquire the necessary and proper knowledge for creative designs.

3.2.3 The bad: Improper knowledge leads to design fixation inhabiting designer creativity

Another phenomenon is design fixation, which is seen as an obstacle to design creativity (Jansson & Smith 1991). Design fixation is defined as "blind adherence to a set of ideas or concepts limiting the output of conceptual design" (Jansson & Smith 1991). One of the distinctive features of fixation is that designers do not know when they are fixated by misleading or poor information (Linsey *et al.* 2010). Kannengiesser & Gero (2019), combing Kahneman's dual system (Kahneman 2011) with FBS (Gero 1990), pointed out two types of design fixation in the design process: 1) system 1: generating an initial idea or concept, and 2) system 2: elaborating the initial structure. Youmans & Arciszewski (2014) also proposed a similar fixation level: unconscious adherence, conscious blocking, and intentional resistance, where conscious blocking and intentional resistance belong to system 2.

It is worth noting that both novice and expert designers are prone to prematurely committing to design solutions (Linsey *et al.* 2010; Viswanathan *et al.* 2016). When designers encounter open-ended design problems, they retrieve potential solution concepts from their existing memory and knowledge base (Jansson & Smith 1991). Therefore, Christensen & Schunn (2007) argue that one of the triggers of fixation is the connection of distant domains. The designer has easier-to-retrieve concepts within closely related domains than domains distant from each other. In addition, the designer's personality types and lacking awareness of technological advances also cause fixation (Moreno *et al.* 2016).

In explaining design fixation following a formal causal reasoning, Nguyen & Zeng (2017a) formalized the structure of design fixation, including potential solutions and designer preferences. Fixation was defined as the condition wherein designers use an inappropriate existing design idea to solve a design problem due to their strong attachment to the idea. In the design solution space, there are various design solutions. If an expected (or actual) design solution fits the designer's preference, design fixation will be more likely to happen. Corresponding to fixation in systems 1 and 2, fixation in system 1 means the designers' strong emotional attachment to their experience and efforts. This leads to failure to transfer knowledge appropriately or limit the design solution space. Fixation in system 2 means the lack of the right knowledge-related skills (including thinking styles, thinking strategy and reasoning). In the mental stress equation shown in Eq. (3-3), designers' different knowledge and skills influence the designer's affect, which is the designer's preference in design fixation structure. When designers lack the proper knowledge and skills, the potential solutions are also influenced by different preferences. Those knowledge-related skills introduced in Section 3 will help designers overcome fixations.

3.3 The ways: knowledge-related skills enable designers to use knowledge properly to achieve creative designs

Applying knowledge to designer creativity aims to avoid the bad and enhance the good role of knowledge. Designer creativity may happen when they use proper knowledge to solve design problems, leading to optimal mental effort successfully. In the design science domain, there are two streams to arrive at this destination: 1) realizing creativity and 2) overcoming fixation. Most design methodologies are for the first stream to solve design problems creatively. Also, some researchers focus on the second stream in terms of finding more implementation methods based on fixation's trigger stimuli (Dong & Sarkar 2011; Moreno *et al.* 2016; Viswanathan *et al.* 2016; Youmans & Arciszewski 2014) and avoid factors of fixation through teamwork (Crilly 2015). This paper focuses on the first stream to realize designer creativity based on the design governing equation, as shown in Eq. (3-2).

Based on the design governing equation, three possible ways may lead to different design states, which can be creative designs, as shown in Figure 3-6. The three ways are 1) formulating a design problem differently, 2) extending synthesis design knowledge, and 3) changing the strategy of environment decomposition. The connection between related activities and ways is shown in Table 3-1. More details are shown in the following subsections.

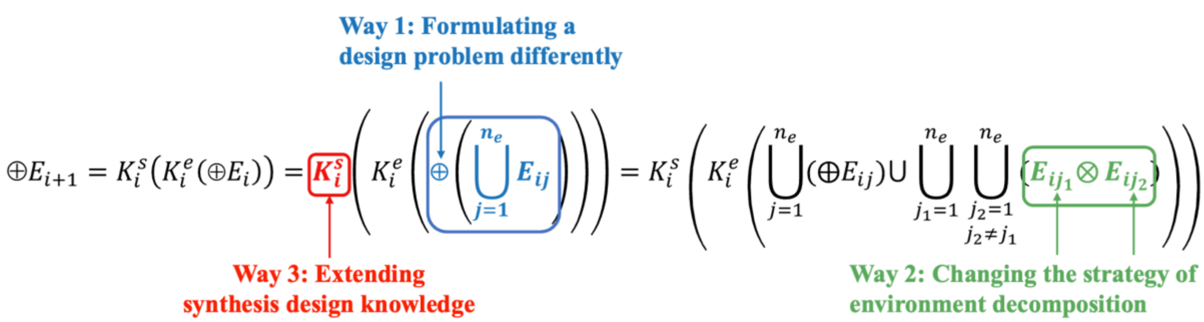

Figure 3-6 Three ways in the design governing equation (n_e: the number of environment components; **E_{ij}:** is an environment component in the same design state **(E_i))**

Table 3-1 The connections between related activities and three ways (C_i: a conflict at the E_i; S_i: the new product)

Ways	Required Knowledge	Related Activities
Formulating a design problem differently (Different E_i)	Evaluation knowledge	***Different*** $\oplus\left(\cup_{j=1}^{n_e} E_{ij}\right)$ → ***different*** E_i → ***different*** K_i^e → ***different*** C_i

Changing the strategy of environment decomposition (Different E_i)	Evaluation knowledge	***Different*** $\boldsymbol{C_i}$= $(\boldsymbol{E_{ij_1}} \otimes \boldsymbol{E_{ij_2}})$ → ***different*** $\boldsymbol{K_i^s}$
Extending synthesis design knowledge (Different E_{i+1})	Synthesis knowledge	***Different*** $\boldsymbol{K_i^s}$ → ***different*** $\boldsymbol{S_i}$ → ***different*** $\boldsymbol{E_{i+1}}$

3.3.1 Way 1: Formulating a design problem differently

When Formulating a design problem differently is in the original design state or during the design process. The initial difference in problem formulation will be amplified in the design process because each design stage will redefine the problem. It is common sense that changing the perspective of seeing a problem may lead to a creative solution.

Function Formulating a design problem differently will result in different initial design states. A design problem is a request to design something that meets a set of descriptions of the request (Zeng 2004). Formulating a design problem is included in the environment structure $\oplus\boldsymbol{E_i}$. The inclusion or exclusion of an environment component $\boldsymbol{E_{ij}}$ will lead to different $\oplus\boldsymbol{E_i}$. Designers may form a design problem differently by grouping different environment components into one assembly, which will lead to a change of $\oplus\boldsymbol{E_i}$. As a result, because of its nonlinearity, different initial conditions of the design problem may lead to different design solutions, some of which might be creative.

In practical applications, these initial conditions may be manifested as different designers or as the same designer designing at different times. Since novice and expert designers have pretty different experiences, they usually apply different methods to formulate the problem. As a result, they got different solutions. Even if the same designer changes a perspective, the design problem will be formulated differently. Consequently, the object $\boldsymbol{C_i}$ (Table 1) could be changed, which in turn changes the initial condition of the design process. The process could result in a significant change in design solutions. Therefore, different knowledge can formulate a design problem differently.

How Formulating design problems is realized through designers' knowledge and skills, such as information search and understanding, which is led by the following activities: 1) search and identify evaluation knowledge, 2) search, identify and redefine critical requirements, 3) generate and update primitive design solutions, and 4) evaluate, analyze and recompose partial design solutions. From a macro perspective, designers may use different methodologies during the design process, which lead to different design formulations. From a microscopic perspective, even if designers use the same methodology, different designers will use different knowledge and experience to formulate problems differently, depending on their affect and perception at the time of designing.

Different design methodologies naturally help designers formulate a design problem differently since different methodologies lead to different evaluation knowledge. According to how a methodology formulates a design problem, Zeng classifies design methodologies into three types (Zeng 2020): 1) product-based, 2) product-environment interaction-based, and 3) environment-based. Product-based methodology mainly focuses on evaluation and optimizations, such as axiomatic design (Suh 1998), decision-based design (Hazelrigg 1998; Wassenaar & Chen 2003), and structural topology optimization (Bendsøe & Kikuchi 1988; Bendsoe & Sigmund 2003). The product-environment interaction-based methodology includes function-based design and affordance-based design. Pahl & Beitz (1988) proposed a systematic approach to formulate design problems in generic systems. Pahl and Beitz combined general systems modelling with functional modelling to model artifacts in a hierarchy of subfunctions sharing flows of material, energy, and information (Pahl *et al.* 1996). Hubka & Eder (1988) also proposed the theory of technical systems in the same year. Umeda *et al.* (1990) developed a function-behavior-state (FBS) connected them through physical phenomena. Gero & Kannengiesser (Gero 1990; Gero & Kannengiesser 2004) proposed situated function-behavior-structure (FBS) to formulate a design problem in terms of three entities (function, behavior and structure) situated in three worlds (external. interpreted, and expected world). Using situated FBS, Becattini *et al.* (Becattini *et al.* 2020) investigated how individually pre-conceived expectations influence the different surprise emergence. Chandrasekaran *et al.* and Bhatta & Goel (Bhatta & Goel 1997; Chandrasekaran *et al.* 1993) proposed the structure-behavior-function (SBF) knowledge representation for engineering systems. Stone & Wood (1999) built a functional basis for engineering design. Quality function deployment (QFD) is a methodology to ensure that customer needs are adequately transformed into engineering characteristics for a new product (Akao & Mazur 2003). The house of quality gives several perspectives on customer requirements and engineering characteristics to formulate design problems differently. Maier & Fadel (2009) proposed an affordance-based design to formulate a design problem regarding a designer–artifact–user (DAU) system. Affordance is a relation that one system (an artifact) provides to another system (a user). DAU system points to artifact-user affordance and artifact-artifact affordance. Dinar & Shah (2012) established a problem map framework to represent a design formulation strategy containing five groups of entities: requirement, function, issue, artifact, and behavior.

