Designing the Synergized Interactions for Human Capacity Enhancement: Theoretical and Empirical Studies

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Abstract

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In a ubiquitous computing world, while technology offers convenience, it also diminishes human capacities due to imbalanced relationships between humans and computers, as evidenced by issues like decreased attention and memory associated with smartphone addiction. The field of Human-Computer Interaction (HCI) has long studied symbiotic/synergetic relationships between humans and computers to mitigate technological threats within imbalanced relationships. In this context, the concept of synergized interactions, introduced in the theory of Human-Engaged Computing (HEC), proposed by Xiangxi Ren, aims at getting "the right balance" to achieve seamless integration in interactions between humans and computers, thus enhancing human capacities.

Despite its potential, synergized interactions largely remain theoretical. To bridge the gap between theory and practice, it is necessary to explore both theoretical and empirical approaches for the effective implementation and enhancement of human capacities, such as creativity and mindfulness.

To address this gap, this dissertation is structured into two parts. Part I presents theoretical studies on synergized interactions, introducing a rhythm approach based on a literature review (Chapter 2) and proposes the Framework for Synergized Interactions through Rhythm Adjustment (FSIRA) (Chapter 3). Part II investigates empirical studies, presenting four case studies: enhancing walking creativity (Chapter 4), running meditation (Chapter 5), synergized game design (Chapter 6), and exploring synergized interactions in digital heritage education from a HEC perspective (Chapter 7).

This dissertation ends with critical reflections and generalizations of synergized interactions based on key findings, general discussions, and suggestions for future work (Chapters 8 and 9). The high-level conceptual framework and design considerations are distilled to inform researchers and practitioners in the field of synergized interactions, aiming to guide the design of promising interactive technologies that enhance human capacities in the HCI and HEC community.

The main contributions of this dissertation are: (1) Proposing the practical framework, FSIRA, which bridges the gap between theory and design of synergized interactions in rhythm-driven tasks. (2) Demonstrating four design studies that explore human capacity enhancement through the development of synergized interaction technologies targeting various levels and domains. (3) Providing insights into previous theoretical and empirical investigations on synergized interactions and contributing to new design implications for future researchers and designers and offering guidance for other conceptual frameworks in the HCI and HEC community.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

This chapter presents the introduction of the doctoral thesis, which includes four parts: (1) background and motivation; (2) problem and approach; (3) contributions; (4) overview, significance and novelty of the dissertation.

1.1 Background and Motivation

1.1.1 Human-Engaged Computing

Since the inception of computers, the relationship between humans and computers has been a significant debate within the Human-Computer Interaction (HCI) community. The earliest discussions can be traced back to Licklider's proposition of "Man-Computer Symbiosis" in the 1960s (Licklider, 1960). Over time, the focus of the debate has evolved through four waves of HCI (Bødker, 2006; Harrison et al., 2007; Bannon, 2011; Rogers, 2022). The progression from the first wave to the third wave marked a gradual shift in focus. Initially centered on a purely technological perspective within industrial engineering and ergonomics, the emphasis gradually moved toward human-centered computing to address social and emotional aspects of HCI Ren (2016). In the current fourth wave, particularly with recent advances in artificial intelligence (e.g., ChatGPT, large language model), there has been a widespread focus on an even more human-centered perspective (Borning and Muller, 2012; Calvo and Peters, 2014; Borning and Muller, 2012; Farooq and Grudin, 2016), within a renewed focus on the enhancement of human capacities Ren (2016). However, previous studies have not yet fully explored an ideal relationship aimed at fully developing and enhancing human capacity through the utilization of promising technologies.

To address this gap, Xiangshi Ren proposed the Human-Engaged Computing (HEC) framework (Ren, 2016), drawing inspiration from Eastern philosophical concepts such as the Doctrine of the Mean (Feng, 1948). This framework aims to synergize the innate human capacity and the technological capacity to enable the realization of our

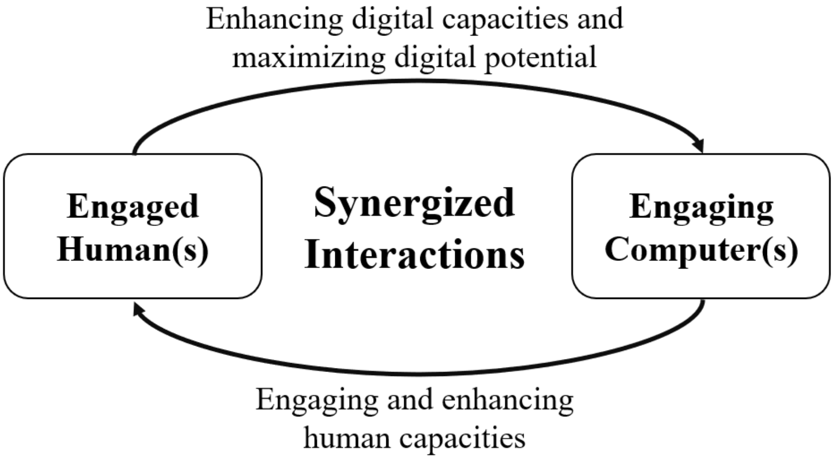


Fig. 1.1: Human-Engaged Computing is comprised of three components: engaged humans, engaging computers, and *synergized interactions* (Ren, 2016).

full potential and the resolution of complex real-world problems (Ren et al., 2019). It emphasizes achieving the "right balance" in the relationship between humans and computers, where human abilities are fully enhanced while simultaneously tapping into the potential of computers.

HEC encompasses the integration of technology and human abilities to achieve a higher level of understanding (Ren et al., 2019). It comprises three essential dimensions (Figure 1.1): (1) *engaged humans*, referring to individuals whose skills are used and enhanced through their active involvement, (2) *engaging computers*, representing computers and software that involve and enhance human abilities, and (3) *synergized interactions*, which entails effectively combining human skills and technological capacities in a seamless manner (Ren, 2016). HEC focuses primarily on improving human abilities through active engagement and enhancing technology to effectively collaborate with humans in meaningful ways (Ren et al., 2019; Wang et al., 2020a). It aims to pay equal attention to human abilities and technology capacities, thus creating a balance between them. In this dissertation, our focus is on exploring the design of *synergized interactions* for human capacity enhancement within this framework.

1.1.2 Current Interaction Modes vs. *Synergized Interactions*

From the perspective of resource allocation, there is an imbalance in the proportions between humans and computers based on the current interaction phenomenon. This imbalance often leads to three situations (Figure 1.2a).

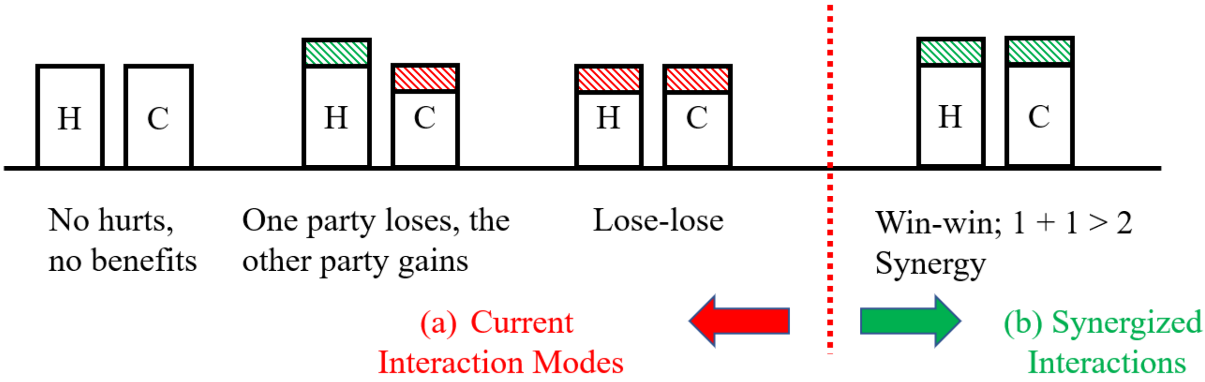


Fig. 1.2: Schematic diagram shows the three conditions of previous interaction modes and *synergized interactions*.

(1) *There are no benefits or drawbacks for either party* (e.g., smartwatches that unilaterally detect a person's heart rate). Although this may seem benign on the surface, it actually has significant risks. The issues of data privacy and security are readily apparent. User health data are collected, stored, and analyzed, potentially for commercial purposes by third-party companies, or even misused by governments or hackers. Users often lack transparency and control over where their data go and how they are used, leading to serious infringements of personal privacy.

(2) *One party experiences losses while the other gains in interactions* (e.g., excessive gaming that threatens cognitive abilities). Excessive gaming not only threatens cognitive abilities, but also involves broader social issues. Gaming companies profit by designing addictive mechanisms, while users, especially young people, can suffer from academic, occupational, and interpersonal disruptions, as well as mental health problems due to prolonged gaming. This imbalance not only affects individuals, but also has negative repercussions on society as a whole, increasing public health and social governance burdens.

(3) *Both parties suffer losses, resulting in a lose-lose scenario* (e.g., uncontrolled autonomous driving causing harm to both humans and vehicles). Uncontrolled autonomous driving technology highlights the risks of technological failure. Although autonomous driving is intended to improve traffic safety and efficiency, lack of regulation can lead to serious traffic accidents. This reflects deeper conflicts between technological advances and social governance, illustrating the challenges in effectively managing new technologies.

In contrast, *synergized interactions* (Figure 1.2b) aim to achieve a "right balance" between humans and computers. This "right balance" is not about absolute equality in proportions, but rather an appropriate allocation of proportions for both parties in the interaction. The goal of this interaction pattern is to achieve win-win situations for both parties and to create a synergized effect where the whole is greater than the sum of its parts (Ren et al., 2019). In fact, in recent years, an increasing number of researchers have explored ideal relationships between humans and computers, such as human-computer integration (Farooq and Grudin, 2016), human-engaged artificial intelligence (Ma, 2018), and human-artificial intelligence collaboration (Wang et al., 2020b). The concept of *synergized interactions* within the HEC framework refers to the effective synergy between engaged humans and engaging computers to fully enhance human capacities and computing capacities (Ren, 2016).

Unlike current interaction paradigms, *synergized interactions* (Figure 1.2b) emphasize mutual consideration of both humans and computers, with attention to each other's needs through rational resource allocation. Ren (2016) introduced the concept of *synergized interactions*, highlighting the effective synergy between humans and computers, an eastern concept detailed in the sidebar "HEC: Getting the Balance Right". Specifically, *synergized interactions* refer to the seamless integration of human capacities and device functionalities to accomplish tasks effectively, presenting them as a unified entity (Ren et al., 2019).

The notion of *synergized interactions* inherits Douglas Engelbart's advocacy of augmenting human capacities (Engelbart, 1962), not only promoting synergy between humans and computers, but also emphasizing how synergy can stimulate the potential of both parties rather than diminish the capacities of one. This advocacy is particularly relevant when human abilities are compromised in interacting with computers, such as diminished concentration span due to distractions from smartphones. In this ideal scenario of *synergized interactions*, computing technology transcends the simple objective of performing tasks more quickly or efficiently. Instead, it is designed to augment and expand human capacities, both current and potential, allowing the achievement of higher-level, possibly still undefined, objectives (Ren, 2016). Sometimes, this harmonious interaction might even involve the decision not to deploy a seemingly beneficial technology.

This concept (*synergized interactions*) offers a new perspective to rethink the relationship between humans and computers and sets new goals for interaction. In recent years, *synergized interactions* have been explored in various fields such as human-engaged artificial intelligence (Ma, 2018), information interaction (Wang et al., 2020a), intelligent vehicle interaction design (Liu et al., 2021), digital heritage education (Tan et al., 2023), meditation training (Niksirat et al., 2017), and cognitive training for the elderly (Yuan and Ren, 2021). However, *synergized interactions* still lack systematic exploration, both theoretically and empirically, such as the construction of a framework for *synergized interactions* to design promising interactive technologies.

1.1.3 Human Capacity Enhancement

In the 1960s, the field of computer science witnessed the emergence of two profound developmental trajectories (Hassani et al., 2020; Zhou et al., 2023): Artificial Intelligence (AI), which focuses on the computing perspective of how tools can be humans (McCarthy, 1960), and Intelligence Amplification (IA), which prioritizes the human perspective of how humans can be better at amplifying their capacities through tools (Engelbart, 1962). Despite their differences, both trajectories underscore the relationship between humans and technology to varying degrees. It should be noted that the HCI community is particularly inclined towards IA. Early thinkers like Douglas Engelbart introduced a framework for augmenting human intelligence (Engelbart, 1962). The notion that the subsequent HEC framework also further accelerates emphasizes the creation of *synergized interactions* to fully unleash human potential while ensuring that human capacities are not compromised when using interactive technologies (Ren et al., 2019).

However, technological advances not only bring convenience to humans but also inadvertently impair human capacities. For example, continued engagement with electronic games and streaming media may lead to a decline in cognitive abilities. Some proponents (e.g., Stephen Hawking, Bill Gates, and Elon Musk) of technological threat express concerns that these technologies may result in the degradation of human capacity. Particularly with advances in AI technologies and applications such as ChatGPT and Sora, fundamental human skills and abilities face significant challenges, with basic skills like drawing and programming potentially being supplanted by AI. Consequently, many scholars have begun to contemplate: Which human capacities will remain irreplaceable within rapid technological advancements? One such category is human soft skills, which represent high-level abilities distinct from the key attributes of intelligent technologies.

In HCI/HEC, the concept of human capacity enhancement has evolved significantly, focusing not only on improving efficiency and performance, but also improving cognitive, physical, and sensory capacities. The early developments in HCI were mainly aimed at creating more intuitive and user-friendly interfaces. However, recent advances have shifted towards integrating artificial intelligence, augmented reality, and wearable technologies to synergize human and machine capacities (Ren, 2016; Oulasvirta et al., 2022; De Peuter et al., 2023; Li et al., 2024). This holistic approach seeks to empower individuals by amplifying their innate potential, thus facilitating more meaningful and productive interactions with technology.

Therefore, the focus of this dissertation is to improve human capacity, particularly soft skills (e.g., creativity and mindfulness), by exploring the theoretical framework and practical techniques of *synergized interactions*. This aims to support humans to thrive in the ubiquitous computing era without being replaced.

1.2 Problem and Approach

1.2.1 Problem

The fundamental goal of this dissertation is to explore the theoretical foundations and empirical studies of *synergized interactions*, as well as to investigate their potential for enhancing human capacities. More specifically, our aim is to address the following three overarching Research Questions (RQ).

- RQ1: How can we construct a computational framework for *synergized interactions*?
- RQ2: How can we develop promising synergized interaction technologies to enhance human capacity?
- RQ3: How can we understand and extend the investigation of *synergized interactions* and provide general knowledge to the HCI/HEC community?

1.2.2 Approach

To address RQ1, in *Part I*, we dive into theoretical studies on *synergized interactions*.

In *Chapter 2*, (1) We analyze the issues with existing interaction patterns and adopt a *rhythm* perspective to understand and expand the interaction process. (2) We review the importance of rhythm and rhythm regulation in the HCI community. (3) Furthermore, for this dissertation we define the scope of *synergized interactions* from a rhythmic perspective.

In *Chapter 3*, we propose a framework for *synergized interactions.* This framework comprises three components: (1) defining the states of *synergized interactions*, (2) proposing protocols for rhythmic regulation mechanisms toward *synergized interactions*, and (3) introducing general procedures and design principles for these mechanisms.

To address RQ2, in *Part II*, we explore three design cases on *synergized interactions.* These three studies represent empirical investigations following theoretical reflections on *synergized interactions*, with the goal of enhancing human capacities.

In *Chapter 4*, we investigate the effects of three general rhythmic interaction patterns on enhancing *creativity* while walking. This foundational study highlights the value of *synergized interactions.* In

Chapter 5, we develop a synergized interaction system and explore, through empirical studies, the positive effects of seven pairs of enhancing *mindfulness meditation* while running.

In *Chapter 6*, we explore a teaching framework to enhance students' *design capacity* while developing synergized rhythm game.