In contrast, the environment-based methodology is centred on the environment to formulate problems. Human-centred design (HCD) is an approach for creative problem-solving in several fields, starting with understanding the product's human environment (Norman 2013), such as stakeholders' needs and requirements. Mike Cooley coined the term "human-centred systems" in the context of the environment transition in the design process (Cooley 1980). Zeng (2004) proposed environment-based design (EBD) to formulate a design problem in terms of product environment, structural requirements, and performance requirements. Structural and performance requirements are related to the product environment, divided into natural, built (physical and digital artifact), economic, and social environments (Yang *et al.* 2020). In EBD, the question-asking tool is applied to help designers formulate problems effectively and efficiently (Wang & Zeng 2009), especially for novice designers. Dorst & Cross (2001) also proposed a process to formulate a design problem by asking a quasi-standard set of questions.

3.3.2 Way 2: Changing the strategy of environment decomposition

When Changing the strategy of environment decomposition happens after designers have developed an in-depth understanding of the design problem and have identified existing conflicts included in the problem. Identified design conflicts can be resolved in different ways. Conflict is an insufficiency of resources for an object to produce a desired action on its environment or to accommodate the object's action on its environment (Zeng 2015). Conflict is different from the notion contradiction in TRIZ. Contradiction refers to the propositions that assert apparently incompatible or opposite things (Altshuller 1984) whereas conflict refers to the insufficiency of resources for an object.

Function A different strategy to decompose the environment results in different combinations of different environment components $\boldsymbol{E_{ij}}$, leading to different problem reformulations. Strategy is a plan intending to achieve a particular purpose. Changing the strategy of environment decomposition is related to how to arrange the order of conflicts to resolve. Designers might decompose the environment of the original design problem once they have developed an understanding of the relationship between environment components. Different strategies of product environment decomposition result in different structural and performance constraints. As a result, the newly decomposed environment will formulate a new design problem. Also, the design process is a nonlinear process that concerns flexibility, uncertainty, and unpredictability of the design problem. Therefore, the environment will be continuously decomposed until the design problem becomes primitive. Generally, no two designers have precisely the same design knowledge, so they will use different ways to decompose the environment. Different sequences of environment decomposition will give rise to different reformulations of the design problem when designers apply their knowledge. As a result, the final solutions may be different.

How Changing the strategy of environment decomposition involves specific skills such as conflict identification and problem generalization. Changing the environment decomposition may be led by two activities: 1) search for critical conflicts and 2) identify evaluation knowledge. This process is related to information understanding from which knowledge is acquired. From a macro perspective, different methodologies have different rules for decomposing the environment. From a microscopic perspective, even if following the same methodology, different designers will use different knowledge and experience to get a strategy to decompose the environment.

The strategy of environment decomposition includes breadth-first and depth-first. Breath-first decomposition explores each subproblem, while depth-first decomposition focuses on a specific subproblem in detail. In general, novice designers tend to use a depth-first approach to explore partial sub-solutions. At the same time, experts prefer a breadth-first strategy to develop sub-solutions in parallel, with a switch to a depth-first approach when facing unfamiliar problems (Cross 2011). That is because the depth-first strategy requires little domain knowledge, whereas the breath-first strategy needs considerable domain knowledge (Chandrasekaran *et al.* 1992). In EBD, the strategy is hybrid rather than depth-first and breadth-first, which is considered the best way to minimize uncertainty and induce creativity in the problem formulation process (Wang *et al.* 2015).

3.3.3 Way 3: Extending synthesis design knowledge

When Extending synthesis design knowledge happens in design solution synthesis. Based on decomposed sub-problems, different or new knowledge might lead to diverse angles to discover a creative solution.

Function Extending synthesis design knowledge will change the relation from conflicts to design concepts $\boldsymbol{S_i}$. The extended knowledge provides the possibility for the selection of different $\boldsymbol{K_i^e}$ and $\boldsymbol{K_i^s}$, which results in the different intermediate design state $\oplus \boldsymbol{E_{i+1}}$. We can see that some new and different primitive products may be generated for a specified environment part by extending synthesis knowledge. The newly generated concepts are considered the environment components and analyzed by combining other identified environment components for generating a new round of design concepts. Therefore, extending synthesis design knowledge can help designers generate more candidate solution concepts, increasing the probability of generating a good concept. As a result, the final design solutions could be significantly different.

There are a few possibilities: first, more conflicts can be chosen at the same time to generate a design concept $\boldsymbol{S_i}$; and secondly, the same design conflict may be resolved by different design concept $\boldsymbol{S_i}$. Both cases will update the environment structure $\oplus\boldsymbol{E_{i+1}}$ differently. When design conflicts are identified by analyzing the relations between environment and product, designers will use their knowledge and experience to generate some candidate solution concepts. The number and quality of the design concepts largely depend on the designers' knowledge and experience. That is also a big difference between novice and expert designers. The generated concepts need to be evaluated to satisfy the specified product requirements. Novice designers cannot often evaluate the generated concepts using the proper criteria and finally fail to generate a good design solution. When we compare designs by a novice designer and an expert designer, we can see a big difference in the design solutions.

How Extending synthesis design knowledge through effective information acquisition, knowledge learning, and scientific discovery. Knowledge cannot be tied to one task but depends on its use (Bylander & Chandrasekaran 1987). Generating new knowledge is a reasoning task (Chandrasekaran *et al.* 1992). Right questions can identify new knowledge sources against relevant information and determine a degree of fit (Chandrasekaran 1986). Different information collection methods require different levels of knowledge. For example, depth-first search requires little domain knowledge, whereas hierarchical classification needs considerable domain knowledge (Chandrasekaran *et al.* 1992). The right level of knowledge acquisition consists of a problem definition, representation and inference strategy (Bylander & Chandrasekaran 1987).

The knowledge structure follows a hieratical pyramid called the data-information-knowledge-wisdom hierarchy (DIKW) (Ackoff 1989). The hierarchy describes knowledge coming from information as information comes from data. Knowledge can also come back to information and data, which is called de-knowledging (Davenport & Prusak 1998). Data, information, and knowledge are related to each other, which forms a recursive process. Knowledge is information with added value, experience, and context, which can provide a framework for synthesizing, evaluating and incorporating new experiences and information (Davenport & Prusak 1998).

Knowledge generation transfer information to knowledge through a cognitive understanding and reasoning process (Polanyi 2012). Reasoning is the process of the mind using existing knowledge to think, understand, conclude, and form judgments logically, which generally includes the minor premise as the situation and knowledge as the major premise. There are four types of reasoning (Zeng & Cheng 1991): 1) deductive logic, 2) inductive logic, 3) abductive logic, and 4) recursive logic, in which only deductive reasoning is deterministic, and all other reasoning modes are implausible (Zeng 2002). Recursive logic combines deductive logic, inductive logic, and abductive logic. As a result, these four types of reasoning lead to four methods that can help designers extend synthesis design knowledge: knowledge derivation, extraction, generalization, and discovery.

Knowledge derivation (deduction)

Knowledge derivation follows deductive logic to derive synthesis knowledge from one or more pieces of information and existing knowledge. Knowledge derivation starts with the assertion of a general rule to reach a logical conclusion, which aims to predict the future based on the information provided in the task description and the existing knowledge. Information is organized or structured data by some purpose and relevance. For example, following the deductive approach, Cascini *et al.* (Cascini *et al.* 2013) proposed a framework applying Gero's Function-Behaviore-Structure (FBS) to represent a product's needs and requirements and their relationship with FBS dimensions and other papers on the same topic (Fernandes *et al.* 2007; Sim & Duffy 2003).

Knowledge extraction (abduction)

Knowledge extraction follows abductive logic to extract synthesis knowledge from small data, which begins with an incomplete set of observations and looks for causes from given effects by applying a set of existing knowledge. As abductive reasoning requires, knowledge extraction hangs on a particular theory in the reasoning process. Through the application of abduction to a small set of data, knowledge can be extracted by removing certain details embedded with the data. For example, Cheligeer *et al.* (2022) proposed ROM-based (Zeng 2008) semantic networks to address knowledge graphs related to the design problem from a seed design statement. Similar efforts can be found in a few other papers (Lin *et al.* 1996; Rockwell *et al.* 2009).

Knowledge generalization (induction)

Knowledge generalization follows inductive logic to generalize synthesis knowledge from big data. Inductive logic begins with observations. Knowledge generalization aims to develop new knowledge from available evidence or collected knowledge. The process related to converting data into information and knowledge makes data meaningful, valuable and relevant. Many methods exist to transform data into information, such as adding meaning to data, categorizing data, mathematically analyzing data, correcting errors in data, and condensing data (Davenport & Prusak 1998). Numerous methods, algorithms and applications can be found in the contemporary machine learning-related literature.

In the field of design, examples of work in this category include the generalization of product customization knowledge through mass customizability analysis (Hou & Jiao 2020; Jiao & Tseng 2004; Zhou *et al.* 2022), emotional design (Zhou *et al.* 2021b), patent data-driven to generalization of engineering knowledge (Jiang & Luo 2022; Siddharth *et al.* 2021; Song *et al.* 2018; Song & Luo 2017), and big data-based customer analytics to generalize knowledge of customer requirements (Jin *et al.* 2016; Liu *et al.* 2020; Tong *et al.* 2022). Cheligeer *et al.* (2022a) summarized machine learning methods for requirements elicitation. In the health domain, Wu *et al.* (2022) use machine learning methods to evaluate and generalize adverse events knowledge from electronic medical record (EMR) data. Notably, Quan *et al.* proposed the ICD coding system as meta-level knowledge for electronic medical administrative data (Eastwood *et al.* 2022; Quan *et al.* 2005). Using ICD coding system, researchers can generalize medical knowledge from the EMR system for precision medicine, such as comorbidities (Quan *et al.* 2005), hypertension (Quan *et al.* 2009), and diabetes (Chen *et al.* 2010).

Knowledge discovery (recursion)

Knowledge discovery follows the recursive logic to discover knowledge from nothing/zero data. Recursive logic combines deductive logic, inductive logic, and abductive logic. Popper (2012) proposed a tetradic schema for knowledge evolution from an initial problem (P_1), tentative theory (TT), attempts at error-elimination (EE) to further problems arising out of the critical process (P_2), which also follows a recursive process. Furthermore, he proposed "Three World" ontology categories (Popper 1978): 1) World 1: the world of physical states and processes, 2) World 2: the mental world of psychological processes and 3) World 3: the world of knowledge in its objective sense.

Knowledge discovery is the same as design problem solving, where researchers must formulate an ill-defined research question and design a research protocol. The problem formulation, research design, and research results evolve simultaneously. At the beginning of knowledge discovery, we only know the environment of the phenomenon to be investigated.

3.4 Summary and discussions

Herein, this paper presents the difference between design and designer creativity to uncover the roles of knowledge in designer creativity, based on which three ways are recommended to use the knowledge in design. First, routine, innovative, and creative designs follow the same design mechanism, and designs from different fields also follow the same design mechanism. That mechanism is the design governing equation. Second, the difference between routine, innovative and creative designs and between designs of different fields lies in the range, content, size and nature of the design space in which the design governing equation works. Finally, design creativity is caused by the initial conditions for the design governing equation, which is solved and reformulated by the designer's creativity capability.

Recursion: Designer creativity for the design creativity

The design process is to change the current environment ($\bigoplus E_0$) into a new environment ($\bigoplus E_1$), where the result can be creative, as shown in Figure 3-7. The fundamental design mechanism is a recursive nonlinear chaotic dynamics, which follows a basic environment evolutionary process (Figure 3-2). Recursive nonlinear chaotic dynamics leads to design uncertainties and is subject to the designer's fixations. Based on Nguyen & Zeng's (2017a) fixation structure, the designer's synthesis knowledge and evaluation knowledge determine the designer's preference, which determines potential design solutions. Then, the designer proposes a design solution by design evaluation and synthesis ($\boldsymbol{K_0^s}(\boldsymbol{K_0^e}(\oplus \boldsymbol{E}_0))$). The environment structure ($\oplus(\boldsymbol{E}+\boldsymbol{S})$) updates every state of the evolving design process.

Design is a problem that will simultaneously formulate the problem, find the knowledge, and generate the solutions (Zeng & Cheng 1991). Design problem formulation, design evaluation and design synthesis are three pillars of a design process. The designer's creativity capability dictates how the design process can generate creative design solutions through the recursive formulation of the design states.

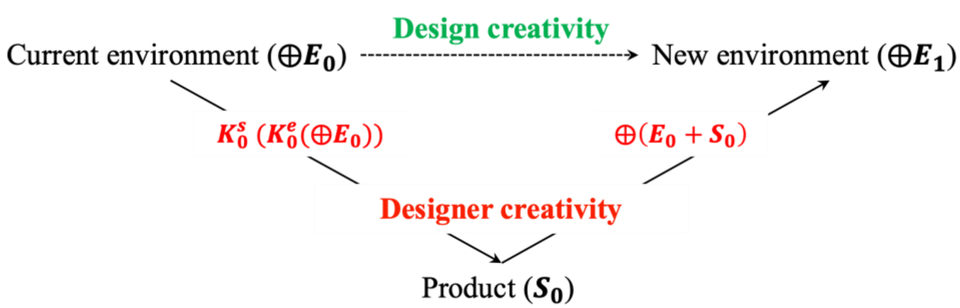

Figure 3-7 Designer creativity for design creativity

Creative thinking and knowledge: If one is missing, only routine design will happen

Creative thinking and good knowledge are two essential characteristics of a creative designer. Producing creative designs is the most desired situation for a design. Unfortunately, routine design is what happens in the majority of cases. Two common scenarios occur for routine design: 1) the designer is creative without knowledge; 2) the designer has knowledge without creative thinking.

By citing the concepts in Figure 3-4, the first scenario describes a situation where the designer's innovative and creative design space is only a subset of the field's routine design space. The designer can be creative only in other people's routine design space. On the other hand, the designer may have rich knowledge, which could be effectively used to produce innovative designs; however, the designer may lack the creativity capabilities to recursively implement the formulation, evaluation and synthesis processes. As a result, the designer's knowledge will probably become a source of design fixations; creative solutions are most unlikely to happen.

Chapter 4

4 Identifying Personalized Barriers for Hypertension Self-Management from TASKS Framework

Abstract

Background: Effective management of hypertension requires not only medical intervention but also significant patient self-management. The challenge, however, lies in the diversity of patients' personal barriers to managing their condition. These barriers are highly individualized, varying significantly from one patient to another based on their unique circumstances, beliefs, emotional states, knowledge levels, and access to resources. Recognizing and addressing these unique challenges are pivotal for crafting patient-centered strategies, enhancing outcomes by aligning support with each patient's specific needs.

Methods: This study utilized the TASKS framework (Task, Affect, Skills, Knowledge, Stress) to identify and categorize personalized hypertension self-management barriers. Analyzing transcripts from eight patients and Global Hypertension Practice Guidelines, it identified emotion, logic, knowledge, and resource barriers.

Results: The analysis uncovered 69 personalized barriers across the participants, with a notable distribution: emotion barriers (49%), knowledge barriers (24%), logical barriers (17%), and resource barriers (10%). These findings emphasize the significant impact of emotional and knowledge-related challenges on hypertension self-management, including difficulties in home blood pressure monitoring and the use of monitoring tools.

Conclusion: This study emphasizes recognizing and addressing personalized barriers to hypertension management, employing the TASKS framework. It reveals emotion and knowledge barriers as prevalent, stressing the need for tailored interventions.

Keywords: hypertension, self-management, personalized, barriers, TASKS framework

4.1 Introduction

Hypertension is a leading global health risk, significantly contributing to cardiovascular diseases such as stroke and heart failure and affecting mortality and morbidity rates worldwide (Brunström & Carlberg 2018; Quan *et al.* 2009; Zhou *et al.* 2021a). Despite the effectiveness of lifestyle modifications and antihypertensive medications (Unger *et al.* 2020), patient adherence varies widely, with nonadherence rates between 10% and 80%, challenging the achievement of optimal blood pressure control (Corrao *et al.* 2011; Mazzaglia *et al.* 2009). Self-management is critical in managing hypertension (Bosworth *et al.* 2009), requiring patients to take an active role in their health care, yet nearly 40% of patients discontinue crucial treatments, and over half fail to adhere to necessary behavioral changes (Liu *et al.* 2014). Factors such as cultural beliefs and past healthcare experiences heavily influence patient attitudes toward self-management (Barrier *et al.* 2003; Chobanian *et al.* 2003).

Recognizing personalized barriers to hypertension self-management is essential for the successful implementation of interventions, aiming to bridge the evidence-to-practice gap in healthcare (Edelman *et al.* 2021). Personalized barrier identification allows for a deeper understanding of individual needs, preferences, and contextual factors, facilitating targeted interventions (Yang *et al.* 2021). Traditional qualitative methods, like thematic analysis (Chow *et al.* 2022; Ndejjo *et al.* 2020), have been used to code interview transcripts in hypertension research, identifying common themes (Strauss & Corbin 1998) across patient experiences. This method begins with interviews, letting themes emerge organically through deductive or inductive reasoning. Various frameworks like Consolidating Framework for Research Implementation (CFIR) (Damschroder *et al.* 2009b), Theoretical Domains Framework (TDF) (Michie *et al.* 2005), Capability Opportunity Motivation Behavior (COM-B) (Michie *et al.* 2011), and Barriers and Facilitators in Implementation of Task-Sharing Mental Health Interventions (BeFITS-MH) (Le *et al.* 2022) have provided predefined coding schemes. However, these methods often struggle to capture the diverse and personalized needs of patients (Huybrechts *et al.* 2021).

To address these challenges, this study introduces the TASKS framework (Yang *et al.* 2021), which focuses on Task (T), Affect (A), Skills (S), Knowledge (K), and Stress (S), offering an approach to understanding the interplay between an individual's mental capabilities, external resources, and the demands of managing hypertension. The framework categorizes barriers into emotion, logic, knowledge, and resource-related, providing insights into the specific reasons behind patients' actions and decisions in self-managing hypertension. Originally applied in various fields such as education (Ma *et al.* 2022), engineering (Mohammadi *et al.* 2022), sustainability (Du *et al.* 2023) and beyond, the TASKS framework's adaptability presents a novel avenue for exploring personalized barriers in hypertension self-management. This research aims to evaluate the framework's effectiveness in identifying these barriers, marking a significant step towards enhancing patient-centered care and improving self-management outcomes in hypertension.

4.2 Methods

4.2.1 Study design and data information

This study employs the TASKS framework to identify personalized barriers from interview transcripts. Data were sourced from Global Hypertension Practice Guidelines (Unger *et al.* 2020) and anonymized interview transcripts from a prior study (Chow *et al.* 2022), with ethical clearance from the University of British Columbia's Clinical Research Ethics Board. Originally, nine patients from two focus groups were considered, but due to inefficiency in one patient's data, eight were ultimately analyzed.

Five transcript analyzers, comprising both medical and non-medical students, underwent intensive training on the coding process, which included defining the coding scheme and jointly coding 20 sentences. They then independently applied the TASKS framework to the transcripts of eight patients, resolving any coding discrepancies through discussion. The analyzers' agreement was assessed by independently coding two shared transcripts. This research aimed to validate the TASKS framework's utility in pinpointing personalized barriers to hypertension self-management.

4.2.2 Coding hypertension guideline

We referred to the Global Hypertension Practice Guidelines (Unger *et al.* 2020) to identify the required TASK components: affect skills, knowledge (ASK), and resources necessary for specific workload/tasks (T). Workload, in this context, denotes the external load assigned by experts or governmental entities, such as recommendations made by physicians for patients. To break down this process, four key steps were undertaken: 1) extracting all required workloads specified in the Global Hypertension Practice Guidelines; 2) determining the life cycle associated with each workload (Yang *et al.* 2020); 3) coding the ASK and resource requirements for each workload based on its life cycle; and 4) consolidating all stages of ASK and resource elements related to a particular workload.