To address RQ3, in *Part II - Chapter 7*, we further extend the guiding significance of *synergized interactions* in the field of digital heritage education. Our overarching goal is to continually enrich the concept of *synergized interactions*, fostering cross-disciplinary empowerment and insight across different fields and disciplines.

Furthermore, in *Chapter 8*, we present general discussions of theoretical and empirical studies on *synergized interactions*, compare differences in existing studies, and present insights in six aspects (perspective, methodology, design, system development, user study, and evaluation).

In *Chapter 9*, we present general conclusions on main findings, contributions, significance, and future agendas and remarks to contribute new knowledge to the HCI/HEC community.

1.3 Contributions

1.3.1 Theoretical Contributions

- In *Chapter 2*, we unveil the dynamism of interactions through the lens of rhythmic analysis. Additionally, we provide a comprehensive definition of the generalized concept of *synergized interactions* for the first time.

- In *Chapter 3*, we introduce a practicable framework for *synergized interactions*, comprising three key contributions. First, the framework delineates the states of *synergized interactions*, termed synergized rhythms, enabling their observability. Second, the framework proposes rhythm adjustment mechanisms to achieve *synergized interactions*, consisting of three adaptable computational algorithms. This facilitates the operationalization of states of *synergized interactions* through actionable protocols. Third, the framework outlines the general procedure and design principles for rhythm adjustment, providing design guidance to future researchers and designers in developing synergized interaction technologies.

1.3.2 Empirical Contributions

- In *Chapter 4* - study 1, we design a Footstep Sound Interactions (FSI) framework and develop an interactive system (i.e., WalkMe) that encompasses three FSI modes to support walking creativity. Subsequently, we conduct a user study in indoor and outdoor environments comparing the effects of three FSI modes with a walking-only condition. Based on the findings, we discuss the FSI framework's implications, roles related to attention and creativity in the walking experience context, and implications for design and future work aimed at enhancing walking creativity through interactive technologies.
- In *Chapter 5* - study 2, we present the design framework and development of the RunMe system, an adaptive sound system specifically designed for running meditation. RunMe integrates stimulation and regulation mechanisms to enhance data interactions between sounds and runners ' footsteps and heart rate. We compare the significance of the RunMe group with three other groups: non-adaptive sound, user-favorite music, and no-music/sound groups. The results show that the RunMe group outperforms the others in attention regulation, body awareness, exercise motivation, and mindfulness. Importantly, RunMe allows users to engage in running meditation without specialized equipment, making it accessible for daily practice.
- In *Chapter 6* - study 3, we propose a Synergized Game Design Teaching Framework (SGDTF) aimed at fostering student engagement and reflective design practices. We conducted a synergized game design workshop at the university, involving 26 students who engaged in phased game design activities guided by the SGDTF. All students participated in qualitative and quantitative surveys to collect their subjective feedback. The study identified the effectiveness of the SGDTF in fostering

students' engagement and reflective game design skills. This also underpins the framework's potential for sustained study in game design education. These findings underscore the importance of adopting the SGDTF as pedagogical approaches to foster a more effective teaching for game design education. This study also provides new pedagogical guidelines for future game design education.

- In *Chapter 7* - study 4, we propose a framework that extends the concept of *synergized interactions* to improve understanding and design of Intangible Cultural Heritage (ICH) in the field of education. To validate the effectiveness of the proposed framework, we design, implement, and track Cantonese Porcelain Creative Design courses over five years. We discuss the theoretical and practical importance of this framework and outline a future agenda for digital heritage education in the classroom. Our framework provides researchers and educators with a new approach to explore how digital technology can effectively support students in understanding and designing ICH.

1.3.3 Implications to Future Considerations

- In *Chapter 8*, we summarize the theoretical and empirical investigations into *synergized interactions* that were undertaken previously. Our contributions extend to a comprehensive discourse on the implications of our findings, critically evaluating their significance within the broader context of HCI. We also delineate the limitations encountered during our research, providing a transparent account of potential constraints and areas for improvement. Moreover, we offer a forward-looking perspective by identifying promising avenues for future research and practical design, aiming to guide and inspire HCI/HEC researchers and designers.
- In *Chapter 9*, we provide a comprehensive summary of the dissertation, highlighting key findings, emphasizing the transition from theoretical to empirical contributions. It underscores the significance of theoretical research in advancing practical applications. Additionally, it outlines future agendas to guide researchers and designers in the HCI/HEC community and concludes with reflections on the entire doctoral dissertation. Overall, the chapter offers readers a deeper understanding and outlook while providing valuable insights and directions for the future development of *synergized interactions*.

1.4 Overview, Significance and Novelty

The Figure 1.3 illustrates the overview of this dissertation, comprising two parts and nine chapters from theoretical investigations to empirical studies. We separately present the overview and significance of both theoretical and empirical studies in the following subsections.

1.4.1 Overview

Theoretical studies. The theoretical studies introduce a novel perspective on achieving *synergized interactions* through rhythm.

Chapter 2 provides a comprehensive literature review on rhythm in interactions, analyzing its positive roles and establishing a clear conceptual boundary for exploring *synergized interactions* from a rhythm perspective.

Chapter 3 builds on this by proposing the Framework for *synergized interactions* through Rhythm Adjustment (FSIRA). FSIRA emphasizes mutual adaptation between humans and computers, offering a structured approach to achieving balanced synergy through rhythm adjustment. This framework includes defining *synergized interactions*, implementing rhythm adjustment mechanisms, and outlining general design principles for creating *synergized interactions.*

Empirical studies. The empirical studies consist of four case studies on achieving *synergized interactions* through investigating its effects of in diverse contexts.

Study 1 developed a rhythmic footstep sound interaction system to enhance walking creativity, demonstrating its effectiveness in a user study (*Chapter 4*).

Study 2 introduced an adaptive sound system, RunMe, which supported running meditation by providing real-time audio feedback, validated through comparative analysis (*Chapter 5*).

Study 3 proposed the synergized game design teaching framework to improve student game design capabilities, confirmed through a workshop involving student engagement and reflective practice (*Chapter 6*).

Study 4 applied the HEC principles to digital heritage education, enhancing student engagement with digital tools to better understand and design intangible cultural heritage (*Chapter 7*).

1.4.2 Significance

Theoretical significance. This dissertation introduces the novel concept of "synergized rhythms" towards *synergized interactions*, characterized by the adjustment of human and computer rhythms to achieve optimal synergy. Diverging from traditional synchronization studies, it emphasizes mutual rhythm adjustment for enhanced interaction harmony. Grounded in multidisciplinary evidence and drawing parallels to natural phenomena, this approach provides a robust theoretical foundation and highlights its universal applicability.

This dissertation also presents FSIRA, a practical framework that bridges theory and design by offering protocols for rhythm adjustment and five guiding principles, significantly advancing practical HCI/HEC design methodologies. By enhancing the theoretical understanding of *synergized interactions* and offering new computational models, this study provides a fresh lens for analyzing and designing HCI systems. Additionally, FSIRA enables designers to assess and improve current interactive systems by addressing rhythm misalignment issues, ensuring that theoretical contributions have a direct impact on enhancing real-world system usability and effectiveness.

Empirical significance. This dissertation makes significant contributions by introducing innovative framework tailored to specific domains, thereby advancing existing knowledge of *synergized interactions* in distinct ways.

First, it develops a comprehensive framework such as FSI and SGDTF, which, respectively, enhance walking creativity and synergized game design through systematic approaches.

Second, it explores new applications in the development of technologies of *synergized interactions*, such as RunMe for running meditation, filling gaps in existing meditation technologies, and demonstrating superior performance in mindfulness and exercise motivation.

Third, it extends theoretical perspectives, as seen in the application of HEC theory to digital humanities education, fostering innovative approaches in understanding and designing cultural artifacts. These contributions not only address current research gaps, but also pave the way for future advancements of *synergized interactions* in their respective fields.

1.4.3 Novelty

Theoretical novelty. The existing conceptualizations of interaction in the HCI community are abstract, hard to observe, and often at a high level of operation. This dissertation proposes an exploration of interaction processes from the perspectives of time and rhythm, examining their unfolding and different states. Furthermore, the dissertation introduces rhythm-based adjustment mechanisms capable of detecting states in interaction unfolding and providing adaptive feedback. This computational interaction framework (operational definition) contrasts with existing HCI approaches (conceptual definitions).

The operational definition of *synergized interactions* introduced in this dissertation offers a practical pathway from concept to design. It provides a more granular and sensitive perspective, bringing designers into the implicit arena of *synergized interactions* to observe and reflect on the root causes of conflict and imbalance in interactions, and toward the allocation of resources for achieving *synergized interactions* between humans and computers. By bridging the gap between abstract concepts and practical design, this dissertation provides a valuable framework for advancing the field of HCI/HEC.

Empirical novelty. Existing interactive systems predominantly rely on one-way drives, leading to an imbalance in resource allocation and consequently underutilizing the potential of at least one party involved in the interaction. This dissertation unveils a comparative study of one-way systems and explores the potential of two-way systems. For the former, this dissertation conducts a first-of-its-kind comparison of three common one-way interaction modes, identifying the challenges and potentials for transitioning towards two-way adaptation in interactive tasks. For the latter, this dissertation introduces and develops the first two-way system of *synergized interactions*, empirically validating its effectiveness over one-way systems.

Furthermore, this dissertation incorporates the theory of *synergized interactions* into the educational domain. By integrating curriculum design, it pioneers the exploration of the importance of *synergized interactions* between students and digital tools in the fields of technology-enhanced learning and design. This exploration also provides inspiration for technology-oriented educational researchers toward the field of HCI/HEC.

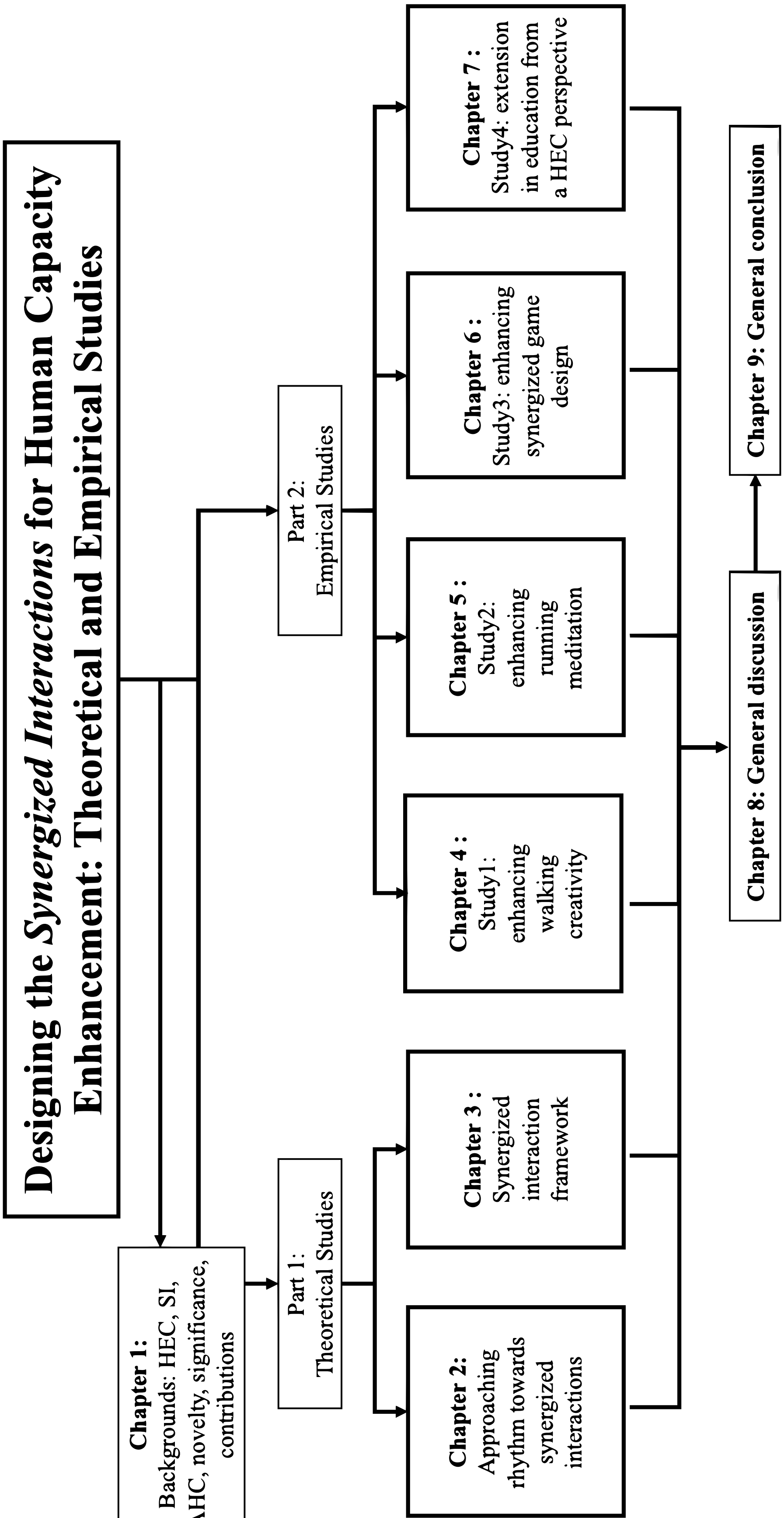


Fig. 1.3: An overview of this dissertation, named *Designing the Synergized Interactions for Human Capacity Enhancement: Theoretical and Empirical Studies*.

Part I

Theoretical Studies

Chapter 2

Approaching Rhythm toward *Synergized Interactions*

This chapter introduces a novel perspective, that is, approaching the rhythm toward *synergized interactions*. We (1) review related conceptualizations of rhythm in interactions; (2) analyze its positive roles in interactions starting from rhythm; and (3) further provide a clearer and observable conceptual boundary for exploring *synergized interactions* from a rhythm perspective.

2.1 Conceptualizations of Rhythm in Interactions

Henri Lefebvre thinks that **rhythm** is cyclical recurrence of a measure at a specific frequency. It transcends traditional boundaries, finding resonance not only in the realm of music but also within the human body itself (Lefebvre, 2013). For example, people move their body to the rhythm of music to put themselves in a happy mood (Witek et al., 2014). Recognizing the inherent connection between rhythm and human engagement, we come to understand that rhythm materializes at the confluence of various elements such as place, time, and energy expenditure (Höök, 2010; Lefebvre, 2013; Costello, 2020b). This holistic perspective reveals rhythm states that encompass harmony, disturbance, and orchestrated control within interactions.

Focusing on the generation of rhythm, Lefebvre's proposed categories, arrhythmia, polyrhythmia, eurhythmia, and isorhythmia, unfold intricate dynamics (Lefebvre, 2013). For example, consider the polyrhythmic complexity in a jazz ensemble, where disparate rhythms coalesce into a harmonious whole. This example encapsulates the conflict, co-existence, and constructive interaction inherent in Lefebvre's rhythmic categories (Duarte and Ramos, 2022). Previous research has emphasized the role of rhythm in elucidating emergent states, fostering possibilities of process, and discerning stability patterns within diverse interactions (Gill, 2012). This underscores the importance of rhythm in revealing evolving conditions.

Lefebvre's lens of rhythm analysis establishes groundwork for investigating various roles of rhythm in various contexts. In HCI, rhythm is a fundamental attribute of interaction and is defined as a regular or repetitive pattern of movement, such as music beats. Interactions between humans and computers involve rhythms, such as human rhythms, e.g., heartbeat, breathing, walking cadence while exercising (Yang et al., 2020; Potočnik et al., 2023), and computer rhythms, e.g., temporal pointing in rhythm games (Lee and Oulasvirta, 2016; Moon et al., 2022). Rhythm can be sensed, felt, and interpreted in an interaction between humans and interactive systems (Costello, 2020a). In interaction design, rhythm has been recognized as a crucial design element for designing promising interactive systems (Jylhä et al., 2012; Niksirat et al., 2019). For example, interaction designers are beginning to integrate rhythm as a design element or pattern into interactive systems to help users efficiently engage in tasks, such as improving rhythmic self-regulation in Parkinson's disease (Mazilu et al., 2015; Georgiou et al., 2016) and mindfulness meditation (Choi and Ishii, 2020). Rhythm began to be seen by designers as a positive design quality and is now being embedded in the design of interactive systems.