4.2.3 Identifying personalized barriers using the TASKS framework

4.2.3.1 Coding affect, skills, knowledge (ASK), and resource

In this step, we streamlined unstructured interview transcripts into a semi-structured format for detailed analysis. This involved classifying text by speaker and evaluating each sentence adhering to analyze underlying messages behind the interviewee's message including Affect (A), Skills (S), Knowledge (K) and Resource, as shown in Table 4-1. Multiple analysts independently undertook this task to ensure a thorough examination of the data.

Table 4-1 The coding structure for the interview transcript

Sentence category	Coding content
Interviewer	1. Interviewers' objective 2. What information/questions can be triggered by the interviewer's message? a. What, To Whom b. Where, when 3. What questions can be triggered by this message?
Interviewee	Underlying messages behind the interviewee's message a. Affect (A) b. Skill (S) c. Knowledge (K) d. Resource

The TASKS framework differentiates between ASK and Resource. Affect relates to emotional experiences affecting task engagement, including attitudes, beliefs, feelings, and ethics. Skills involve cognitive and affective capabilities, emphasizing logical reasoning—deductive, inductive, abductive, and recursive (Zeng & Cheng 1991) -to use knowledge in practical scenarios. Knowledge refers to understanding, including facts and cause-effect relationships related to the task at hand. Resources are considered as external aids like time, money, or physical tools.

For instance, in the provided transcript: "*My run marathons I've done 18 of them, I do yoga, I do everything that is possibly able to reduce blood pressure and has not been able to do that*," the patient exhibits (Affect) frustration and disappointment due to their extensive efforts not yielding the anticipated blood pressure reduction. They employ (Skills) deductive logic, assuming activities like running marathons and yoga would lower blood pressure based on common knowledge. This patient demonstrates (Knowledge) experience in activities linked to blood pressure reduction.

4.3 Results

4.3.1 Hypertension guideline results

In our analysis, we systematically extracted and categorized all essential workloads outlined in the Global Hypertension Practice Guidelines (Unger *et al.* 2020) into four primary types: 1) Having a healthy lifestyle; 2) Monitoring blood pressure (BP) regularly at home, 3) Taking medication(s) regularly as prescribed, and 4) Creating a hypertension support system: family, friends, and healthcare professionals (HCPs). The comprehensive breakdown of necessary ASK and resources for each workload is detailed in Table 4-2. This table serves as a valuable implementation resource, aligning with the recommendations laid out in the Global Hypertension Practice Guidelines.

Table 4-2 Required ASK and resources for each workload in Global Hypertension Practice Guidelines

<table>
<tr><th>Workload</th><th>Affect</th><th>Skills</th><th>Knowledge</th><th>Resource</th></tr>
<tr><td>1. Having a healthy lifestyle
• Adhere to a balanced diet.
• Restrict sodium intake and limit alcohol consumption.
• Abstain from smoking and avoid environments where others smoke.
• Engage in regular physical activity and maintain a healthy weight.
• Strive for a stress-free lifestyle.</td><td>1. Motivation to make the necessary effort in a healthy lifestyle.
2. Patience in adhering to recommendations such as reducing sodium intake, limiting alcohol consumption, not smoking, and maintaining a healthy weight.</td><td rowspan="3">• Long-term thinking strategic
• Deduction logic
• Logical thinking
• Calculation
• Organization</td><td>3. Dietary Approaches to Stop Hypertension (DASH) diet and the importance of a balanced diet for managing hypertension.
4. Limitations on sodium intake (alcohol intake, smoking) to control blood pressure.
5. Healthy weight goals in relation to hypertension management.
6. Different types of exercises are beneficial for managing hypertension.
7. Knowledge about stress relaxation techniques</td><td>8. Friends and family
9. Time
10. Hypertension guidelines
11. DASH resource
12. Relaxation techniques
13. Take note of ways and health-related apps</td></tr>
<tr><td>2. Monitoring blood pressure (BP) regularly at home</td><td>1. Motivation to record daily readings.
2. Willingness to confront their own BP readings.
3. Patience with regular BP check-ups.</td><td>4. Information about their BP
5. Knowledge of BP terminology and interpreting measurement
6. Realistic goals for hypertension level
7. Instructions for using the blood pressure monitor.</td><td>8. Blood pressure monitor machine
9. Take note of ways
10. Time</td></tr>
<tr><td>3. Taking medication(s) regularly as prescribed</td><td>1. Motivation to take daily medications.
2. Willingness to confront their own health conditions.
3. Patience with consistently taking medications as prescribed.
4. Trust in the effectiveness of medication or treatment.</td><td>5. Professional knowledge regarding medication and prescribed information
6. Knowledge about side effects and adverse reactions</td><td>7. Medications</td></tr>
<tr><td>4. Creating a hypertension</td><td>1. Motivation to visit HCP for checkups.</td><td>5. Communication with</td><td>6. Information about their BP.</td><td>8. Friends and family</td></tr>
</table>

support system: family, friends, and healthcare professionals (HCPs) • Regularly visit your HCP for checkups. • Seek immediate medical attention from your HCP in case of emergencies.	2. Patience with regularly visiting HCP for checkups. 3. Trust in the physicians or HCPs. 4. No white coat syndrome, which refers to elevated blood pressure in a medical setting due to anxiety or stress.	others (friends and family, HCPs)	7. Signs of side effects, such as stroke or heart attack.	9. Physician /HCP 10. 911

4.3.2 Barriers

Using the TASKS Framework, we compared the required Affect, Skills, and Knowledge (ASK) components outlined in the guidelines (Table 4-2) with each patient's individual ASK profile. Our analysis identified a new workload category, "2a. Using Blood Pressure Tools," emphasizing tool usage. Personalized barriers for eight patients were identified, each denoted by (○○○○○○○○). Supplementary file 1 provides more detailed patient-specific barriers information. We also categorized all barriers into emotion, logic, knowledge, and resource types, detailed in Table 4-3.

Table 4-3 All hypertension self-management barriers using the TASKS framework

Workload	Emotion barriers	Logic barriers	Knowledge barriers	Resource barriers
1. Having a healthy lifestyle	1. Lack of motivation to make the necessary effort in a health lifestyle (○○○) 2. Impatience in adhering to recommendations such as reducing sodium intake, limiting alcohol consumption, not smoking, and maintaining a healthy weight (○○○) 3. Lack of persistence in self-management practices (○○) 4. Avoidance to confront personal challenges ○ 5. Passivity in problem-solving ○ 6. Prone to stress or worry easily ○	7. Lack of long-term strategic thinking skills ○○ 8. Ineffective problem-solving abilities ○○	9. Dietary Approaches to Stop Hypertension (DASH) diet and the importance of a balanced diet for managing hypertension. (○○○○○) 10. Limitations on sodium intake to control blood pressure. (○○) 11. Different types of exercises are beneficial for managing hypertension. ○○	14. Unavailability of relaxation techniques ○

			12.Healthy weight goals in relation to hypertension management. ○ 13.Lack of knowledge about stress relaxation techniques. ○	
2. Monitoring blood pressure (BP) regularly at home	1. Lack of motivation in recording daily readings (○○) 2. Impatience with regular BP check-ups (○○○) 3. Resistant to the long-term strategy of monitoring BP (○○) 4. Reluctance or fear in facing their own BP readings (○○○○○) 5. Experience stress and anxiety when checking blood pressure readings ○○ 6. Negative expectations and frustration associated with tracking BP at home (○) 7. Confusion by spreadsheet structure and information loss. ○ 8. A desire for a solution to record data ○ 9. Confusion in optimizing data utility amid varied measurements ○ 10. Difficulty understanding BP terminology ○○ 11. Annoyance or frustration with changing BP standards ○○○○ 12. Experience of additional stress due to other health conditions, such as kidney. ○	13. Lack of long-term strategic thinking skills (○○○○○) 14. Disorganization ○○○ 15. Ineffective problem-solving abilities ○○○○ 16. Limited logical thinking abilities ○	17. Information about their BP ○○○ 18. Knowledge of BP terminology ○○ 19. Difficulty in understanding and interpreting blood pressure readings. (○○○) 20. Lack of realistic goals or target goals due to changing blood pressure standards. (○○○○○○) 21. Hypertension management does not require long-term strategic planning. (○)	22. Lack of access to a blood pressure monitor machine ○ 23. Limited time availability ○ 24. Lack of support from friends and family (○○)
2a. Using blood pressure (BP) tools	1. Confusion and uncertainty regarding the use of technology: Feeling unsure about how to use devices, getting frustrated with frequent app updates, and facing challenges with software compatibility. ○○ 2. Dissatisfaction with BP apps: the performance or quality of available apps and the reliability of the app. ○○ 3. Disappointment with BP machines: Feeling unsatisfied with the functionality or reliability of the	7. Ineffective problem-solving abilities ○ 8. Difficulty operating smartphones ○	9. Challenges with the compatibility of technology and software. ○ 10. Challenges with the reliability of the BP apps. ○	11. Lack of smartphone or mobile device ○ 12. Unavailability of monitoring tools or devices ○

	blood pressure monitoring devices. ○ 4. Disappointment with the healthcare system's approach to BP management. ○ 5. Lack of trust in the accuracy and feedback provided by the BP monitor. ○ 6. Feeling ashamed or embarrassed by receiving negative or critical messages from the app. ○			
3. Taking medications regularly as prescribed	1. Concerns about long-term side effects and adverse reactions to medications. (○○○○○○) 2. Confusion and uncertainty, feeling nervous about unknown aspects of the condition or treatment such as complications or impact on pregnancy. ○○○○ 3. Lack of trust in the effectiveness of medication or treatment. (○○○○○) 4. Impatience with consistently taking medications as prescribed. (○○) 5. Reluctance to confront one's own health condition or face personal challenges. ○ 6. Lack of enjoyment or negative experiences associated with taking medications. ○	7. Lack of long-term strategic thinking skills ○○○ 8. Disorganization ○○ 9. Ineffective problem-solving abilities ○○	10. Lack of professional knowledge regarding medication ○○○ 11. Lack of knowledge about side effects and adverse reactions (○○○○○○) 12. Lack of knowledge about complications in specific situations such as pregnancy. ○	
4. Creating a hypertension support system: healthcare professionals (HCPs)	1. Anxiety or nervousness when communicating with doctors, especially when it comes to providing comments or asking questions. ○○ 2. Stress and discomfort related to public speaking or expressing oneself in a medical setting. ○ 3. Frustration and annoyance when facing difficulties in contacting doctors or healthcare providers. ○○ 4. Feeling disappointed and lacking trust in physicians or medical professionals. ○ 5. Experiencing white coat syndrome, which refers to elevated blood pressure in a medical setting due to anxiety or stress. ○	6. Lack of effective communication abilities with healthcare professionals ○○○		7. Lack of access to a healthcare professional or physician ○○

4.4 Discussion

4.4.1 What is the added value of personalized barriers for hypertension self-management

Our research delved into personalized barriers in hypertension self-management, utilizing descriptive statistics to highlight common themes while acknowledging individual differences. Among the eight patients interviewed, a total of 69 barriers were identified, with emotion barriers being the most prevalent (49%), followed by knowledge (24%), logic (17%), and resource barriers (10%). Emotion barriers were the most prevalent, indicating significant stress and anxiety related to self-management tasks, such as monitoring blood pressure at home, which presented the highest challenge (34.78%). This was closely followed by difficulties in using blood pressure monitoring tools, medication management, and adopting a healthier lifestyle, each presenting substantial obstacles due to emotion and knowledge barriers. The least encountered barriers involved creating a support system with healthcare professionals (10.14%), yet still predominantly emotional.

This distribution highlights the critical role of emotion and knowledge barriers in hypertension self-management. Our analysis emphasizes the need for tailored interventions that address these specific challenges. By ranking these barriers (see Figure 4-1), we aim to provide healthcare professionals with a clear understanding of the primary barriers faced by patients, guiding the development of targeted strategies to improve self-management outcomes. Emotion support, information provision, and enhancing patient-healthcare professional relationships emerge as key areas for intervention.

4.4.2 How to guide intervention strategy?

To ensure the success of interventions, it is crucial for patients to possess the necessary capabilities to initiate their mental efforts. An effective intervention strategy involves tailoring to the personalized needs of each patient. It goes beyond just providing information about barriers; it fosters a comprehensive cause-and-effect understanding of these barriers (Zeng 2011). Consequently, we analyzed the cause-and-effect relationships between all identified barriers (refer Table 4-3) and identified primary or root barriers within the complex web of cause-and-effect relationships (Zeng 2011), and their selection was based on their frequency.

A comprehensive analysis reveals that although half of the barriers are emotion-related, logic and knowledge hurdles form the majority. Emotional challenges often stem from underlying logic and knowledge gaps. Lack of long-term strategic thinking skills is a crucial barrier in areas like lifestyle maintenance and medication adherence.

Figure 4-1 Frequently encountered four types of barriers in hypertension self-management (*BP:* Blood pressure, *HCPs:* healthcare professionals, *DASH:* Dietary Approaches to Stop Hypertension)

Fundamental skills such as problem-solving and organization are vital. Directly addressing these barriers is difficult, but tailored tools can shape patient behavior naturally. Physicians can assist by breaking tasks into manageable steps or adjusting intervention strategies, enhancing patients' abilities to manage their hypertension effectively.

Within the realm of having a healthy lifestyle, two distinct barriers emerge: a lack of motivation leading to insufficient effort and a dearth of persistence in self-management practices. The former stems from deficits in long-term strategic thinking and problem-solving skills, coupled with avoidance of confronting personal challenges. The latter involves impatience with lifestyle changes and heightened susceptibility to stress. Notably, limited knowledge, particularly about the DASH diet (Dietary Approaches to Stop Hypertension) and balanced nutrition's importance, fuels impatience-related emotions. The DASH diet underscores the significance of balanced nutrition in hypertension management, promoting a sustainable eating pattern aligned with lifelong heart health goals.(National Institutes of Health (NIH) 2018) However, some patients, as observed in interviews, held a belief that a vegetarian diet equates to a balanced diet, emphasizing the need for targeted knowledge interventions. Addressing these nuanced barriers requires tailored approaches, emphasizing not only education but also the cultivation of essential skills and emotional resilience.

In home blood pressure monitoring, two key barriers emerge: impatience with regular check-ups and a need for effective data recording. Changing BP standards or target goals create uncertainty, impacting motivation to maintain daily records. Lack of basic BP knowledge, essential for understanding one's health, fosters reluctance and fear during readings and heightens stress and anxiety. Knowledge gaps, particularly concerning BP terminology, and the absence of support from friends and family intensify these emotional barriers. In addition, problem-solving skills shape experiences of stress levels, while long-term strategic thinking influences motivation. In the latter situation, where patients desire effective data recording tools, confusion stems from challenges in understanding and interpreting varied BP measurements. Knowledge gaps in BP terminology further complicate matters, leading to suboptimal data utilization. The struggle with ineffective problem-solving abilities and disorganization amplifies this confusion, particularly in managing spreadsheet structures and preventing information loss.

When considering the use of BP tools, confusion and uncertainty arise from technological unfamiliarity and a lack of trust in the accuracy of BP monitors. Ineffective problem-solving, especially concerning smartphone operation, further exacerbates this situation, especially for elderly patients. The unavailability of monitoring devices raises concerns about the reliability of BP apps and monitor machines, with patient embarrassment over negative or critical app messages adding to the challenge. Addressing these multifaceted emotion and logic barriers necessitates tailored interventions, emphasizing not only technological education but also enhancing problem-solving skills and providing reliable, user-friendly tools for effective BP management.

In the realm of taking medications as prescribed, impatience with consistent intake stands as a primary challenge. Beyond issues related to long-term strategic thinking, disorganization, and problem-solving, a significant factor is the lack of trust in the effectiveness of medication or treatment. This trust is influenced by various uncertainties, including concerns about side effects and adverse reactions or other unknown aspects of the treatment. Possessing professional knowledge regarding medication and its potential side effects does alleviate some of these uncertainties to a certain extent.

In forming a hypertension support system with physicians and healthcare professionals (HCPs), two key challenges emerge. Firstly, individuals experience anxiety when communicating with doctors due to a lack of effective communication skills, amplified by stress and discomfort in medical settings like white coat syndrome. Research showed about 10%–30% of subjects attending clinics due to high BP have white-coat hypertension (Unger *et al.* 2020). Secondly, frustration arises when there is limited access to healthcare professionals, intensifying disappointment and distrust in medical professionals. These barriers underscore the vital need for enhanced communication training and improved accessibility to foster trust and alleviate patient anxieties in healthcare interactions. The findings imply that integrating a team-based hypertension management program could significantly reduce the burden on healthcare systems caused by hypertension (Yu *et al.* 2023).

4.4.3 Is the TASKS framework applicable for guiding data analysis?

In health research, qualitative studies aim to comprehend the motivations and perceptions influencing health behaviors (Green 1999). Employing a theoretical framework, like the TASKS framework, enhances the grounding of findings in robust theory, enriching the field's knowledge base. This framework uniquely focuses on the complex interplay between an individual's tasks and their mental capabilities—Affect, Skills, and Knowledge—and how this interplay is affected by mental stress, following an inverted U-shaped curve (Yerkes & Dodson 1908). This dynamic demonstrates how mental effort correlates with mental stress, wherein both low and high stress levels can diminish mental effort, but moderate stress may optimize it (Yang *et al.* 2021).

The TASKS framework categorizes implementation barriers into emotion, logic, knowledge, and resource types through a precise equation involving the ratio of perceived tasks to mental capability (Nguyen & Zeng 2012). It employs a systematic approach to align guideline requirements with individual circumstances, using a top-down to bottom-up method for coding and modeling mental capabilities and resources. This detailed categorization aids in accurately identifying barriers to hypertension self-management, showcasing the framework's potential as a comprehensive analytical tool.

Furthermore, the framework explains the interactive relationship between the perception of workload and the application of skills and knowledge. It underscores the significance of understanding emotional responses to perceived workloads, thereby establishing a recursive logic in behavioral performance (Zeng & Cheng 1991). Achieving a balance between workload and mental capability is essential (Zhao *et al.* 2023), underscoring the need for an in-depth analysis of the cause-and-effect relationships among various barriers (Zeng 2011). Such detailed analysis can uncover valuable insights, enabling the development of targeted intervention strategies that meet the unique needs of patients, ultimately improving self-management outcomes.

4.4.4 Limitation

Our study, focusing solely on hypertension self-management barriers, may not apply to other disease contexts, suggesting the need to test the TASKS framework more broadly. With a limited sample of eight patients, findings might not capture the full diversity of self-management experiences; thus, a larger sample is recommended for greater reliability. Moreover, conducting interviews only in English could introduce cultural biases and exclude non-English speakers. Future research should include multiple languages or translation services to better account for the impact of linguistic and cultural differences on self-management barriers.

4.5 Summary

In conclusion, our study highlights the critical importance of personalized barriers in the self-management of hypertension, with emotion and knowledge barriers identified as the most significant. By applying the TASKS framework, we have unraveled the interplay between individual mental capabilities and the demands of self-managing hypertension. Emotion barriers were the most significant, followed by knowledge, logic, and resource barriers, emphasizing the need for tailored interventions. The TASKS framework guided our data analysis, effectively categorizing barriers and facilitating the development of precise interventions. While our focus was on hypertension, the framework's adaptability suggests its broader applicability in healthcare research. Nonetheless, limitations such as a small sample size and linguistic bias warrant further investigation. Overall, our research contributes to promoting patient-centered care and refining hypertension management strategies.

Chapter 5

5 Unearthing Stakeholder Behavior Patterns to Enhance Sustainable Product Design

Abstract

Sustainable product design (SPD) is a critical approach for mitigating environmental impacts and promoting socio-economic welfare. This paper explores stakeholder behavior patterns throughout the life cycle of sustainable design, emphasizing their role in shaping product sustainability. Combining natural and cognitive resources within design methodologies elevates SPD beyond mere functionality, ensuring environmental stewardship and user satisfaction. Leveraging the TASKS framework illuminates stakeholder behavior complexities, optimizing cognitive resources for sustainable outcomes. Addressing implementation barriers and leveraging facilitators unlock the driving force behind stakeholder engagement, fostering active participation in sustainable design practices. The study envisions a future where informed stakeholder behaviors inherently promote sustainability, emphasizing the pivotal role of stakeholder behavior in achieving sustainable product design excellence. Through comprehensive analysis and strategic interventions, this research seeks to bridge the gap between sustainability objectives and practical implementation in product design, ultimately fostering a more sustainable future.