Costello (2020b) emphasizes the importance of paying attention to rhythm, unfolding processes, dynamic temporality, and patterns of change and continuity in interactions. Costello argues that a temporal approach can provide deeper insights into how users experience systems over time. Accounting for the temporal nature of interaction allows researchers and designers to better understand the evolving needs and contexts of the users (Costello, 2018). It also helps to ensure that systems dynamically adapt to maintain alignment with users as their tasks and goals change. Many researchers and designers have been inspired to explore the rhythmic attributes of humans and computers in interaction processes more deeply (Choi et al., 2022; Albert et al., 2022).

Höök (2010) also highlights the importance of rhythm in bodily experiences and the design of meaningful interactions. Through analyzing a horseback riding experience, she explores how rhythm and balance create particularly intense bodily experiences. She emphasizes the significance of rhythm in describing the sensitive and subtle relationships between unspoken symbols and signals. In her case, the two bodily agents —a human and a horse, have the potential to achieve a true centaur-like connection through rhythm. In contrast, our dissertation suggests that this promising idea inspires the realization of a harmonious zone between body and mind, as well as between subject and object.

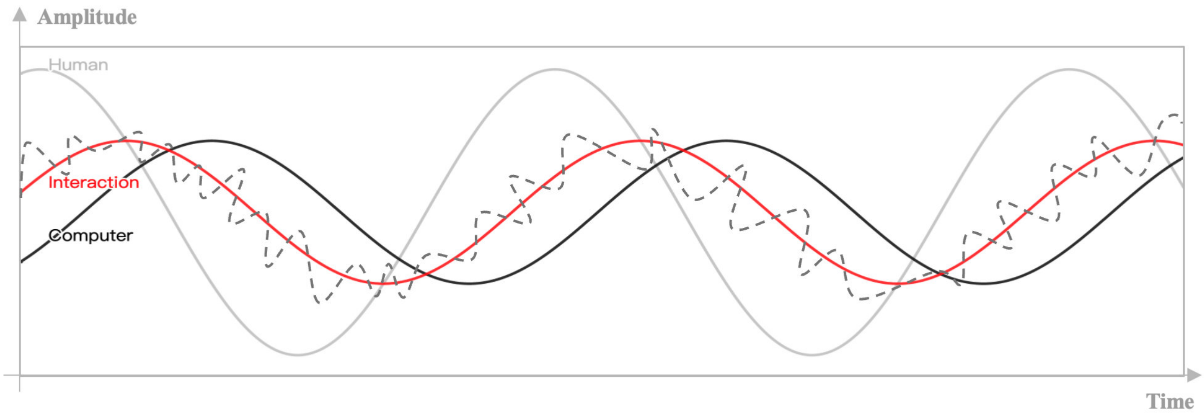


Fig. 2.1: Schematic diagram shows the three waves represent human rhythm, computer rhythm, and interaction rhythm respectively. Interaction rhythms represent an entangled state between human rhythms and computer rhythms in a time series.

Past studies have provoked people to rethink interactions between humans and computers. Studying interaction from a temporal and rhythmic perspective is emerging as a novel lens through which to uncover nuances regarding interaction flows and qualities. Adopting such an approach has the potential to elicit fresh insights into the unfolding nature of interactions between users and technology over dynamic periods of time.

2.2 Rhythm Adjustment in Interactions

Interactions between humans and computers involve rhythms, such as human rhythms, e.g., cadence while exercising (Yang et al., 2020; Potočnik et al., 2023), and computer rhythms, e.g., the frequency of visual and audio feedback in rhythm games (Costello, 2018; Moon et al., 2023). Rhythm can be sensed, felt, and interpreted in an interaction between humans and interactive systems (Costello, 2020a,b). At the outset of interactions, human rhythms exhibit a certain degree of confusion and uncertainty. Interaction rhythms represent an "entangled state" between human rhythms and computer rhythms (Figure 2.1). The initial inputs' rhythm of each party may not be very coordinated and require time to reach a consensus. This "entangled state" of rhythm is similar to the process of chaos transforming into order in dynamical systems theory (Lefebvre, 2013; Frauenberger, 2019). To address this "entangled state", two concepts have been widely explored in rhythm adjustment in interactive systems, namely *adaptation* and *synchronization*, which collectively form theoretical foundations. In the early stages of interactions, rhythm primarily eliminates differences to achieve synchronization. The essence of synchronization lies in understanding how one party adapts to another, creating a harmonious state of coordination dynamics (Sakti et al., 2023).

However, subtle differences in rhythms would further constrain and influence interactive actions (de Reus et al., 2021). Through continuous adaptation between humans and computers, their actions of rhythm gradually form a dynamically balanced system. That is, the rhythm of each participant would transition from an initial conflicting state to a relatively stable rhythm. This realizes the dynamic transition from the "entanglement" to the "order". In an interactive system, adaptation and synchronization represent crucial processes in rhythm adjustment, where, through a continuous iterative approximation, the rhythm of both parties in interactions gradually optimizes. We need to pay attention to how to drive human and/or computer rhythms to maintain optimal states in interactive systems to stimulate potentials of both sides in interactions (Ren, 2016; Ren et al., 2019).

In summary, recent studies illustrate the need for rhythm adjustment to establish more adaptive interactive systems, emphasizing the need for a paradigm shift beyond existing interaction modes. This paper advocates the concept of *synergized interactions*, with the goal of seamlessly adjusting the rhythm between human engagement and the affordance of computers (Ren et al., 2019).

2.3 Scoping *Synergized Interactions* from a Rhythm Perspective

Rhythm can provide a reference at the framework level for scoping *synergized interactions*. The rhythm patterns in the interactions reflect the need for consistency and adaptability in *synergized interactions*. Rhythm in interactions involves reciprocation and ongoing feedback, crucial aspects for the development of synergies. The parallel between rhythm and *synergized interactions* highlights how both result in higher-level structures that go beyond the sum of their parts. The concept of rhythm is ingrained in everyday experiences such as music, dance, and exercise, making it accessible to people. Leveraging rhythm to understand *synergized interactions* taps into this intuitive understanding, bridging the gap between abstract concepts and tangible, relatable experiences.

Fig. 2.2: Schematic diagram shows synergzied rhythms between human (rhythms) and computer (rhythms) toward *synergized interactions*.

The concept of *synergized interactions* in the theory of human-engaged computing refers to "*effective task performance accomplished through the seamless integration of human capacities and device characteristics that perform as a single entity, with a single focus and a common purpose*" (Ren et al., 2019). The essence of *synergized interactions* lies in the dynamic process where humans and computers interactively adjust their respective rhythm. This ongoing feedback and mutual adaptation of action patterns and time points maintain a dynamically balanced rhythm throughout the interaction process. Achieving a state of synergized interaction optimizes rhythm collaboration between humans and computers, leveraging both subjective capacities and objective characteristics.

The "synergized-" state is a dynamic process where humans and computers continuously adjust their positions to a comfortable state in a progressively efficient interaction (Costello, 2020b). This process involves dynamically allocating adjustments in proportion to the respective benefits of humans and computers, emphasizing the importance of a harmonious function. The key criterion for achieving synchronicity in *synergized interactions* is the continuous adjustment of attributes to the optimal efficiency of a task (Ren et al., 2019). This optimal state, while not defined by a specific numerical value, signifies pertinent performance compared to non-synergized approaches. Balancing the attributes of humans and computers is crucial to achieving the right synchronicity and, consequently, successful *synergized interactions* (Ren et al., 2019).

Therefore, in this study, we present a definition of "*synergized interactions*" - *synergized interactions denote a condition characterized by synergized rhythms, achieved through fine-tuning of human and computer rhythms in a time series with the aim of realizing an optimal state of rhythm alignment independently for each entity* (Figure 2.2). In fact, this proposition of achieving *synergized interactions* through rhythm adjustment is grounded in substantial evidence, drawing on a breadth of research across domains involving *synergized interactions* among humans and other organisms or systems (Thaut et al., 2015; Ravignani, 2019; Bouwer et al., 2021). Nature examples consistently highlight the synergy achieved through precisely tuned rhythms between participants (Couzin, 2018). For instance, fireflies synchronize lighting displays by aligning flash timing according to others' rhythms. In human interactions, conversation is based on alternated speech governed by implicit rhythms, facilitating seamless interchange of perspectives (Dunbar et al., 2022). Thus, proportional synergy of the rhythm may endow HCI with the same synergized potentials observed across natural synchronizing systems. The state of *synergized interactions* can be achieved by progressive rhythm adjustment, where the actions and responses of humans and computers align harmoniously.

Chapter 3

FSIRA: A Framework for *Synergized Interactions*

This chapter presents a practical framework (i.e., FSIRA) for *synergized interactions* through rhythm adjustment. The FSIRA includes three parts, (1) introducing the definition of *synergized rhythms*, which makes *synergized interactions* can be observed; (2) constructing the protocol of *synergized rhythms* to adjust rhythms in interactions toward *synergized interactions*; and (3) presenting the procedure and design of *synergized rhythms* to guide designers to engage in development of synergized interaction technologies.

3.1 Introduction

In the field of Human-Computer Interaction (HCI), the increasing emphasis on human-computer symbiosis/synergy has highlighted enduring challenges in both academic and industrial domains (Licklider, 1960; Weiser, 1994; Dourish, 2001; Calvo and Peters, 2014; Ren, 2016; Farooq and Grudin, 2016). Despite the conceptual evolution towards human-computer integration (Farooq et al., 2017) and human-AI collaboration/symbiosis (Wang et al., 2020b), the practical implementation of these ideas faces challenges such as technical integration issues during human engagement (Yu et al., 2023), suboptimal information flow (Wang et al., 2020a), and the complexity of achieving synergistic effects in collaboration (Stephanidis et al., 2019). Empirical studies focus on adaptation in HCI, including computer adaptation to humans, human adaptation to computers, or a combination thereof (Figure 3.1a). They often overlook potential imbalances between interacting parties (Grudin, 1991; Oulasvirta et al., 2022), which can result in under-utilization of capabilities between humans and computers (Ren, 2016), leading to decreased task performance.

Moreover, a predominant focus on unilateral adaptation rather than mutual adjustment raises concerns about the disproportionate allocation of human resources (e.g., cognitive load). Inappropriate resource allocation in interaction has been observed to negatively impact skill training (Salden et al., 2006; Flegal et al., 2019), learning (Szafir and Mutlu, 2012; Kirchner et al., 2016), mental health (Kostoulas et al., 2012; Hinss et al., 2022), and medical rehabilitation (Karime et al., 2013). Efforts to address the challenges associated with HCI imbalances, such as asynchrony or delays in interactions (Pelikan and Hofstetter, 2023), have been explored through predictive algorithms (Shin et al., 2020). However, these solutions face technical limitations, such as insufficient knowledge of user habits and preferences and limited prediction capabilities for complex tasks.

Recent studies have explored computational interaction methods to mitigate these challenges based on the Bayesian framework (Kristensson et al., 2019; Liao et al., 2023) and simulation (Fischer et al., 2023; Yun et al., 2023). For example, Howes et al. (2023) proposed to enhance the machine's understanding of humans based on computational rationality to maximize optimal given human-like bounds. Niksirat et al. (2019) proposed a self-regulated mindfulness technology design framework that integrates detection, feedback and regulation mechanisms for data interactions between humans and computers. While these methods support the human loop within interactive systems (Kim et al., 2019; Chan et al., 2022), existing frameworks are often domain-specific and one-way adaptation-centric, lacking generalizability and restricting their applicability to broader contexts.

In response to these challenges, this study aims to formulate a practical framework tailored to address *synergized interactions* (Figure 3.1b). This focus is particularly relevant amid the ongoing paradigm shift in HCI, characterized by a transition toward more human-centered, engaged, and symbiotic models of interaction between humans and computing technologies. The fourth wave of the paradigm shift in HCI underscores the timely need for holistic solutions to promote sustainable development in the field of HCI (Bannon, 2011; Kuutti and Bannon, 2014; Bødker, 2015).

Synergized interactions, distinct from existing frameworks and paradigms, offer a unique philosophical perspective, namely "the right balance" (Doctrine of the Mean in the field of Chinese philosophy) (Ren, 2016). Specifically, this concept advocates that (1) humans and computers should receive proportional, not equal, consideration based on their respective contributions to achieving overall harmony and synergy in any given interaction; and (2) potential inefficiencies and waste should be weighed

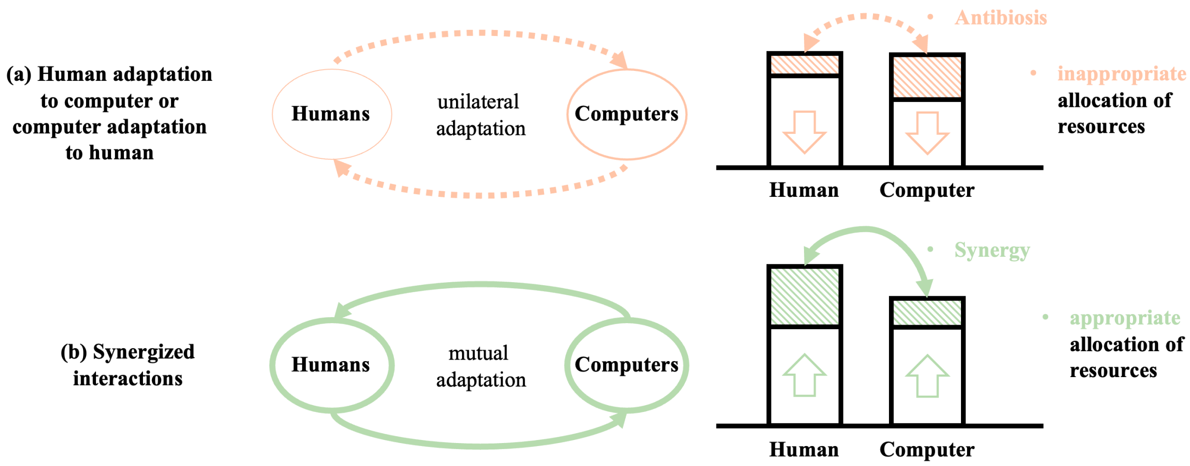


Fig. 3.1: A high-level diagram depicting the relationship and allocation of resources between humans and computers in interactions. (a) is the unilateral adaptation in interactions that highlight respective adaptations from one side to the other. (b) highlights "the right balance" between humans and computers, where the seamless integration of human capacities and device affordances performing as a single entity with single focus and common purpose (Ren, 2016).

against antibiosis (Figure 3.1a) arising from lack of cooperation between parties. The goal is to achieve an ideal relationship between humans and computers, creating a mutually enhanced state where combined wisdom surpasses what either humans or computers could achieve independently (Figure 3.1b). On the practical level, *synergized interactions* deviate from traditional adaptation frameworks that focus on unilateral adaptation between humans and computers. *Synergized interactions* strive for mutual adaptation, where both parties enhance each other through synergized efforts.

However, investigation of *synergized interactions* remains at a conceptual level (Ma, 2018; Wang et al., 2020a; Tan et al., 2023), highlighting the gap between theory and design (Höök and Löwgren, 2012; Beaudouin-Lafon et al., 2021). The realization of *synergized interactions* can exist in various practical approaches. As an initial exploration, this paper focuses on one of the approaches grounded in the perspectives of rhythm within a time series.

Rhythm is a fundamental attribute of interaction and is defined as a pattern of movement in interaction (Costello, 2020b; Tan and Ren, 2023). Past studies indicate that rhythm significantly impacts user experience, behavior, and performance in HCI (Costello, 2020b; Wiberg and Stolterman, 2021). Adjusting rhythm has the potential to ameliorate interaction mismatches in a time series, thereby improving subsequent user experiences and task performance.In this paper, we emphasize the entangled state of rhythm in interactions and reveal how to adjust the rhythm of both interacting parties towards an ideal state, i.e., *synergized interactions*. However, existing frameworks that incorporate time and rhythm perspectives have been limited to analyzing user behavior or optimizing systems (Pelikan and Hofstetter, 2023; Howes et al., 2023). These frameworks have not been further developed, especially in terms of an in-depth understanding of *synergized interactions*, and a fundamental framework has yet to be established.

To this end, we introduce the Framework for Synergized Interactions through Rhythm Adjustment (FSIRA). Unlike existing frameworks focused on adaptive studies in interactive systems, FSIRA emphasizes mutual adaptation between humans and computers. This approach advocates achieving balanced synergy based on the properties, significance and impact of human stewardship (Ren et al., 2019). FSIRA includes (1) definition of *synergized interactions* in Section 3.3, that is, synergized rhythms; (2) rhythm adjustment mechanism in Section 3.4 that integrates the corresponding algorithm to modify the imbalance issues between humans and computers towards *synergized interactions*; (3) general interactive procedures and design principles in Section 3.5 to design rhythm adjustment mechanisms for *synergized interactions*.

The contributions of this paper are twofold: (1) This paper introduces the practical framework, FSIRA, bridging the gap between theory and design of *synergized interactions*. FSIRA presents the definition of states of *synergized interactions*, the protocol of rhythm adjustment mechanisms, and interaction procedures, and five FSIRA-based principles to guide designers in designing technology of *synergized interactions* within domain-based tasks. (2) It advances our understanding of *synergized interactions* at the theoretical and computational levels, offering a lens to guide other conceptual frameworks in the HCI community. Designers can use this framework to conduct an examination of the issues present in existing interactive systems, thus proposing improvement strategies.

3.2 Introduction of FSIRA

We introduce the structure of FSIRA for understanding the main contributions that tackles three key challenges within solutions. It exhibits the capacity for *synergized interactions* based on proportional consideration of rhythms between humans and computers.

Definition: The inherent ambiguity that characterizes the state of *synergized inter-*

actions, bereft of a precise definition and scope (Law et al., 2009; Dimara and Perin, 2019), reveals complexities in the observation and assessment of concrete instances within interactive systems. This inherent ambiguity impedes researchers and designers, leaving them insufficiently guided in bridging the theoretical-practical gap concerning synergized interaction in interactive systems. In Section 3.3, we address this challenge by explicitly defining the state of *synergized interactions*, that is, *synergized rhythms*, to represent the ideal state achievable in a time series inspired by previous studies(Ren et al., 2019; Tan and Ren, 2023).

Protocol: The instability of interaction protocols for *synergized interactions*, stemming from the inherent vagueness of the state, necessitates the establishment of a unified protocol standard. The absence of such a standardized approach often results in poorly developed *synergized interactions*, creating imbalances between humans and computers (Ren et al., 2019). In Section 3.4, we address this challenge by concentrating on the development of rhythm adjustment mechanisms. We define the terminology and basic rules of rhythm adjustment mechanisms. These mechanisms aim to towards *synergized interactions* through the achivement of synergized rhythms between humans and computers. Our proposed adjustment mechanisms operate at the algorithmic level and involve fine-tuning synergized rhythms.

Design: Analogous to challenges faced by other conceptual frameworks, gap between theory and design in the empirical study of *synergized interactions* results in suboptimal efficiency levels. Designers necessitate explicit specifications and frameworks to guide their practices within specific domains (Höök and Löwgren, 2012; Velt et al., 2017). In Section 3.5, we tackle this issue by presenting an interaction procedure and design tailored to assist designers in creating effective interaction mechanisms. This procedure integrates judgment mechanisms and incorporates rhythm adjustments within interactions between humans and computers.

FSIRA presents a theoretical foundation and a practical guide for the realization of *synergized interactions* by rhythm adjustment. FSIRA provides insight into user behavior and interaction by facilitating the optimization of interaction systems. As an approach, FSIRA helps rectify misaligned interaction behaviors over time, providing valuable guidance for the development and application of integrated interactions in interactive systems.

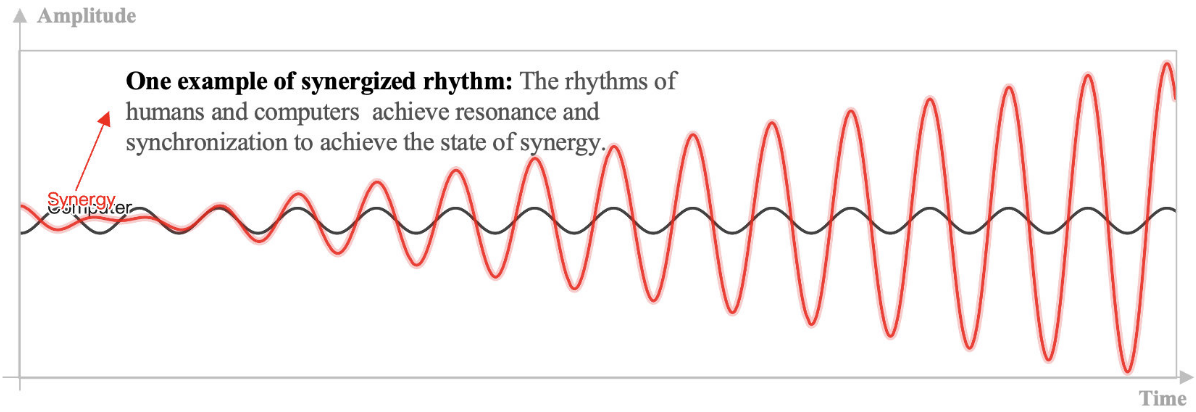


Fig. 3.2: The figure shows an ideal example of synergized rhythms, where human and computer rhythms reach resonance, and at this time the performance of both the human and the computer is maximized. The universal waves are used to visualize the dynamic changes of human and computer rhythms during interactions. The three waves represent the human rhythm, the computer rhythm, and the interaction rhythm respectively. We draw this expression from the symbolization of waves in physics.

3.3 FSIRA (1): Definition

In this section, we first define the state of *synergized interactions* can be achieved by adjusting the interaction rhythms towards synergized rhythms. Second, we present two characteristics of synergized rhythms. Third, we describe two states toward synergized rhythms in interactions.

3.3.1 Definition of Synergized Rhythms

Synergized rhythms refer to the attainment of effective synergy through progressive adjustment of the rhythm in interactions between humans and computers in a time series. It emphasizes the dynamic nature of the interaction process and requires continuous optimization of the rhythm based on historical information/data to achieve current and continuous synergy. As shown in Figure 3.2, an ideal example of synergized rhythms, where human and computer rhythms reach resonance, and at this time the performance of both the human and the computer is maximized. Our goal is to adjust a random state of interaction rhythms to synergized rhythms, so that the rhythm configurations of human and computer continue to be comfortable with each other.

In the state of synergized rhythms, the rhythms of humans and computers can be highly matched and coordinated to form a resonant rhythm system. The realization of synergized rhythms requires that the rhythm patterns of the participants produce synergistic gains with each other, such as using the computing power of computers to improve people's work efficiency. Different from the general interaction concepts, it does not pursue simply achieving the task goal, but uses the rhythm adjustment mechanism to optimize the resource allocation of humans and computers. To achieve a state of synergized rhythms requires a gradual approach through continuous learning and adjustment, and is not the result of overnight success.

The merits of synergized rhythms lie in the rational allocation of human and computing resources to *synergized interactions* (Ren et al., 2019). This allows (1) more complete stimulation and utilization of human and computer abilities for tasks; (2) optimized resource deployment to reduce consumption and waste; (3) higher efficiency yielded from each element's resources; and (4) a steadier interactive state between humans and computers.

3.3.2 Characteristics of Synergized Rhythms

Synergized rhythms cultivate well-balanced, mutually-calibrated human-computer synergy/dynamics. This equilibrium stimulates greater synergy through proportional allocation of attention and harmonized tempos. It exhibits two characteristics that enable *synergized interactions*.

First, a befitting balance of states must be achieved between humans and computers, i.e., proportional attention by adapting to each other's pace and requirements. This state formation considers: (1) Establishing mutual trust and understanding during interaction. (2) Building a mutually beneficial cooperative relationship in which humans leverage computational capabilities and computers gain data for self-improvement. (3) Making interaction tasks driven rather than computer-led, with computers providing selective assistance based on human work pace/needs. (4) Developing models that accommodate individual differences with a configuration based on user types/rhythm sensitivity. Implementation of this state needs consideration of details like measuring following speed-matching degrees, balancing states in different phases, and optimizing individual difference settings.

Second, an appropriate balance of effectiveness must be achieved between the improvement of human abilities and the optimization of task performance. This balance can be achieved from two aspects: (1) Computers should primarily focus on assisting the improvement of human capabilities, such as providing reference cases and suggestions

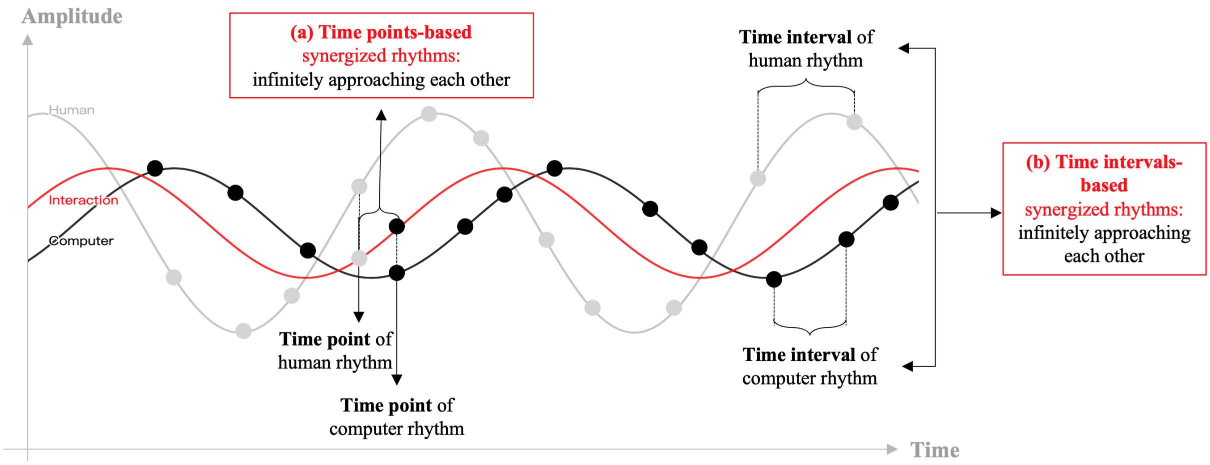


Fig. 3.3: Schematic diagram shows the three waves represent the human rhythm, the computer rhythm, and the interaction rhythm respectively. Among them, the points scattered on each wave represent an action of either humans or computers in the time series. These waves undergo rhythm adjustment toward synergized rhythms. This includes two states: (a) time points-based synergized rhythms, where humans and computers infinitely approach each other at the same time points; (b) time intervals-based synergized rhythms, where humans and computers infinitely approach each other within the same time intervals.

to help humans enhance work quality and efficiency, instead of directly replacing human job components. (2) Computers should also take a comprehensive approach to improve overall task efficiency, such as automatically performing some simple repetitive work through artificial intelligence technologies, screening out key information for humans, etc. However, this should not replace the leading decision-making role of humans.

3.3.3 The States toward Synergized Rhythms

The realization of synergized rhythms in interactions requires a nuanced approach that involves synchronization and adaptation as pivotal states. In this paper, synchronization refers to the alignment of the rhythms of the two interacting parties, and adaptation refers to the mutual adjustment of the rhythms during the interaction. The overarching goal is to align human and computer rhythms, striking a delicate balance that minimizes information loss and maximizes efficiency. The crux lies in adaptive synchronization, where temporal differences in actions are systematically reduced to near-zero values. Synergized rhythms address the intricate dynamics of ahead-of-time and delays in interactions. Two complementary adjustments facilitate this process.

Time points-based synergized rhythms: This process facilitates collaborative syn-

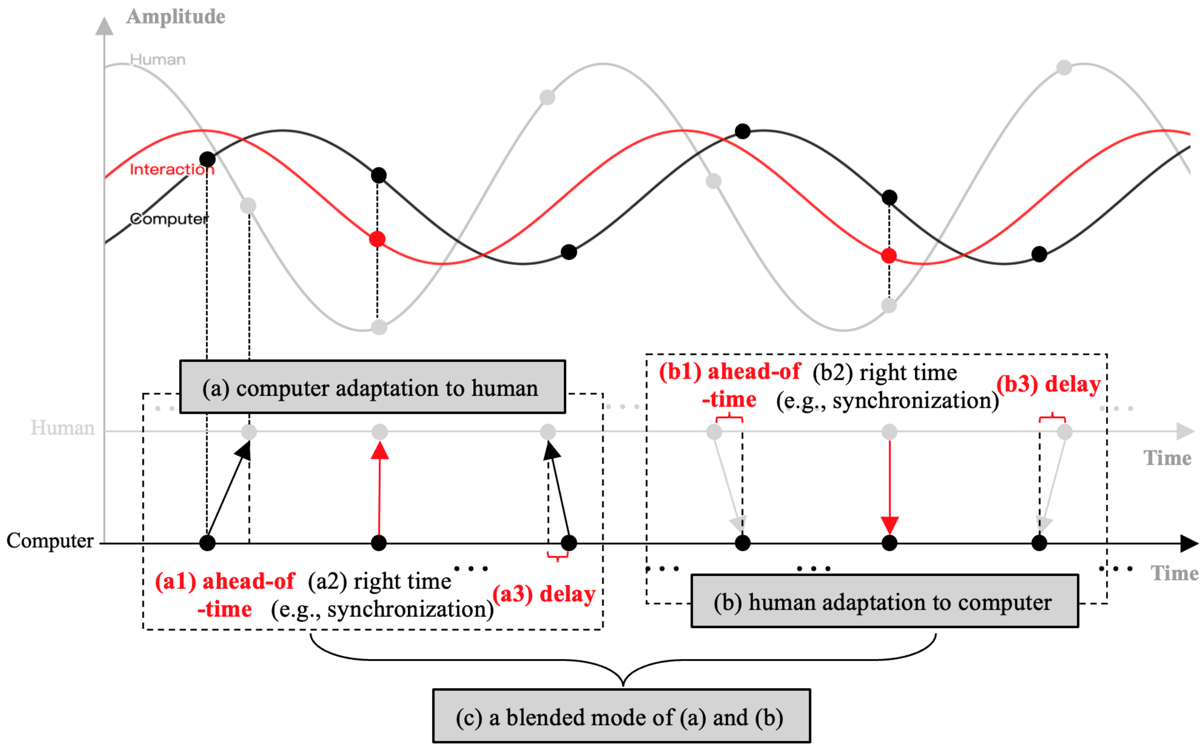


Fig. 3.4: Upper part of the figure shows the three waves represent the human rhythm, the computer rhythm, and the interaction rhythm respectively. The scattered points represent respective actions in the time series. illustrates a mapping relationship between scattered points in this region and the points in the upper section. In this context, the scattered points representing the temporal sequence of interactions between humans and computers are connected by one-way arrows, revealing three distinct interaction modes: (a) computer adaptation to human, (b) human adaptation to computer, or a blended mode of both (a) and (b). When interactions occur, three situations of the time of actions between humans and computers exist: *ahead-of-time* - (a1) and (b1), *right time* - (a2) and (b2), and *delay* - (a3) and (b3). *Ahead-of-time* and *delay* are the difference in the duration of time between human actions and computer actions. *Right time* is an ideal state or duration in interactions.

chronization between human and computer rhythms by implementing precise adjustments at specific time points (Figure 3.3a). For example, in a collaborative music composition system, the user plays an instrument while the computer generates accompanying music (Turchet and Barthet, 2019; Suh et al., 2021). The user's rhythm is analyzed by the computer, which identifies crucial synchronization points. If the user's rhythm aligns perfectly, the computer generates seamless accompanying music. However, if the user's rhythm deviates slightly, the computer provides real-time feedback for adjustment. The user and the computer fine-tune their rhythms, achieving synchronization at critical points. By aligning their rhythms at these strategic junctures, both the human and computer can achieve a harmonized and efficient interaction.