Keywords: sustainable product design, stakeholder, behavior pattern, cognition, sustainability.

5.1 Introduction

Sustainable product design aims to create products and systems that meet functional requirements while minimizing environmental impacts and promoting social and economic well-being (McLennan 2004). It takes into account the entire lifecycle of a product, from raw material extraction to waste disposal, and evaluates the environmental, social, and economic performance of the design (Yang *et al.* 2020). Design is the key stage at which 80% of sustainability impacts are determined for a product (Ahmad *et al.* 2018; Diaz *et al.* 2021), while addressing sustainability issues at later stages, such as manufacture and use, is challenging and costly (Birch *et al.* 2012; Ramani *et al.* 2010).

The behavior patterns of stakeholders throughout the life cycle of sustainable design are important to understand. The life cycle stages of a product or system encompass product design, resource extraction, manufacturing, *transportation*, sales, use, maintenance, and end-of-life treatment (Yang *et al.* 2020). Products are not just objects with desired functions; they act as catalysts capable of reshaping user behaviors (Bhamra *et al.* 2011). Designers can leverage this to foster responsible product use, thereby influencing environmentally sustainable actions (Linder *et al.* 2022). Taking sustainable products as an effective intervention for sustainability is an objective of sustainable product design (Geller 2002).

The success of sustainable product design depends not only on the designers themselves but also on the collaboration with various stakeholders along the value chain, including customers, suppliers, and local communities. Despite growing academic interest (Geng *et al.* 2020; Kempeneer *et al.* 2021; Linder *et al.* 2022), a gap remains between sustainability and practical activity in product design (Jiang *et al.* 2021). Existing research primarily focuses on sustainable technologies to directly improve design sustainability, relevant policies to drive product sustainability, and the driving factors for sustainable transition (Chen *et al.* 2023; Gan *et al.* 2018; Pahle *et al.* 2021). However, the role of stakeholders in sustainable design has received limited attention (Cairns *et al.* 2016; Du *et al.* 2020; Fu *et al.* 2020).

Under such circumstances, it is imperative to unearth stakeholder behavior impact in sustainable product design from a life cycle perspective. It integrates financial, time, and human resources, resolves conflicts, and balances multiple interests related to interdisciplinary issues (Shan *et al.* 2021). To ensure sustainability throughout the entire life cycle, this study systematically addresses the following questions:

- What is the role of stakeholder behavior in sustainable product design?
- How does stakeholder behaviors interact sustainable product design?
- How to analyze stakeholder behaviors for sustainable product design?

These inquiries aim to enhance the understanding of the behavior patterns of stakeholder behavior throughout the life cycle of sustainable design. It envisions a future where product design inherently promotes sustainability through informed stakeholder behaviors.

5.2 Stakeholder behavior and sustainable product design

A product operates within an environment from which it cannot be detached (Zeng & Cheng 1991). As depicted in Figure 5-1, this environment comprises stakeholders such as designers, users, society, and government, along with natural elements (Yang *et al.* 2020; Zeng 2004). In interacting with its surroundings, a product must adhere to natural laws, societal norms, professional regulations, and user requirements.

Interactions between products and their environments manifest as actions or responses (Zeng 2002; Zeng & Gu 1999a), where components causally engage with each other and their surroundings to produce behaviors that deliver intended functions (Gero's FBS, Tomiyama's FBS, Goel's SBF, and other main models about functions) (Bhatta & Goel 1997; Gero 1990; Umeda *et al.* 1990). Design's primary aim is to create products that effectively function within their designated environments by providing desired functionalities through their behaviors (Chen & Zeng 2006).

Energy serves as a fundamental catalyst for product-environment interactions (Kaushika *et al.* 2016). Different interactions typically require and consume varying amounts of energy (Oliveira & Antunes 2004). For instance, manufacturing choices significantly impact energy usage. Excessive or redundant interactions can lead to inefficient energy resource utilization. Notably, a product's energy consumption intricately ties to how its functionality is engaged and initiated, influenced by user behavior, design decisions, and stakeholder expectations, as depicted in Figure 5-1. Therefore, a product's energy efficiency hinges on the complex interplay among user actions, design considerations, and stakeholder requirements, necessitating holistic and sustainable design practices to minimize unnecessary energy usage and foster resource efficiency.

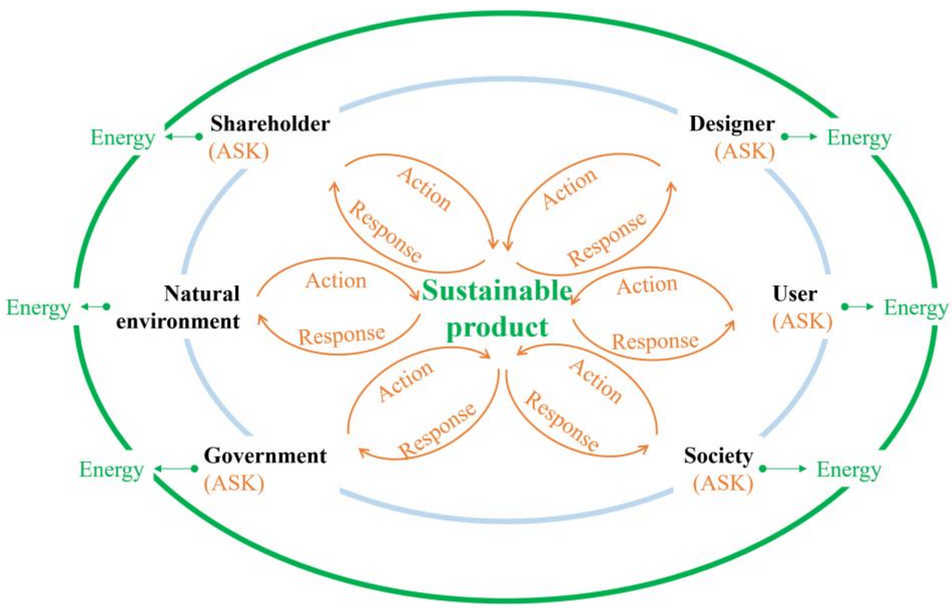

Figure 5-1 The relationship between the stakeholder behavior and sustainable product design

Therefore, active and meaningful stakeholder engagement is imperative for ensuring the sustainability of the Earth's ecosystem across a product system's entire lifecycle. This holds particular significance in multi-purpose product systems, where diverse stakeholders with varying goals and degrees of influence are involved in production, governance, and utilization. Effective stakeholder engagement enables the integration of diverse perspectives, addresses stakeholders' goals, and navigates product system complexities in alignment with sustainability objectives. Such engagement empowers stakeholders to contribute to decision-making processes and advance sustainability goals.

5.3 Sustainable product design: cultivating sustainability through product design

5.3.1 Fueling sustainable product design through natural and cognitive resources

Sustainable product design (SPD) is an ethically driven, long-term approach that integrates design principles with sustainability considerations (Portney 2015). It represents a paradigm shift in how products are conceptualized, developed, and utilized, focusing on minimizing environmental impacts while maximizing social and economic benefits throughout the product lifecycle. This approach requires a deep understanding and innovative use of both natural and cognitive resources to enhance product design in ways that are not only environmentally friendly but also resonate with users and stakeholders. The convergence of these resources within the sustainable product design process plays a pivotal role in achieving sustainability objectives while ensuring product functionality, performance, and positive user perception.

5.3.1.1 Leveraging Natural Resources for Sustainable Functionality and Performance

The efficient utilization of natural resources, particularly renewable energy sources such as solar, wind, and hydroelectric power, is central to reducing the environmental footprint of products (Turconi *et al.* 2013). This approach aligns with the principles of Green Design (Glantschnig 1994; Mackenzie *et al.* 1997), followed by EcoDesign (Karlsson & Luttropp 2006; Pigosso *et al.* 2013), Cradle-to-Cradle Design (McDonough & Braungart 2010), Life Cycle Engineering and Design (Alting 1995; Ramani *et al.* 2010), and Cleaner Technology Innovation (Foxon & Pearson 2008), which collectively aim to minimize waste and energy consumption throughout a product's life cycle (Sherwin 2004). By integrating renewable energy sources and adhering to the principles of the circular economy (Geng *et al.* 2013), designers can significantly contribute to the development of products that are sustainable in their production, use, and disposal phases.

The incorporation of natural resources into product design is not just about reducing environmental impact but also about enhancing product functionality and performance. Design for X (DfX) is a broader concept that encompasses various design considerations, including design for environment

(DfE) (Giudice *et al.* 2006), design for manufacture and assembly, design for quality, design for maintainability, design for reliability, and design for cost (He *et al.* 2020; Jawahir *et al.* 2007). Renewable energy technologies can provide new ways to power products, reduce operational costs, and extend product lifespans. Strategic integration of these technologies requires in-depth comprehension of the natural environment and the potential of these resources to meet the needs of both the product and its users.

5.3.1.2 Harnessing Cognitive Resources to Meet User Needs and Preferences

Cognitive resources encompass the affect, skills, and knowledge of stakeholders (Yang *et al.* 2021), equally vital in shaping sustainable product design. Understanding user behaviors, preferences, and decision-making processes enables designers to create products that align with user needs and values, thereby increasing the likelihood of widespread adoption and satisfaction (Ahmad *et al.* 2018; Saari *et al.* 2021). This user-centric approach is a cornerstone of Human-Centred Design (HCD) (Norman 2013) and Environment-Based Design (EBD) (Zeng 2004), methodologies that prioritize the needs, requirements, and environment of users within the design process.

In sustainable product design, cognitive resources offer a dual benefit. First, they provide insights into how products can be designed to be more intuitive and engaging, thereby enhancing user interaction and satisfaction. Second, they inform strategies to encourage sustainable behaviors among users, such as energy conservation and responsible product disposal. Using cognitive resources allows designers to create products that fulfill functional requirements while resonating with users emotionally and psychologically.