Time intervals-based synergized rhythms: This process investigates adaptive synchronization by focusing on adjusting and aligning time intervals within a time series of human and computer rhythms (Figure 3.3b). For example, in a collaborative dance performance system, a human dancer performs intricate movements while a computer generates visual effects based on their movement (Evola and Skubisz, 2019; Raheb et al., 2019). The computer analyzes the time intervals between each movement to establish the desired synchronization intervals. If the dancer's intervals match, visual effects are seamlessly generated. If there are deviations, the computer provides real-time feedback for adjustments. Through this process, the dancer and the computer gradually synchronize their rhythms, creating a coordinated and harmonized performance. By addressing temporal misalignments, this mechanism offers a comprehensive solution to enhance overall synchronicity and achieve a harmonized collaborative rhythm between humans and machines.

In essence, achieving synergized rhythms is a sophisticated dance between humans and computers, orchestrated through meticulous synchronization and adaptive adjustments. This process transcends mere temporal alignment; it is a strategic alignment that minimizes friction, reduces information loss, and propels human-computer collaboration to unprecedented depths of efficiency. The proposed rhythm adjustment methods, with their dual focus on time points and time intervals, emerge as a critical step toward realizing the full potential of *synergized interactions*.

3.4 FSIRA (2): Protocol

Rhythm adjustment underlies coordinated human interactions, which involve mutual adaptation through dynamic perception and feedback over time. To achieve synergized rhythms, we propose a protocol for rhythm adjustment mechanisms that aims to avoiding issues like "ahead-of-time" (a1 and b1 in Figure 3.4) or "delay" (a3 and b3 in Figure 3.4), which can affect efficiency and user experience in a time series (Ghomi et al., 2012; Lamport, 2019; Costello, 2020b; Rapp et al., 2022). The goal of this protocol is to explore the possibilities of rhythm adjustment within three interaction modes (see Figure 3.4a, b, and c) to ultimately address interactions issues to achieve *synergized interactions* through synergized rhythms, such as temporal synchronization ("right time", a2 and b2 in Figure 3.4) between a human and a computer. To this end, we first define

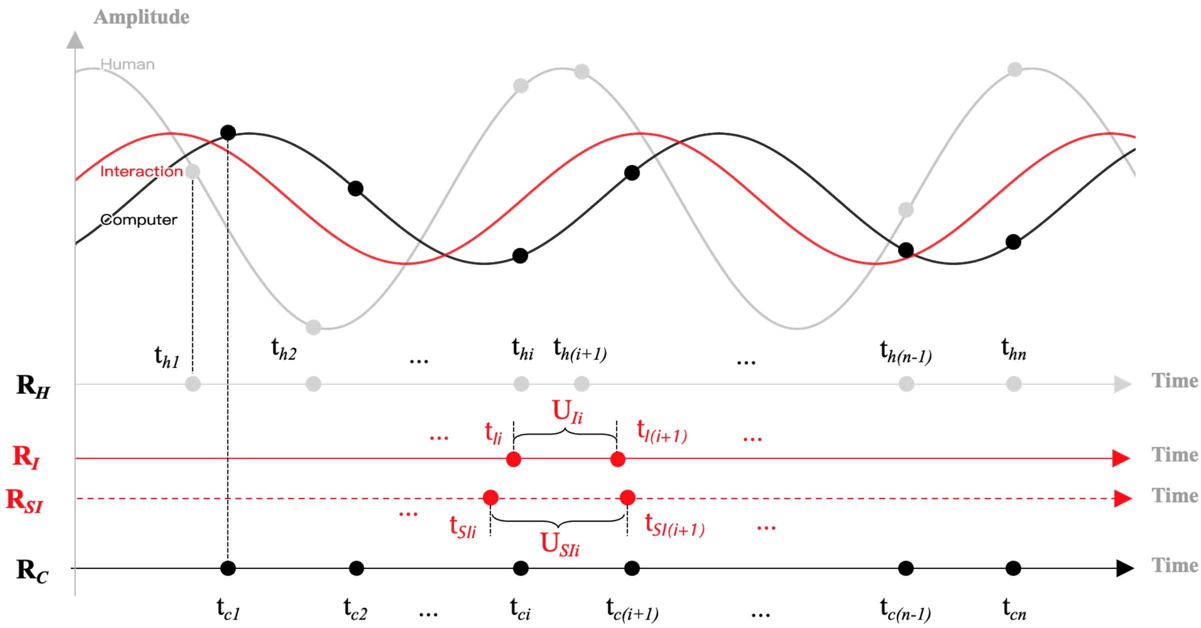


Fig. 3.5: The figure illustrates the dynamic relationship between human and computer interactions and maps their respective actions on a timeline. The four horizontal lines below depict the interaction rhythms R_I towards synergized rhythms R_{SI} (dashed line) between human rhythms R_H and computer rhythms R_C. Here, R_{SI} represents the ideal state of R_I after rhythmic adjustment. The horizontal arrows represent a time series, the vertical dotted lines represent the adaptation of R_I between R_H and R_C, and the dots represent the time of human or computer actions in a time series. The two-way dotted arrow indicates a rhythm unit U, where the interaction rhythm unit and the synergized rhythm unit at the i-th point are U_{Ii} and U_{SIi} respectively. These units refer to the time interval between two consecutive time points of human or computer actions.

the terminology and basic rules of this protocol. Second, we present three rhythm adjustment mechanisms from synchronization to adaptive synchronization between human rhythms and computer rhythms in interactions.

3.4.1 Definition of Terminology and Basic Rules

We define these concepts and rules for the temporal and rhythmic adjustment with the purpose of quantitatively describing and measuring the degree of rhythm adjustment in HCI. By tracking the errors of time points and time intervals, we can evaluate whether the system is able to respond to human actions in a timely manner and realize a smooth interactive experience. By defining terminology such as *Rhythms*, *Rhythms units*, *Deviation* and *Basic rules*, we have established a framework for quantitatively analyzing the degree of rhythmic synchronization in human-computer interaction (Figure 3.5).

This provides a metrological foundation for subsequent studies on the mechanisms of adjusting rhythms in HCI.

Rhythms. We use *rhythm R* as the rhythm of human actions and computer actions. Human rhythms R_H are a series of time points of human actions. As shown in Figure 3.5, computer rhythms R_C are a series of time points of computer actions. Interaction rhythms R_I are jointly formed by the actions of both parties and are represented as the integration of time points of their actions. R_{SI} represents the ideal state of R_I after rhythmic adjustment. This needs to be initiated by humans or computers, specifically, by human adaptation to the computer, or by computer adaptation to computer.

Rhythm units. We assume that R is composed of a series of rhythm units, where a *rhythm unit* U is a time interval between two consecutive time points of human actions or computer actions. We use R_{SI} as synergized rhythms and U_{SI} as the rhythm unit of *synergized interactions.* If the interaction rhythms approach synergized rhythms, this means that the rhythms of both humans and computers in interactions of time points-based and time intervals-based synergized rhythms match.

Deviation ranges. We use ω ($0 < \omega \leq 1$) to represent the allowable deviation range for synergized rhythms based on time intervals between U_{SI} and U_I. As shown in Figure 3.5, the i-th time interval of both U_{SIi} and U_{Ii} should meet the following conditions to achieve synergized rhythms: $|U_{SIi} - U_{Ii}| \leq \omega$. Furthermore, we use ε ($0 < \varepsilon \leq 1$) to represent the allowable deviation range for synergized rhythms based on time points between t_{SI} and t_I. The i-th time point of both t_{SIi} and t_{Ii} should meet the following conditions to achieve synergized rhythms: $|t_{SIi} - t_{Ii}| \leq \varepsilon$. Additionally, we recommend setting ω to 0.1 seconds, which means that the maximum error between the time intervals of U_{SI} and U_{SI} can reach 0.1 seconds. ε is set to 0.05 seconds, which means that the error of the time points is controlled within 50 milliseconds. These settings can meet the smooth requirements of human-computer interaction.

Basic rules. The adjustment mechanisms operate based on the following temporal rules, illustrated using the example of the i-th time point (Figure 3.5): (1) There is a direct mapping between computer time points (t_{ci}) and human time points (t_{hi}) for every i. (2) The occurrence of t_{hi} is detected by tci at any given i. In other words, the system recognizes and identifies time points of the human action or events based on corresponding time points in the computer's timeline. (3) At $t_{c(i+1)}$, the system provides feedback for t_{hi} and adjusts itself by incorporating previous information. This adjustment aims to improve the alignment between computer actions and subsequent human action $t_{h(i+1)}$. By contrast, at $t_{h(i+1)}$, the same logic as before.

3.4.2 Adjustment Mechanisms

Our aim, in response to existing generic interaction modes (Figure 3.1a), is to achieve synergized interaction through the design of a new rhythm adjustment mechanism. This mechanism consists of two stages: *synchronization* and *adaptive synchronization*, which are performed through three adjustment mechanisms. The former stage focuses on achieving time points-based synergized rhythms, while the latter aims to establish time intervals-based synergized rhythms.

Each adjustment mechanism operates in a loop, providing adaptive feedback and self-regulation for subsequent action points when the rhythm between humans and computers deviates from the desired synchronization. This iterative process ensures that the interactions between humans and computers remain in harmony, continuously adapting to each other's rhythms for optimal collaboration.

To facilitate understanding, some special symbols need to be denoted in advance. As shown in Figure 3.6, the rhythm unit of interaction U_I is the time interval between the actions of the corresponding output of the computer and the input of the human (or the output of the human) and the corresponding input of the computer. We use *2i* and *2i-1* to represent the time points of human and computer actions in the arrangement and combinations of odd and even columns, respectively. Thus, the i-th rhythm unit of interaction is $U_{I(2i)} = \left|t_{hi} - t_{c(i+1)}\right|$ or $U_{I(2i-1)} = |t_{hi} - t_{ci}|$.

The three appendices represent three rhythm adjustment mechanisms in Section 3.4.2 respectively. Before reading the algorithm below, readers need to understand some basic rules and definitions of concepts. The initial loop counter is set as i equal to 1. "$'$" represents the time after acceleration adjustment, and '$''$" represents the time after acceleration adjustment. The notation Δ_{ta} represents the range of acceleration of time, while Δ_{td} represents the range of deceleration of time. Similarly, Δ_{ra} denotes the range of rhythm acceleration and Δ_{rd} denotes the range of rhythm deceleration. The i-th rhythm unit of the human is $U_{Hi} = t_{h(i+1)} - t_{hi}$, and the i-th rhythm unit of the computer is $U_{Ci} = t_{c(i+1)} - t_{ci}$.

Stage 1: synchronization. During the synchronization stage, our primary objective is to address the interaction challenges associated with the computer's adaptation to humans and vice versa. This stage involves the implementation of two adjustment

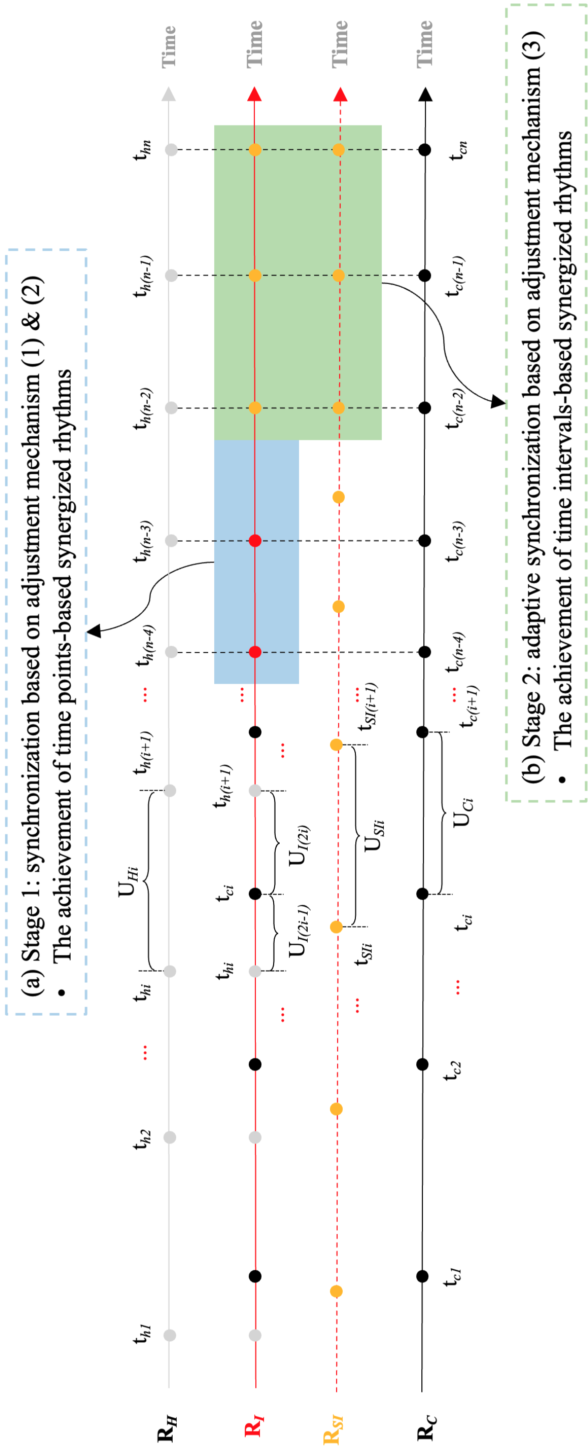


Fig. 3.6: Schematic diagram shows the adjustment of interaction rhythms R_I toward synergized rhythms R_{SI} between human rhythms R_H and computer rhythms R_C rhythm adjustment mechanisms in a time series. The rhythm adjustment process includes two stages: (a) - Stage 1 means the achievement of time points-based synergized rhythms (blue area) where synchronization can be achieved between R_H and R_C by integrating adjustment mechanism (1) and (2). (b) - Stage 2 means the achievement of time intervals-based synergized rhythms (green area) where adaptive synchronization can be achieved between R_I and R_{SI} using the operating adjustment mechanism (3).

mechanisms: adjustment mechanism (1) and (2) (Figure 3.6a). The goal is to achieve *synergized interactions* by aligning the rhythms of the involved parties at specific time points.

Adjustment mechanism (1). In this mechanism, we focus on the computer's adaptation to human behavior. First, we set R_{SI} to be equal to R_H, indicating that the computer rhythm should align with the human rhythm. This establishes a foundation for *synergized interactions.* R_C, representing the computer's rhythm, is always accompanied by R_H, providing adaptive feedback based on human conditions. Furthermore, we adjust the user interface U_I within R_I, with the aim of minimizing $U_{I(2i-1)}$ and making $U_{I(2i)}$ approach U_{Hi}, which represents the desired state of the user interface for the computer. The ultimate goal of this adjustment mechanism is to make R_C equal to R_H and ensure that R_{SI} includes both R_C and R_H. A detailed description of this mechanism can be expressed as algorithm 1.

Algorithm 1 for adjustment mechanism (1)

while $|t_{ci} - t_{hi}| > \varepsilon$ **do**
  if $t_{ci} - t_{hi} > \varepsilon$ **then**
    $t_{c(i+1)'} = t_{c(i+1)} - \Delta_{ta}$, where Δ_{ta} ¡ $|t_{ci} - t_{hi}|$
  else
    $t_{c(i+1)''} = t_{c(i+1)} + \Delta_{td}$, where Δ_{td} ¡ $|t_{hi} - t_{ci}|$
  end if
end while

Adjustment mechanism (2). In this mechanism, we focus on humans adapting to the mode of operation of the computer. We set R_{SI} equal to R_C, indicating that the human rhythm should align with the computer rhythm. R_H is always accompanied by R_C, allowing the computer to regulate the rhythm based on adaptive feedback. Similarly to the adjustment mechanism (1), we adjust U_I within R_I, with the aim of minimizing $U_{I(2i-1)}$ and make $U_{I(2i)}$ approach U_{Ci}, which represents the ideal state of the user interface for the computer. The goal of this adjustment mechanism is to make R_H equal to R_C and ensure that R_{SI} encompasses both R_C and R_H. A comprehensive explanation of this mechanism can be expressed as algorithm 2.