5.3.1.3 Integrating Natural and Cognitive Resources in Design Methodologies

Integrating natural and cognitive resources in sustainable product design involves a multifaceted approach that spans several design methodologies. Product-based, product-environment interaction-based, and environment-based methodologies each offer unique perspectives and tools for incorporating these resources into the design process (Yang *et al.* 2023). From Axiomatic Design (Suh 1998), Systematic Approach (Pahl & Beitz 1988), Technical System (Hubka & Eder 1988), Decision-based Design (Hazelrigg 1998; Wassenaar & Chen 2003), Structural Topology Optimization (Bendsøe & Kikuchi 1988; Bendsoe & Sigmund 2003), Structure-Behavior-Function (SBF) (Bhatta & Goel 1997; Chandrasekaran *et al.* 1993), Function-Behavior-State (FBS) (Gero 1990; Gero & Kannengiesser 2004), Quality Function Deployment (QFD) (Akao & Mazur 2003), and Affordance-based Design (Akao & Mazur 2003) to Environment-Based Design (EBD) (Zeng 2004), these methodologies can provide a specific aspect analysis or combining them to achieve sustainability goals while meeting user needs.

By leveraging both natural and cognitive resources, designers can formulate, evaluate, and synthesize product designs that are innovative, sustainable, and user-centric. This integrative approach not only enhances the functionality and performance of products but also ensures that users perceive them positively, thereby contributing to the broader goals of sustainability and environmental stewardship.

5.3.2 Achieving sustainable product design through stakeholder behaviors: catalyzing sustainability habits through sustainable products

Sustainability habits, characterized by actions performed almost automatically and without conscious effort, are integral to fostering sustainable practices. Sustainable products possess the innate potential to mold and influence user behavior (Bhamra *et al.* 2011), thus catalyzing the formation of sustainability habits. As articulated by Zeng, the design process can be envisaged as an environment-changing endeavor (see Figure 5-2), wherein products interact with and evolve within their environments (Zeng 2002, 2015). By incorporating design requirements that facilitate sustainable practices, products can effectively steer users towards adopting sustainable behaviors as the default option.

This symbiotic relationship between sustainable design and sustainability habits creates a reinforcing feedback loop, wherein the continuous use of sustainable products strengthens sustainable behaviors over time (Mohammed 2021). However, it is imperative to recognize that technological solutions alone are insufficient to address the environmental impact resulting from human-product interactions. Instances of offsetting behaviors or unexpected product uses may lead to excessive energy usage and resource consumption (Tang & Bhamra 2012; Verbeek & Slob 2006). Concepts like Design for Sustainable Behavior (DfSB) aim to realign users' consumption habits towards more sustainable use patterns (Bhamra *et al.* 2011; Boks *et al.* 2017). Approaches such as emotionally durable design (Chapman 2012) and design for social intervention (Geller 2002) delve into the psychological and social factors influencing consumption patterns, offering avenues for promoting sustainable behaviors through targeted interventions. Additionally, scholars have integrated behavior change-related theories of different disciplines into the field of design such as the Theory of Planned Behavior (TPB) (Fogg 2009b), and the Theoretical Domain Framework (TDF) (Michie *et al.* 2005).

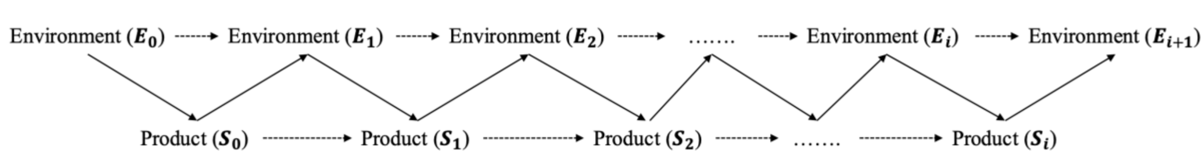

Figure 5-2 Design: environment changing process

5.4 Stakeholder behavior in sustainable product design: maximizing the potential of sustainable product design

Stakeholders encompass both individuals and groups who have the potential to influence or be impacted by the achievement of specific objectives (Freeman 1984; Mitchell *et al.* 1997). This includes a wide range of entities, such as persons, groups, organizations, institutions, and societies, who are recognized as actual or potential stakeholders. Stakeholders could evolve in a dynamic environment and become interdependent (Getahun & Selassie 2017; Merrilees *et al.* 2005).

5.4.1 Unlocking the power of stakeholder behavior: ASK as vital cognitive resources

In the context of stakeholder behavior in sustainable product design, the TASKS Framework (Yang *et al.* 2021) serves as the underlying mechanism to understand and analyze behavior. The framework comprises five key components: Task (T), Affect (A), Skills (S), Knowledge (K), and the mental Stress-effort (S) relationship.

The behavior of individuals is influenced by their perceived tasks and mental capabilities, which are referred to as mental stress (Nguyen & Zeng 2012). The relationship between mental stress and mental effort can be understood through the adaptation of the Yerkes-Dodson Law (Yerkes & Dodson 1908). According to this law, a U-shaped curve relationship exists between performance and stress. Nguyen and Zeng adapted the Yerkes-Dodson Law to address the relationship between mental stress and mental effort (Nguyen & Zeng 2012), implying that an appropriate range of mental stresses will lead to optimal mental efforts, as illustrated in Figure 5-3. It is important to note that both low and high levels of mental stress tend to result in low levels of mental effort, while moderate levels of mental stress are associated with optimal mental efforts.

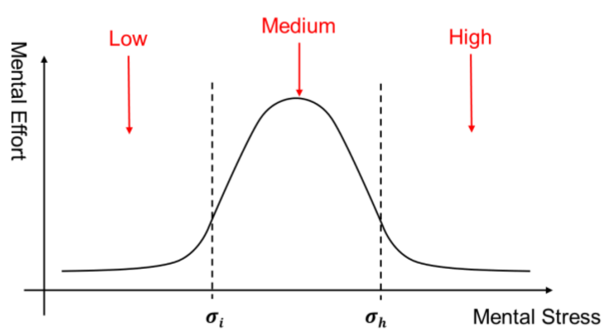

Figure 5-3 Relationship between mental stress and mental effort (Nguyen & Zeng 2012; Yang *et al.* 2021)

The TASKS Framework provides a valuable lens for understanding how stakeholders' cognitive resources, including their affect, skills, and knowledge, shape their behavior. Skills can be categorized into cognitive and affective, for which logical reasoning is critical. Different thinking styles, strategies, and methods of reasoning can lead to diverse behaviors. Affect pertains to the spectrum of emotions and feelings experienced by individuals, ranging from distress to joy. The degree of affect, ranging from 0 to 1, can determine the extent to which a stakeholder's knowledge and skills are activated and utilized when performing a given task. It influences their ability to effectively harness their cognitive resources. The cause-effect relationship of mental stress is shown in Equation (5-1) (Nguyen & Zeng 2012). Considering these factors, practitioners and researchers in sustainable product design can gain valuable insights into how varying levels of mental stress can influence stakeholders' engagement, decision-making processes, and overall behavior. This understanding is essential for effectively harnessing the potential of stakeholder behavior to drive sustainable design practices and achieve desirable outcomes.

$$\boldsymbol{Mental\ stress} = \frac{Task\ workload}{Mental\ capability} = \frac{Perceived\ task\ workload}{(Knowledge + Skills) \times Affect},\ \boldsymbol{A} \in (\boldsymbol{0}, \boldsymbol{1}) \qquad \textbf{(5-1)}$$

5.4.1.1 Designer behavior

Who: Business entity, government needs to analyze designer behavior.

Goal: The goal of designers in sustainable design is to create solutions that effectively address environmental, social, and economic challenges while minimizing negative impacts and promoting long-term sustainability. Design is an action from the human rational system to the natural system (Zeng 2002). To achieve this, designers need to cultivate a range of affect, skills, and knowledge.

ASK: Affect refers to the designer's motivation, passion, and empathy for sustainability-related issues. It involves their commitment to making a positive environmental and societal impact through their design requirements. The logic of design is recursive (Zeng & Cheng 1991); thus, design solutions can be highly unpredictable. Designers usually have uncertainty for the sustainability requirements. Designers with a strong affect for sustainability are more likely to prioritize sustainable principles and actively seek innovative solutions (Klotz *et al.* 2019). If designers need to add sustainability as additional requirements, their affect will be toward negative.

Knowledge is an interaction between the rational system, which is dependent on reasoning (Chandrasekaran 1986) and represents the cause-effect relationships between information. Design requirements as the basic knowledge for designers can be defined as evaluation knowledge, synthesis knowledge, and initial requirement (Zeng 2002). Knowledge in sustainable design involves familiarity with best practices, regulations, and emerging trends in sustainability.

Moreover, an understanding of stakeholder dynamics, including user preferences and societal values, enables designers to create solutions that resonate with diverse stakeholders (Blackburn 2009; Klotz *et al.* 2019).

Skills encompass the technical, creative, and analytical abilities necessary for sustainable design. Basic skills needed in conceptual design include: 1) identify, 2) search for, 3) generate, 4) evaluate, 5) analyze, 6) redefine, and 7) recompose. Combining different knowledges, these seven actions inform basic skills in conceptual design (Nguyen & Zeng 2012).

5.4.1.2 User behavior

Who: Everyone except user itself needs to analyze user behavior.

Goal: The goal of users in sustainable design is twofold: to acquire valuable products and engage in environmentally responsible behaviors. Their aim is to align their choices and actions with sustainable principles, supporting positive environmental and social impacts (Klotz *et al.* 2019). Sustainable products have the potential to unconsciously and naturally influence user sustainability habits, leading to the development of sustainable practices over time. Therefore, the specific tasks undertaken by users are crucial considerations in product design, as they contribute to a positive feedback loop that reinforces sustainability habits (Mohammed 2021).

ASK: User workload plays a significant role in shaping their interaction with products, influencing the specific affect, skills, and knowledge they possess. User affect in sustainable design encompasses their attitudes, values, and motivations towards sustainable products and sustainability as a whole. Positive affect empowers users to embrace sustainable behaviors and actively engage in initiatives promoting sustainability habits. If user need to add more workload or finance value to use sustainable product, their affect will be toward negative. Users also require certain skills to effectively participate in sustainability practices, including the ability to understand and incorporate sustainable products into their lives, leading to the formation of sustainable habits. Furthermore, users need knowledge about sustainability principles, energy-efficient practices, waste management, and the environmental and social impacts associated with their choices (Lilley 2009). When required knowledge and skills are easier, user affect towards sustainable products tends to be more positive.