Stage 2: adaptive synchronization. The adaptive synchronization stage addresses the challenges that arise in the blended mode of interaction, where neither party's rhythm serves as the standard for establishing *synergized interactions.* In this context,

Algorithm 2 for adjustment mechanism (2)

while $|t_{hi} - t_{ci}| > \varepsilon$ **do**
  if $t_{hi} - t_{ci} > \varepsilon$ **then**
    $t_{h(i+1)'} = t_{h(i+1)} - \Delta_{ta}$, where Δ_{ta} ¡ $|t_{hi} - t_{ci}|$
  else
    $t_{h(i+1)''} = t_{h(i+1)} + \Delta_{td}$, where Δ_{td} ¡ $|t_{ci} - t_{hi}|$
  end if
end while

we introduce the concept of a separate standard, referred to as the synergized rhythm (R_{SI}). The goal is for both parties to approach this initial conceptualized standard, which involves two steps.

Adjustment mechanism (3). First, in the first step of adjustment, both parties strive to achieve a synergized rhythm at the specified time points (Figure 3.6a). This involves matching the time point between t_{ci} (computer rhythm) and t_{hi} (human rhythm), with the objective of making $U_{I(2i-1)}$ approach 0. This adjustment aims to synchronize the actions of both parties at specific time points. Second, in the second step of adjustment (Figure 3.6b), either or both parties are dynamically fine-tuned at the level of rhythm units to match the rhythm intervals of $U_{I(2i)}$ (the state of computer rhythms) and U_{SIi} (the state of synergized rhythm). The goal here is to make $U_{I(2i-1)}$ approach 0, $U_{I(2i)}$ approach U_{SIi}, and align the time intervals t_{hi} and t_{ci} with t_{SIi}. This adjustment mechanism operates in two steps, as described in detail and can be expressed as algorithm 3. To initiate the adaptive synchronization stage, the system first executes either adjustment mechanism (1) or (2) until R_H and R_C achieve synergized rhythms at the specified time points. Once this initial synchronization is achieved, the system is transferred to the second stage of adjustment.

3.5 FSIRA (3): Procedure and Design

Based on the findings presented in Sections 3.3 and 3.4, we first present the interaction procedures of the rhythm adjustment mechanisms to *synergized interactions.* Second, we present five principles for the design of rhythm adjustment. These investigations aim to provide guidance for designers in developing promising synergized interaction technologies.

Algorithm 3 for adjustment mechanism (3)

while $|\mathrm{U}_{I(2i-1)} - \mathrm{U}_{SIi}| > \omega$ **do**
  if $\mathrm{U}_{I(2i-1)} - \mathrm{U}_{SIi} > \omega$ **then**
    $\mathrm{U}_{I(2i)'} = \mathrm{U}_{I(2i)} - \Delta_{ra}$, where Δ_{ra} ¡ $|\mathrm{U}_{I(2i-1)} - \mathrm{U}_{SIi}|$
  else
    $\mathrm{U}_{I(2i)''} = \mathrm{U}_{I(2i)} + \Delta_{rd}$, where Δ_{rd} ¡ $|\mathrm{U}_{SIi} - \mathrm{U}_{I(2i-1)}|$
  end if
end while

3.5.1 Procedure of Rhythm Adjustment

This subsection shows a general interaction procedure (Figure 3.7) that can be adjusted to the rhythm toward *synergized interactions.* Interaction procedures involve a specific trajectory and method. The goal of this procedure is to achieve synergized rhythms at the time points and time intervals between human rhythms and computer rhythms.

As shown in Figure 3.7, the implementation of the rhythm adjustment procedure involves two loops. The first loop aims to detect whether the human rhythm falls within the appropriate time-point range. If it does not, the computer provides feedback t1, prompting the user to make the corresponding regulation (t1). Subsequently, the system continues to assess whether the human rhythm falls within the appropriate time-point range. If it does, the process proceeds to the second loop, which aims to detect whether the user's rhythm falls within the right time interval range. If it does not, the computer provides feedback U2, prompting the user to make corresponding regulation (U2). The system continues this assessment process until the user's rhythm falls within the desired range, at which point both the user and the computer maintain their respective states and continue operation. Throughout this process, the computer continuously monitors the state of the user.

In addition, the design of interaction procedures includes three parts. First, the procedure of *detection-judgment* involves the detection and judgment of human rhythms by the computer. The basis for judgment is whether the human rhythm is *right time points* in a time series. Second, the procedure of *feedback-judgment* occurs when the judgment indicates the right time. In this case, synergized rhythms are achieved between human rhythms and computer rhythms; then, their current rhythms are maintained in a time series. If the judgment indicates *ahead-of-time* or *delay*, adaptive feedback is provided

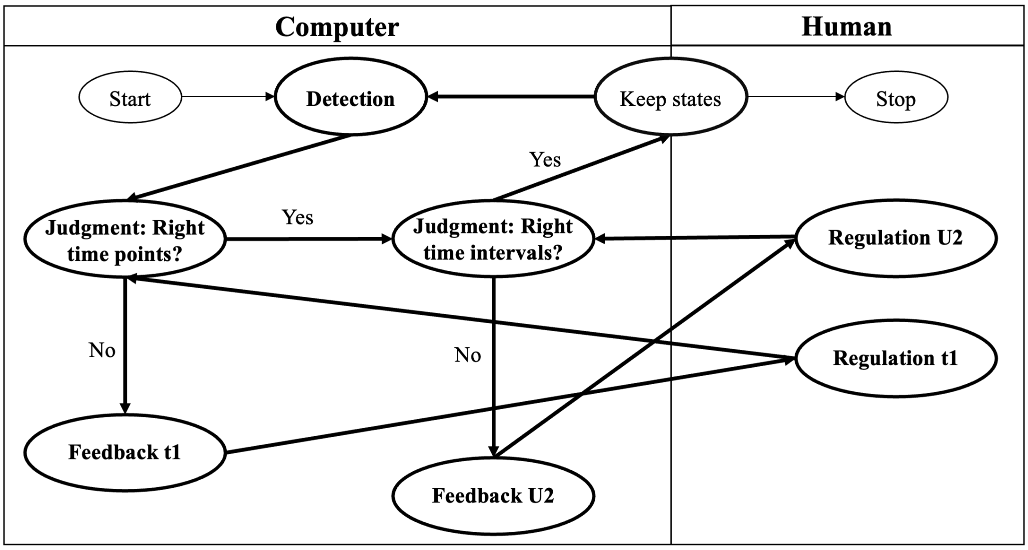


Fig. 3.7: The figure shows the interaction procedures of rhythm adjustment mechanisms toward *synergized interactions*.

by computer, followed by human judgment based on the computer feedback. Third, the procedure of *regulation-detection* refers to the iterative process of continuous detection and feedback, which allows human rhythms and computer rhythms to gradually adapt to each other. At this stage, both humans and computers detect each other's rhythms in real time. If they detect that they are still within the *right time intervals* range, they maintain their respective rhythms. However, if they detect that they have deviated from the right time range, they re-execute the entire loop to detect, judge, feedback, and regulate rhythms in interactions.

3.5.2 Design of Rhythm Adjustment

Based on the rhythm adjustment procedure, we present five principles by integrating rhythm in the design of the interaction mechanism. These principles demonstrate that designers observe, realize and measure *synergized interactions* between humans and computers at the computational level. These principles consist of two components: (1) From the perspective of interaction mechanisms, they encompass the design of rhythm-based detection, feedback, and regulation (Figure 3.8a1, a2, and a3). (2) From the standpoint of interaction procedures, they involve detection for computer-based judgment and feedback for human-based judgment (Figure 3.8b1 and b2). Next, we discuss these principles separately.

Rhythm-based detection (Figure 3.8a1) represents an approach that emphasizes ac-

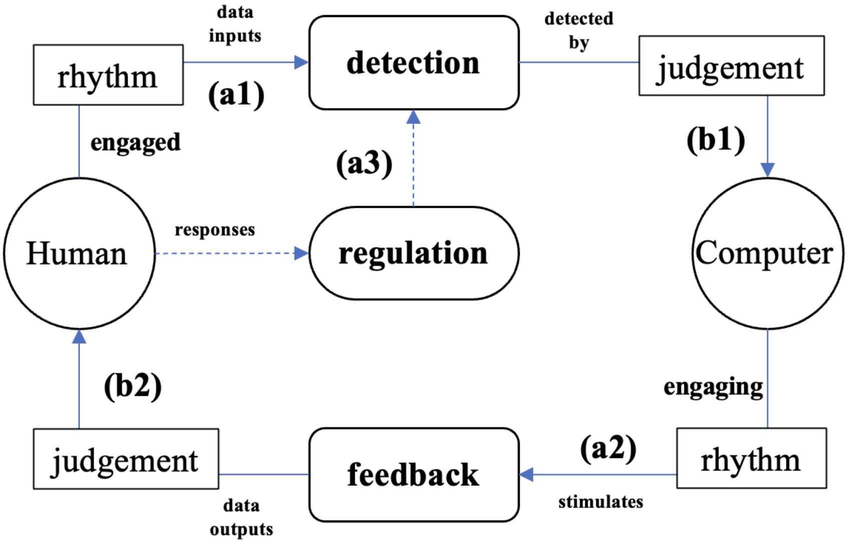


Fig. 3.8: The image depicts five principles by integrating rhythm in the design of interaction mechanism. It encompass the design of (a1) rhythm-based detection, (a2) rhythm-based feedback, (a3) rhythm-based regulation, (b1) detection for computer-based judgment, and (b2) feedback for human-based judgment.

curate measurement of time and rhythm, which aims to improve precision and stability in data detection by considering time points and time intervals during the detection process. Time points-based detection focuses on capturing and recording events or behaviors at specific time points. Time intervals-based detection focuses on time intervals between events or behaviors. Based on this principle, we can obtain timestamps for key events, thereby gaining insight into the precise moments of event occurrence.

Rhythm-based feedback (Figure 3.8a2) includes the perspective of time points and time intervals, and the feedback design can be optimized to enhance its effectiveness. Time points-based feedback delivers feedback at specific moments, aligning with user actions or system events, enhancing the user experience in task completion, error detection, and decision-making (Caldwell et al., 2022; Robinson et al., 2023). On the other hand, time intervals-based feedback provides continuous feedback, emphasizing the management of rhythm and pace for a smooth user experience. This principle can be further optimized through feedback consistency, gradual progression, and adaptive timing. Designers can create a comprehensive feedback system that delivers timely, accurate, and contextually relevant information.

Rhythm-based regulation (Figure 3.8a3) involves controlling the timing of interventions and the intervals between them in order to optimize their effectiveness and facilitate self-regulation and adaptation. Time points-based regulation triggers interventions or feedback, where designers can provide timely assistance, reducing cognitive load, and improving task performance by carefully selecting and timing these interventions. Time interval-based regulation means that designers must find the right balance between providing support and allowing individuals to self-regulate and perform tasks independently.

Detection of computer judgement (Figure 3.8b1) involves three dimensions in a time series: right time, ahead-of-time, and delay. *Right time judgment* means making accurate decisions at the appropriate moment by identifying and analyzing relevant data points corresponding to human actions or events. Timely feedback can be provided on the basis of the correct time. *Ahead-of-time judgment* involves the computer's ability to anticipate and make judgments ahead of events or actions by detecting patterns or trends in time-series data. This proactive decision making allows for timely interventions. *Delay judgment* refers to the ability of the computer to detect and respond to past events by analyzing historical data and identifying relevant patterns or correlations. This helps in retrospective analysis, trend identification, and information on past events.

Feedback for human judgment (Figure 3.8b2) includes three temporal aspects to consider: the right time, ahead-of-time, and delay in the judgement made of the human. *Right time feedback* means that timely provision of feedback is essential for conscious judgments. Syncing of the feedback with user actions based on time and rhythm significantly improves their understanding and interpretation of the feedback. *Ahead-of-time feedback* is beneficial for unconscious judgments, where users can take action more easily without conscious intervention by providing feedback slightly in advance. By contrast, *delay feedback* can be detrimental to the judgment process. Delay feedback may interfere with user understanding and hinder accurate interpretation of the information. To ensure timely and effective judgments, it is crucial to minimize significant delays in feedback.

3.6 Discussion

In this section, we first discuss how FSIRA differs from current interaction frameworks. Second, we discuss the implications of FSIRA for methodology, design, and practice. Third, we discuss the limitations of this study and outline possibilities for future work.

3.6.1 FSIRA vs. Current Interaction Framework

First, FSIRA focuses on the realization of two-way adaptation in interactions. Current interaction frameworks focus on enabling one party to adapt and understand the other. This may ignore the active participation and influence of the user on the system, leading to a mechanical equilibrium state of one-way interaction and restricting true cooperation and win-win (Lin et al., 2017; Pelikan and Hofstetter, 2023). FSIRA takes the interaction between both parties into consideration, emphasizing not only the transmission and reception of information, but also the process of mutual understanding and co-creation. The goal is to ensure that the interests of both parties are not compromised in the task but that higher-level goals are achieved through collaboration.

Second, FSIRA focuses on states' changes and dynamic adjustments during interactions. The current interaction framework pays more attention to the macrointeraction vision, such as collaboration and integration, but often ignores the microstage state changes in the interaction process (Farooq and Grudin, 2016; Inga et al., 2023). FSIRA proposes the state adjustment of synergized rhythms by paying attention to the unstable state in interaction, so that both parties can more flexibly adapt to changes in interaction instead of being fixed in a static state of cooperation. FSIRA provides a more detailed observation and analysis perspective, helping to identify potential problems and optimization points.

Third, FSIRA focuses on the practical operations and computing methods of interactive adjustment. The current interaction framework is too theoretical and difficult to apply directly in actual design and development and lacks an operation manual to provide designers with specific guidance (Reeves and Beck, 2019; Beaudouin-Lafon et al., 2021). FSIRA introduces a dynamic scaling method to provide more specific and actionable guidance for handling changes and adjustments in interactions. Unlike previous frameworks that focused on mechanical interactions, FSIRA involves dynamic adjustment to allow designers to more flexibly adapt to changes in user needs, thereby improving the practicality and adaptability of the system.

3.6.2 Implications of FSIRA

Implications for methodology. FSIRA establishes a standardized framework for data detection and feedback. By introducing the concepts of rhythm, rhythm adjustment, and synergized rhythm, researchers can more precisely capture and analyze participants' interaction patterns during data interactions. In addition, the adoption of unified standards facilitates a more holistic examination of experimental data, allowing researchers to gain a deeper understanding of participants' interactive behaviors across various scenarios. This facilitates the exploration of potential patterns and relationships within the data. Furthermore, FSIRA supports the establishment of assessment standards for evaluating the quality and effectiveness of interactive systems. This advancement aligns participants more closely with real-world application scenarios and providing more targeted feedback and improvement suggestions for interaction design.

Implications for design. FSIRA provides a rhythm analysis perspective (Lefebvre, 2013) that provides new design implications for future interactive systems in detection, feedback, and regulation.

Implications for detection design. The adoption of rhythm analysis as a perspective for detection design allows designers to observe dynamic interaction patterns between users and systems. This approach empowers designers to deep users' intentions and needs, furnish more precise feedback for the design process, and ensure congruence between design outcomes and user expectations. Moreover, designers can discern shifts in user behavior and flexibly modify the system's response speed and mode to align with the diverse interaction preferences of users (Tan and Ren, 2023). This adaptability provides designers with a mechanism to fine-tune the system. By understanding interaction rhythms, designers can more precisely target users' data, enabling the system to closely align with users' needs and perform optimally across varied usage scenarios. Additionally, the detection of interaction rhythms aids designers in identifying potential interaction issues and areas for optimization. Timely detection of these issues enable designers to foster continuous improvement in the system, ensuring it aligns more closely with the user's desired interaction state. This incremental optimization process contributes to building a stronger bond between users and the system, enhancing system usability and user satisfaction.

Implications for feedback design. The utilization of proportional feedback adjustment provides designers with a flexible framework in design. Through this approach, designers can dynamically consider the design requirements of the feedback mechanism, allowing them to adjust the feedback mechanism according to user needs and specific situations. Proportional adjustment can be applied not only across different user groups but also in diverse environmental conditions, thereby enhancing the adaptability of feedback mechanism (Ren et al., 2019). Designers can precisely adjust the sensitivity and mode of the feedback mechanism based on the perspective of rhythm analysis, ensuring consistent and effective feedback in various interaction situations.

Implications for regulation design. Focusing on the unstable states in the interaction process is pivotal in regulation design. This underscores the substantial implications that interactive parties have in identifying and resolving unstable states. Through in-depth analysis of instability, designers can comprehend the uncertainties and constraints users may face during interactions. This flexibility enables designers to adjust the system, enhancing its adaptability to changes and ensuring better alignment with dynamic user needs. Furthermore, rhythm adjustment mechanism have became a key facilitator of intelligent system adjustment, fostering seamless cooperation between the system and the user. This intelligent adjustment mechanism allows the system to detect and feedback to changes more sensitively, effectively preventing the occurrence of unstable states.

Implications for practice. The practical distinction from traditional conceptual interaction frameworks is that FSIRA provides a potential rhythm adjustment mechanism. This mechanism presents clear practical guidance for the development of new interactive systems. Designers are expected to achieve breakthroughs in innovation by re-examining existing systems in specific application areas (e.g., designing a training system for Parkinson's disease) and introducing rhythm adjustment mechanisms. In addition, the application of FSIRA is not only a breakthrough at the theoretical level, but also directly guides users in their daily tasks. Of particular interest is the fact that the application of FSIRA shows significant advantages when considering user limitation (e.g., delay of input due to distraction, (Pelikan and Hofstetter, 2023)) in the training task. Furthermore, moving toward a vision of *synergized interactions* can stimulate participants' motivation, experience, and performance through a staged synergized rhythms approach in interaction. During the system iteration process, designers can explore new design concepts and technical practices, and even open up new industry directions, such as developing synergized interaction technologies in different domains.

3.6.3 Limitations and Future Work

Although FSIRA primarily focuses on single-user and single-computer contexts, the reliability validation of this framework is based on reflective analysis of existing case studies. Future research could expand the framework to include multiuser and multicomputer interactions and conduct empirical studies to enhance its reliability and practicality. Furthermore, *synergized interactions* is a high-level concept and vision in the field of HCI/Human-Engaged Computing (HEC). This study has explored an approach to realize *synergized interactions* through time and rhythm. However, there are other potential methods, such as the integration of AI and agent technology, that can further implement the concept of *synergized interactions*.

In addition, rhythm has numerous advantages as a unified standard in interaction. However, to ensure its universality, detailed validation across diverse domains and scenarios is imperative. This may involve considering various demographics of users, task types, and environmental conditions. Although rhythm adjustment mechanisms contribute to adaptive synchronization in HCI, calibration issues persist in the state of *synergized interactions*. For instance, under conditions of entry and fade-out, there may be a need for more precise definition and calibration of human characteristics and system responses. This would contribute to ensuring the consistency and predictability of interactions in diverse contexts. Furthermore, a comprehensive evaluation method is necessary to quantify the regulatory effects of the interaction rhythm. This process may involve the formulation of specific metrics and measurement tools.

3.7 Conclusion

The concept of *synergized interactions* offers the powerful potential to guide researchers and designers to explore a holistic goal and vision to integrate human and computer capabilities. To bridge concept and design, this study first proposes a Framework for Synergized Interactions through Rhythm Adjustment (FSIRA). By establishing FSIRA, this research takes a crucial step toward maximizing the potential of *synergized interactions* in the field of HCI/HEC.

This framework provides a definition of the state itself, the adjustment mechanisms and procedures, and the rhythm adjustment design strategy. Our focus is on presenting the design strategy and the design implications for *synergized interactions*. In fact, a few studies, particularly in specific domains, such as meditation tools, have demonstrated promising indications of the use of synergized interaction mechanisms, although not in a complete *synergized interactions* form, and have confirmed their effectiveness (Niksirat et al., 2017, 2019).

FSIRA serves as a bridge between theory and the design of *synergized interactions*. It demonstrates the importance of adjusting time and rhythm in interactions where *synergized interactions* may be achieved, observed, and measured by synergized rhythm based on time points and time intervals. This framework-based design approach highlights the value of empirical methods. FSIRA offers computational guidelines for designing interactive systems and enables the derivation of general design strategies applicable to diverse domains and environments.

Furthermore, this study contributes valuable knowledge about frameworks, algorithms, and design to the relevant community. In addition, at the application level, this work provides a compelling vision and practical guidelines for interactive tasks, such as rehabilitation training for Parkinson's disease or human-robot collaboration in surgery (Su et al., 2019), leading to direct implications for design considerations in these specific areas. The insights and findings of this study have implications for future industries, providing valuable directions for the development and advancement of interactive technologies in various sectors.

Part II

Empirical Studies

Chapter 4

Study 1：Enhancing Walking Creativity

This chapter introduces a study that investigates one-way adaptation in interactions between humans and computers. The study aims to explore the effects of rhythmic footstep and sound interactions on creativity. It includes two parts: (1) developing a system of footstep and sound interactions to combine three modes of one-way adaptation; (2) conducting a user study to evaluate the effects of three modes on creativity while walking.

This study serves as a micro-level exploration of our theoretical framework (i.e., FSIRA). It validates the limitations of one-way adaptation in interactions and highlights the potential of two-way adaptation in achieving *synergized interactions* between users and devices.

4.1 Introduction

Walking creativity generally refers to the practice of engaging in a creative process or generating innovative ideas while walking (Oppezzo and Schwartz, 2014). Innovators (e.g. *Steve Jobs* and *Murakami Haruki*) have mentioned that walking can stimulate their creativity integrated with attention focus and rhythmic footsteps (see Figure 4.1a and Section 4.2.1) (Jabr, 2014). A growing body of studies has begun to focus on the benefits of walking on physical and mental health (Chen et al., 2015; Rabbi et al., 2011), cognitive function (Ruddle et al., 2011), creativity (Overall, 2015), and emotion (Perrinet et al., 2013; Sturm et al., 2022). With the development of mobile technologies, walking listening to sounds has become a daily practice. Some studies suggest that sounds such as pleasant music (Murata et al., 2017), fast-paced music (Otsubo et al., 2020), ambient music (Cochrane et al., 2021), and white noise (Fukumoto and Ichikawa, 2022), can help walkers concentrate and relax to inspire their creative thinking (see

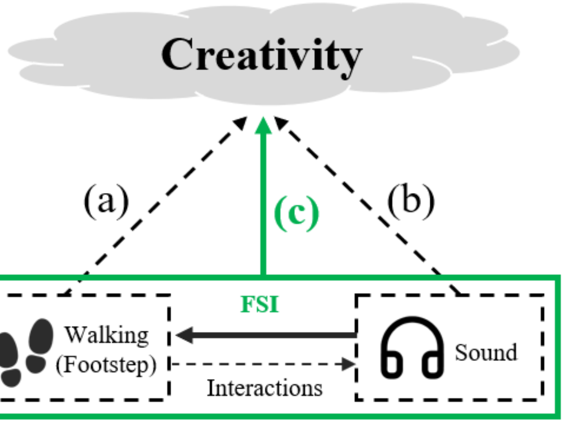


Fig. 4.1: The diagram depicts previous studies of either (a) walking (footstep) or (b) sound can stimulate creativity; and the purpose of this study (c) aims to investigate the effects of Footstep Sound Interactions (FSI) on creativity.

Figure 4.1b and Section 4.2.2) (Zhou et al., 2020; Cloutier et al., 2020). Although previous studies have investigated either walking or sounds can stimulate creativity, little study has explored the effects of *Footstep Sound Interactions* (FSI) on creativity (see Figure 4.1c and Section 4.2.3).

Creativity is an ability that involves generating ideas or concepts and finding innovative solutions to problems in our daily life (Sternberg, 2005). In HCI, creativity research has been explored for more than 20 years, with a significant body of literature focused on creativity support tools aimed at improving human creativity in specific tasks (Shneiderman, 2008; Frich et al., 2018, 2019; Chung et al., 2021). However, there is a scarcity of research on technology's role in enhancing walking creativity, especially in comparing the effects of different modes of FSI on creativity during walking. Furthermore, the assessment of creativity during walking involves the evaluation of divergent thinking (Oppezzo and Schwartz, 2014; Zabelina, 2018). An unexplored area of research pertains to the enhancement of sustained creativity through FSI supported by technology when users are engaged in walking scenarios.

Moreover, environmental factors significantly impact creativity performance while walking. Studies have indicated that outdoor environments can disrupt attention, potentially hindering cognitive function during walking activities (Legrand et al., 2022). Additionally, control of flexible attention is vital to maintain focus during creative tasks and promote divergent thinking. However, excessive focus or distraction can hinder its development (Zabelina, 2018). This intricate relationship between attention and creativity is influenced by sensory stimuli and environmental conditions. Furthermore, the diversity and characteristics of environmental stimuli play an important role in attention allocation, resulting in varying levels of focus based on sensory inputs (Torquati et al., 2017). Although previous studies highlight the importance of changes in attention in creativity, there remains a significant gap in understanding the relationships between environmental stimulation, attention in movement, and divergent thinking.

Building on existing studies, we formulate the four Research Questions (*RQ*) to guide our study. *RQ1*: What are the design considerations to develop a system to map the current FSI modes and support walking creativity? *RQ2*: Which FSI mode is more effective in improving walking creativity? *RQ3*: What are the effects of different FSI modes on sustained performance during walking creativity? *RQ4*: What are the effects of indoor and outdoor environments on various FSI modes in enhancing walking creativity?

To this end, we designed an FSI framework and then developed a rhythmic footstep sound interaction system in Section 4.3 to answer *RQ1*, which offers three modes (FSS, SFR, and FSR, Figure 4.2) of FSI for walking creativity. We conducted a user study (64 participants) in Section 4.4 to evaluate the effectiveness of FSS in walking creativity. The results of this study include three parts in Section 4.5: (1) We compare the effects of three FSI modes between groups to answer *RQ2*. (2) We investigate the impacts of WalkMe for sustained creativity in two stages within groups of creative tasks to answer *RQ3*. (3) The experiments were conducted indoors and outdoors between the groups to answer *RQ4*. The scope of this study involves exploring FSI for attention regulation, self-awareness between body and mind, and creativity while walking.

The contributions of this study are four-fold: (1) A comprehensive FSI framework for guiding the design of systems to enhance walking creativity. (2) Assessment of the impact of three FSI modes on creativity in both indoor and outdoor settings. (3) Exploration of the role of rhythm in fostering creativity and investigation of the relationship between external auditory stimuli and internal attention regulation in creativity. (4) Development of design principles for FSI systems aimed at promoting walking creativity. This study is inclusive for users; even novices can choose different modes to stimulate creativity and enhance their creative performance and walking experience.

4.2 Related Work

Three main areas of previous studies influence our work in investigating footstep sound interactions for walking creativity: (1) the effect of walking on creativity, (2) the role of sounds on creativity, and (3) understanding the types and biodynamics of footstep sound interactions.

4.2.1 The Effect of Walking on Creativity

Many researchers examined whether walking promotes creativity by inducing relaxation, improving attention focus, stimulating blood circulation, and facilitating the delivery of more oxygen and nutrients to the brain (Jabr, 2014; Ahtinen et al., 2016). Some studies suggest that walking with rhythmic footsteps can help improve focus on attention and promote flexible thinking (Overall, 2015; Mäkelä and Aktaş, 2023), while other studies indicate that walking can distract attention due to environmental and personal fatigue, thus affecting creative performance (Yeh et al., 2022; Xia et al., 2023). The impact of changes in attention during walking on creative performance remains inconclusive and deserves further exploration.

The rhythmic footsteps involved in walking create a state of focused attention, aiding concentration and improving cognitive performance (VanLeeuwen, 2018; Mäkelä and Aktaş, 2023). Despite the automaticity of walking, it allows minimal conscious effort once the pattern is established, allowing attention to be diverted to other cognitive tasks (Helfrich et al., 2018). This ability to perform secondary tasks during walking has been explored in divergent thinking, uncovering the relationship between attention, motor control, and creativity (Kuo and Yeh, 2016). Other studies investigated how the integration of the environment during walking influences attention allocation and creativity. Oppezzo and Schwartz (2014) demonstrated that people generated significantly more appropriate and novel divergent thinking when walking outdoors than indoors.

Studies consistently showed that walking had a positive effect on creativity. However, there is not yet a clear understanding of the role of attention during walking in relation to creativity, particularly in the context of environmental limitations.

4.2.2 The Role of Sounds on Creativity

Sounds such as fast-paced music, pleasant music and ambient music have been shown to have a positive impact on creative thinking (Murata et al., 2017; Cochrane et al., 2021). This is because the human sensory and physiological system is capable of detecting and interpreting various characteristics (e.g., frequency, intensity, and rhythm) of sounds (Burger et al., 2013; Varlet et al., 2020). Specifically, the processing of rhythm in sounds can affect the speed and flexibility of human thought, which may influence their ability to think creatively (Bishop, 2018; Cheng, 2022). The rhythm of sounds plays a crucial role in facilitating creativity by modulating the attention of participants (Schmidhuber, 2007), helping to achieve flow states (Csikszentmihalyi, 1997), regulating neural oscillations (Reedijk et al., 2013), and modulating emotions (McPherson et al., 2016).

In particular, the harmonization of rhythmic patterns in sounds with an individual's internal rhythms, such as heart rate and brainwaves, has been established to induce a state of coherence that correlates with increased creativity and open-minded thinking (Dikaya and Skirtach, 2015; Eskine, 2023). This synchronization mechanism is crucial to facilitating the processing of information across diverse brain regions and to fostering the origin of innovative ideas, associations, and connections. Furthermore, this state of coherence is believed to optimize the distribution of neural resources, thus improving the effective use of cognitive capacities (Jung et al., 2013; Schiavio et al., 2019). Consequently, individuals are better equipped to direct their attention to the current task while simultaneously facilitating the spontaneous emergence of new ideas.

These studies demonstrated the benefits of sounds in creativity. Given that listening to music during walking has become a common daily activity, it is essential to understand the effects of sound stimuli while walking on regulating attention and stimulating divergent thinking.

4.2.3 Understanding Footstep Sound Interactions (FSI)

Some studies propose that consciously synchronizing footsteps with rhythmic sounds can enhance creativity by aiding attention regulation (Cochrane et al., 2021; Tajadura-Jiménez et al., 2015). However, there remains a lack of consensus on this matter, with previous research indicating potential drawbacks due to the cognitive demands involved (Kuo and Yeh, 2016; Frith et al., 2020). In contrast, scholars with

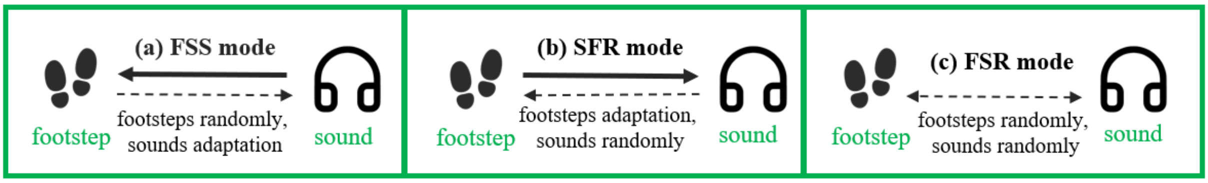


Fig. 4.2: The diagram depicts three modes of FSI that we identiifed based on previous studies. It includes Footstep-centered Sound Stimulation (FSS), Sound-centered Footstep Regulation (SFR), and Footstep Sound Interactions Randomly (FSR) based on previous studies.

opposing points of view argue that unrestricted walking, without synchronization, may positively influence creativity (Leman et al., 2013). Therefore, understanding the effects of the combinations of footstep and sound on walking creativity is crucial to advance our understanding of this phenomenon.