5.4.1.3 Society behaviors

Who: Business entity, designers and government need to analyze society behaviors.

Goal: The goal of society in sustainable design is to foster the development and implementation of sustainable design products that minimize negative environmental impacts, enhance social well-being, and contribute to long-term sustainability (Arlati *et al.* 2021). Society seeks design products that align with principles of ecological responsibility, resource efficiency, and social equity.

ASK: Positive affect of society drives designer behavior in design, such as environmental consciousness, empathy, and a sense of responsibility. A positive affect toward the environment motivates individuals to act in ways that minimize harm and promote sustainable products (Sun *et al.* 2015). Oppositely, a negative affect toward the environment prevents individuals from the sustainable products. collaboration skills enables individuals to collaborate the environmental and social work of sustainability, while systems thinking helps understand the interconnectedness of design choices within larger contexts (Haleem *et al.* 2022). A comprehensive understanding of sustainability principles, environmental impacts, and social dynamics is essential for society to engage effectively in sustainable design (Leal Filho & Brandli 2016).

5.4.1.4 Government behavior

When: Business entity, designers, users need to analyze government behaviors.

Goal: The goal of government in sustainable design is to foster the development and implementation of policies, regulations, and initiatives that promote sustainable design across various sectors, including architecture, urban planning, and construction (Arlati *et al.* 2021). Their aim is to balance economic growth with environmental protection and social well-being.

ASK: A positive affect toward sustainability drives government policymakers' motivations to create and enforce regulations that foster sustainable practices (Haleem *et al.* 2022), such as environmental consciousness, a commitment to public welfare, and a long-term vision for sustainability. Governments skills allow policymakers to navigate complex challenges, evaluate the environmental and social impacts of design decisions, and develop targeted interventions (Lilley 2009), such as policy development and analysis, stakeholder engagement, strategic planning, and interdisciplinary collaboration etc. Governments must possess comprehensive knowledge of sustainability principles, environmental science, urban planning, and policy frameworks related to sustainable development. Informed decision-making based on sound scientific knowledge ensures that policies and regulations align with sustainable design objectives (Arlati *et al.* 2021).

5.4.2 Unlocking the driving force behind stakeholder behavior: implementation barriers and facilitators as critical opportunities

Identifying and addressing implementation barriers while leveraging facilitators can unlock the driving force behind stakeholder behavior in sustainable design. Implementation barriers refer to the factors that hinder individuals from successfully completing certain tasks. On the other hand, facilitators enable and support stakeholder engagement and behavior in sustainable design. The presence of barriers can be observed through various activities and the underlying determinants of stakeholders' behavior during the product life cycle. When designing sustainable products, designers need to consider four essential criteria: usefulness, sustainability, safety, and usability. Designers rely on available resources, affect, knowledge, and skills to fulfill these criteria (Nguyen & Zeng 2012; Yang *et al.* 2021). However, discrepancies between the ideal and actual state of these four aspects can give rise to barriers.

As outlined in Table. 5-1, the TASKS framework categorizes four types of implementation barriers and facilitators (Yang *et al.* 2021). By analyzing and addressing these driving forces, stakeholders can be empowered to actively participate in sustainable design practices. This, in turn, enables the successful integration of sustainability principles into the design process and the realization of sustainable outcomes.

Table. 5-1 Barriers/facilitators classification in the TASKS framework (Yang et al. 2021)

Categories	Content
Emotion	Motivation, attitudes (such as cognitive/awareness, expectation, value), beliefs (such as acceptance, optimism), feelings (such as anxiety, pressure, fear), or ethics
Logic	Thinking styles, thinking strategies, or reasoning methods
Knowledge	Knowledge and actionability
Resource	All environment components (such as time, money and cognitive capacity)

It is crucial to acknowledge that stakeholders' engagement and behavior in sustainable design are influenced by a complex interplay of various factors. Understanding and addressing implementation barriers and leveraging facilitators create opportunities for stakeholders to overcome challenges, enhance their capacity, and contribute effectively to sustainable design practices. By systematically considering the barriers and facilitators, practitioners and researchers can develop strategies and interventions that promote stakeholder involvement and foster the adoption of sustainable design principles.

5.5 Conclusion

In the pursuit of excellence in sustainable product design, understanding stakeholder behavior patterns emerges as pivotal. Recognizing the role of products as catalysts for reshaping user behaviors underscores the significance of stakeholder engagement in promoting sustainability throughout the product lifecycle. By integrating natural and cognitive resources within design methodologies, sustainable product design can transcend mere functionality to embrace environmental stewardship and user satisfaction. Utilizing the TASKS framework sheds light on the complexities of stakeholder behavior, providing insights into optimizing cognitive resources for sustainable outcomes. Moreover, addressing implementation barriers and leveraging facilitators unlock the driving force behind stakeholder engagement, empowering them to actively participate in sustainable design practices. Through informed stakeholder behaviors, sustainable product design becomes more than just a vision but a tangible reality, ushering in a future where products inherently promote sustainability.

Chapter 6

6 Conclusion and Future Research Directions

6.1 Conclusion

In conclusion, this thesis has made significant development in addressing task implementation problem-solving by highlighting the importance of personalized barriers. Utilizing the TASKS framework, we have uncovered the intricate dynamics between individual mental capabilities and task demands across various domains. The main contributions of this research span three areas: knowledge in designer creativity, personalized barriers for hypertension patients, and stakeholder behavior in sustainable product design.

Firstly, Chapter 3 has enriched our understanding of how human capability, particularly knowledge, influences designer creativity. Routine, innovative, and creative designs all follow the same design mechanism, represented by a recursive integration of three basic design activities: formulation, evaluation, and synthesis. By utilizing TASKS framework to discuss the dual roles of knowledge in design problem-solving, we have provided valuable insights for enhancing creative design processes: 1) Formulating design problems differently, 2) Extending synthesis design knowledge, and 3) Changing the strategy of environment decomposition. The TASKS framework serves as a robust tool for analyzing design problems, highlights the importance of considering both the designer's knowledge/experience and their creative thinking process in design research, practice, and education.

Secondly, Chapter 4 employs the TASKS framework to identify and categorize personalized barriers to hypertension self-management. It offers an approach to comprehend the interplay between an individual's mental capabilities, external resources, and the demands of managing hypertension. Through qualitative analysis of interview transcripts from eight patients and reference to Global Hypertension Practice Guidelines, the study identifies 69 personalized barriers across participants. These barriers are classified into four categories: Emotion Barriers (49%), Knowledge Barriers (24%), Logic Barriers (17%), and Resource Barriers (10%). The study underscores the necessity for tailored interventions that acknowledge and address personalized barriers, particularly those related to emotions and knowledge, in hypertension management. The implications of these findings are extensive, representing a significant advancement in personalized healthcare and the management of chronic conditions like hypertension. This underscores the effectiveness of the TASKS framework in identifying personalized healthcare barriers and marks a notable progression in personalized healthcare.

Thirdly, Chapter 5 explores stakeholder behavior patterns throughout the product design lifecycle, highlighting their significant role in shaping sustainability. By integrating natural and cognitive resources, we emphasize the importance of stakeholder engagement in sustainable practices. Leveraging the TASKS framework, we analyze stakeholder behaviors to optimize cognitive resources for better sustainable outcomes. This research underscores the critical role of implementation barriers and facilitators in driving stakeholder behavior toward sustainable product design.

6.2 Future research directions

Some future research directions still exist based on my thesis topics, as shown below:

1) Development of tools for streamlining analysis of personalized barriers

The identification of personalized barriers for hypertension patients underscores the effectiveness of the TASKS framework but highlights its time-consuming nature and demands substantial human effort. Future research should focus on developing tools to streamline the analysis process. Integration of the TASKS framework with advanced technologies like natural language processing and large language models can facilitate automated or semi-automated tools, enhancing scalability and efficiency in personalized healthcare research. This advancement could revolutionize the way personalized healthcare is approached, making it more accessible and effective for a broader disease.

2) Dynamic problem-solving

Traditionally, designers' knowledge and skills are considered constant throughout the design process, facilitating the synthesis of diverse perspectives and the discovery of creative solutions. However, the utilization of knowledge within the realm of human capability for creative problem-solving is a dynamic process. Therefore, the implementation of human tasks needs to unfold within a dynamic framework. Future research endeavors could concentrate on adapting dynamic process analysis to effectively address problem-solving challenges. Such an approach would enable more agile and responsive problem-solving strategies, particularly in dynamic environments.

3) Team behavior

The success of task implementation relies not only on individual capabilities but also on effective collaboration among stakeholders. Future research should explore team design and organizational management, offering insights into enhancing stakeholder collaboration and improving outcomes.

Addressing challenges and fostering collaboration in specific domains can lead to significant advancements in stakeholder-engaged tasks, ultimately resulting in more effective and sustainable outcomes.

Specifically, the United Nations' third Sustainable Development Goal focuses on ensuring that every person can live a healthy life and promoting well-being for all at all ages. Research into healthcare systems reveals a complex network of interconnected entities, each with its own interests, roles, and responsibilities. The concept of a Learning Health Care System (LHS), which integrates research, practice, and education, is central to the evolution of modern healthcare delivery. This system aims to continuously improve patient care by leveraging real-world data and evidence. Unlike traditional healthcare systems, the LHS actively learns from patient outcomes and adapts accordingly. However, its implementation and ongoing development face several challenges, including data integration and interoperability, data quality and governance, patient privacy and consent, cultural and organizational change, clinical implementation and adoption, cost and funding, legal and regulatory issues, and equity and access.

Addressing these challenges requires a concerted effort from all healthcare stakeholders, including policymakers, healthcare organizations, technology vendors, researchers, and patients. By collaboratively overcoming these barriers, the LHS has the potential to transform healthcare delivery and improve patient outcomes on a sustainable systemic level.

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