This study identified three general modes of technology-supported FSI (Figure 4.2). The first mode is the *Footstep-centered Sound Stimulation* (FSS, Figure 4.2a), where the sound system adapts to the footsteps of the users and provides feedback (Tajadura-Jiménez et al., 2015, 2018). This mode involves using footstep as an input modality to trigger the corresponding sounds as output. For example, the Nike+ running app adjusts the sound according to the footsteps of users to improve running performance (Cochrane et al., 2021). The second mode is the *Sound-centered Footstep Regulation* (SFR, Figure 4.2b), where users synchronize their footsteps with the sound rhythm provided by the system (Feltham and Loke, 2017; Leow et al., 2018; Faulkner et al., 2021). This approach has shown the role of sounds as an input modality in improving gait abnormalities in people with Parkinson's disease (Karageorghis et al., 2020; Ashoori et al., 2015). The third mode is the *Footstep Sound Interactions Randomly* (FSR, Figure 4.2c), where the user walks within the music without any adaptation between footsteps and sounds.

The biodynamics of FSI involves the principles underlying the interaction between human movement and auditory stimuli. Existing studies aim to understand how the human body responds to auditory cues during walking (Hajinejad et al., 2016) and how these responses influence walking behavior and perception (Visell et al., 2009; Altaf et al., 2015). For example, some researchers explore how auditory feedback affects gait patterns, posture, balance, and overall coordination of movement (Altaf et al., 2015). They also investigated the neural mechanisms involved in processing auditory information during walking and how these mechanisms interact with motor control and decision-making processes (Cornwell et al., 2020). Furthermore, current studies on the biodynamics of FSI focus on how different types of auditory stimuli, including rhythm, pitch, and volume, affect walking performance and subjective experiences (Toso and Gomes, 2020). This includes examining the role of auditory feedback in improving spatial perception, guiding navigation, and reducing the risk of falls or accidents during walking. However, we find that existing studies mainly focus on the interaction between movement and auditory stimuli and their feedback on physical activity and performance. Little study explores the influence of this biodynamics on mental activity, particularly the performance of creative activities.

In summary, stimulation of creativity by sounds or footsteps can be attributed to rhythmic auditory stimuli and gait movements. This explicit stimulation enhances attention regulation, thereby facilitating the activation of divergent thinking. However, there is a paucity of studies investigating the effect of FSI on creativity. The previous understanding in this field remains limited. Specifically, there are two issues still unclear while walking creativity - (1) the role of FSI in influencing creativity; and (2) the associations between external rhythmic stimuli and internal attention regulation to creativity.

4.3 Design Framework and Development

In this section, we describe the design framework and development of a system for walking creativity. It includes two parts: (1) design a framework for the FSI mechanism, and (2) develop a system called WalkMe for FSI while walking creativity.

4.3.1 Design Framework of FSI

Inspired by previous studies on FSI frameworks (Tajadura-Jiménez et al., 2015; Turchet et al., 2016; Tajadura-Jiménez et al., 2018; Faulkner et al., 2021), the design of the rhythmic interaction framework for FSI involves considerations of two mechanisms: rhythm detection and rhythm feedback (Tan and Ren, 2023). The mechanisms of FSI aim to support effective interactions between user and system to stimulate user's attention, body awareness, and creativity while walking. The design framework of the mechanisms presents distinctive challenges and design strategies.

Rhythm detection (Figure 4.3a). Designing a robust and inclusive FSI detection mechanism faces challenges, such as diversity in walking footsteps, complicating the detection of user data (Yang and Li, 2012). Simultaneously, real-world environmental

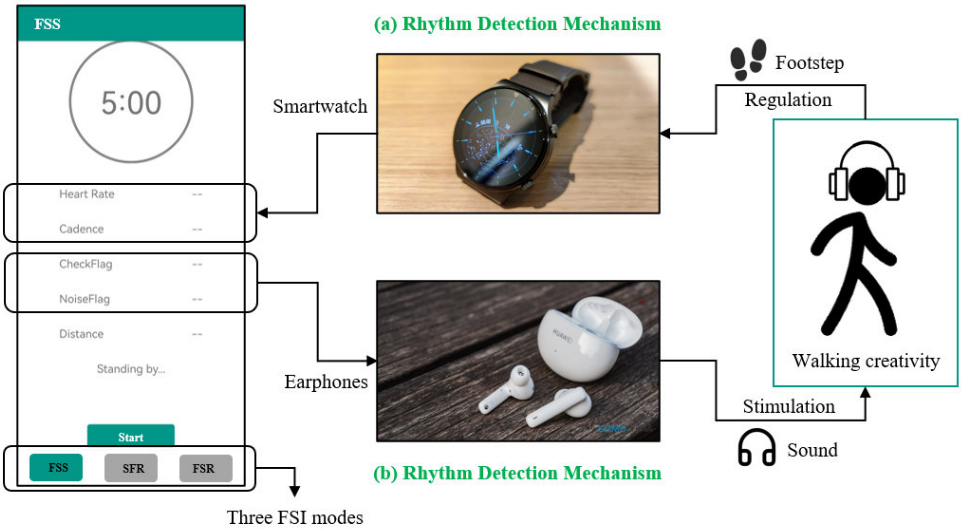


Fig. 4.3: The diagram depicts design framework of a rhythmic Footstep Sound Interaction (FSI) system for walking creativity through integrating three FSI modes and apparatus.

noise, such as background music, conversations, and traffic sounds, may interfere with gait detection, necessitating the assurance of system reliability in complex acoustic environments (Franěk et al., 2018). Individual differences in gait characteristics, such as stride length, walking speed, and step frequency, also require the system to be adaptable (Hak et al., 2013). To enhance detection accuracy, integrating rhythm as a feature by recognizing the relationship between footsteps and sounds rhythm can be beneficial. This not only creates a more musically engaging interactive experience, but also facilitates the design of interactive approaches with sounds, such as altering sound styles or speeds under specific rhythms (Burger et al., 2013; Maculewicz et al., 2016). Using digital signal processing techniques, such as beat detection algorithms, to extract rhythm information from audio is an aspect. Furthermore, combining these techniques with gait calculation algorithms for model training enables the identification of associations between known gaits and musical data (Ashoori et al., 2015; Leow et al., 2021). Design solutions for rhythm detection should focus on adaptability to individual differences, noise mitigation strategies, user customization options, and rigorous usability assessments to address the challenges presented in different interaction modes.

Rhythm feedback (Figure 4.3b). In the design of feedback systems, striking a balance between providing positive feedback and preventing user interference is crucial, especially in various walking creativity activities within three FSI modes. To achieve this objective, the system should offer a configurable and rhythmic feedback range, allowing users to dynamically receive feedback based on their needs (Maculewicz et al., 2015; Maculewicz, 2016). Simultaneously, the system should possess the adaptability to adjust the sound of the feedback to meet diverse user requirements. Additionally, incorporating an appropriate rhythm can offer users unique inspiration. By employing algorithms to analyze the rhythm of user footsteps and align it with musical elements, the system can provide users with music feedback that aligns with their walking pace (Moens et al., 2014; Frigola Camps, 2022). This rhythm-based feedback enhances the dynamism and liveliness of the created music, establishing a closer connection between the music and the user's walking activity through synchronization with their footsteps. Real-time analysis of user walking patterns, coupled with synchronous rhythm feedback, allows the system to make music feedback more expressive and closely aligned with the user's behavioral dynamics (Jylhä et al., 2012; Maes et al., 2019). This rhythm feedback not only enhances the user's sense of participation in the creative process, but also enables them to perceive their interactive influence on the musical rhythm. In this way, the system not only offers an engaging creative experience, but also facilitates a deeper integration of users into the realm of creative activities.

4.3.2 WalkMe: Development of the FSI system

In this subsection, we describe the development of WalkMe, which includes (1) the sound materials utilized by the system; (2) the estimation of footstep sound interactions, and (3) the system architecture and apparatus for synthesis.

Sound material utilized by the system. The selection of sound material includes three types, that is, ambient sounds, tempo sounds, and soft cues.

Ambient sounds have incorporated binaural beats, in which the brain generates an internal sound known as binaural beats when each ear is exposed to two nearly identical tones (Cooper, 2021). Past research indicates that binaural beats positively impact creativity and attention focus by stimulating brain waves (Reedijk et al., 2013; Basu and Banerjee, 2023). Brain waves encompass five waveforms: Delta, Theta, Alpha, Beta, and Gamma (Pandey et al., 2022). Different waveforms, corresponding to different frequencies, exert varied stimulative effects on the state of the brain (Gao et al., 2014). Given that Delta frequencies are conducive to sleep, while Gamma frequency are conducive to alertness, our study opts for Theta, Alpha, and Beta as binaural beat stimuli. Refer to Table 4.1 for specific sound attributes[*1].

[*1] https://mynoise.net/.

Table 4.1: The table shows the characteristics of the selection of ambient sounds for walking creativity.

Brain waves	**Frequency**	**States**
Theta	4 Hz	Drowsy
Theta	6 Hz	Fantasy
Alpha	8 Hz	Relaxed
Alpha	12 Hz	Conscious
Beta	16 Hz	Focused
Beta	24 Hz	Active

Tempo sounds, meticulously captured through MixPad Multitrack Recording Software for people engaged in walking creativity activities. One notable advantage of tempo sounds lies in their ability to enhance attention during walking. The rhythmic nature of these sounds can serve as a meditative anchor, drawing the walker's focus to the present moment (Cochrane et al., 2021). Moreover, the motivational aspect of tempo sounds plays a crucial role in sustaining the momentum of the walker. The rhythmic audio background acts as a supportive companion, energizing, and encouraging the individual to maintain their walking routine (Edensor, 2010). In addition, rhythmic patterns can stimulate neural networks in the brain, promoting a state of flow that is conducive to the generation of new ideas and fostering a creative mindset (Feltham and Loke, 2017).

Soft cues*[2] - brown noise (e.g., the sound of a singing bowl being struck (Goldsby et al., 2017)), refers to gentle and subtle prompts or stimuli aimed at assisting walker maintain focus and mindfulness. They serve as reminders to help walkers stay vigilant and prevent their thoughts from wandering.

Estimation of footstep sound interactions. As shown in Table 4.2, the design of a rhythmic sound system for walking creativity shows a thoughtful approach in defining the intervals for footsteps, tempo sounds, and their corresponding ambient sounds. The decision to set the general interval for footsteps between 75 and 135, with each interval of detection of the rhythm of footsteps spanning 5 steps, is based on a combination of biomechanical consideration (Lee and Hidler, 2008) and a pilot study in our initial experiments. The range of 75 to 135 captures a moderate to brisk walking pace, encom-

*[2] https://noises.online/.

passing a spectrum from leisurely strolls to more energetic walks. The choice of 5 steps per footsteps rhythm detection interval aligns with the average step frequency during walking and ensures that the system remains responsive to the user's natural cadence. This interval strikes a balance between capturing subtle changes in pace and preventing overly frequent adjustments that might disrupt the user's flow while walking (Edensor, 2010).

Defining tempo sounds as the median value within each rhythm detection interval of footsteps adds a layer of musical coherence to the system (Altaf et al., 2015; Roberts et al., 2017). By using the midpoint, the tempo sounds become representative of the overall pace within that specific range, promoting a smooth transition between different tempo sounds. This not only enhances the synchronization between the user's footsteps and the auditory stimuli, but also contributes to the overall immersive and harmonious experience. Pairing specific ambient sounds with each combination of footsteps and tempo sounds further enriches the walking experience.

The decision to associate ambient sounds based on the frequency bands (Theta, Alpha, Beta) and their corresponding mental states (Drowsy, Fantasy, Relaxed, Conscious, Focused, Active) demonstrates a nuanced understanding of the potential impact of auditory stimuli on cognitive states during walking (Reedijk et al., 2013; Basu and Banerjee, 2023). For instance, the choice of 4 Hz-Theta-Drowsy for the footsteps interval of 75-80 suggests a calming and drowsy state, aligned with a slower walking pace. As the pace increases, the system dynamically adjusts the ambient sounds to match the corresponding mental state, creating a seamless progression from relaxation to increased alertness (Schnebly-Black and Moore, 2003; Amos, 2013). This deliberate mapping of Tempo sounds to specific mental states contributes to a holistic and adaptive walking experience that not only considers the physical aspect of walking, but also aims to evoke various cognitive responses.

System architecture and apparatus for synthesis. WalkMe was developed to integrate data synthesis in interactions between footsteps and sounds. The system included technical architecture and the set-up of three FSI modes. The architecture of WalkMe comprises three components (Figure 4.4): (1) a HUAWEI wearable smart watch to capture the users ' heart rate and footstep, (2) Huawei Health Kit, which is a android application responsible for transmission the users' biodata in real-time and analyze biodata after walking; and (3) WalkMe is the Android App which involved the HUAWEI Health Kit API and cover adjusting tempo sounds & ambient sounds in real time accord-

Table 4.2: The table shows the estimation of footsteps and sounds for rhythmic sound system supports walking creativity.

Foosteps	Tempo sounds	Ambient sounds
75-80	78	4 Hz-Theta-Drowsy
80-85	83	4 Hz-Theta-Drowsy
85-90	88	6 Hz-Theta-Fantasy
90-95	93	6 Hz-Theta-Fantasy
95-100	98	8 Hz-Alpha-Relaxed
100-105	103	8 Hz-Alpha-Relaxed
105-110	108	12 Hz-Alpha-Conscious
110-115	113	12 Hz-Alpha-Conscious
115-120	118	16 Hz-Beta-Focused
120-125	123	16 Hz-Beta-Focused
125-130	128	24 Hz-Beta-Active
130-135	133	24 Hz-Beta-Active

ing to the users' biodata. Meanwhile, WalkMe will show the suggestion and control the wearable device to start/stop recording biodata according to the real-time movement status of users. Then, we develop the algorithms of WalkMe based on design framework and estimation of WalkMe. This architecture aims to monitor and estimate data interactions during walking creativity, which includes synthesis of three parts - synthesis for Footstep-centered Sound Stimulation (FSS), Sound-centered Footstep Regulation (SFR), and Footstep Sound Interactions Randomly (FSR).

4.4 User Study

We conducted a user study to evaluate the effects of three FSI modes on walking creativity. This study was approved by the University Ethics Review Committee.

4.4.1 Experimental Design

To compare the effects of FSI on walking creativity, three interaction modes were designed within the WalkMe system (Figure 4.3). We also compared with walk only condition (i.e., No Sound while Walking, NSW) which serves as the baseline. This ex-

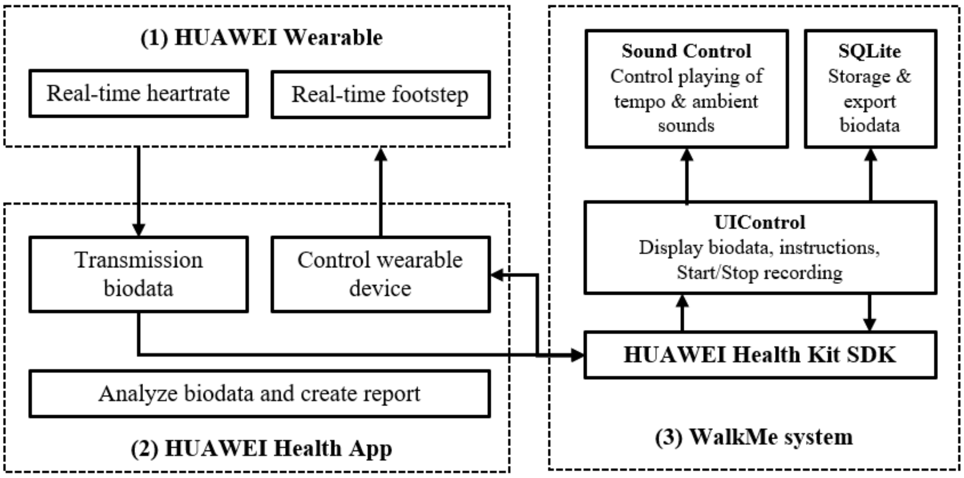


Fig. 4.4: The diagram depicts the architecture of a system called WalkMe for footstep sound interactions while walking creativity.

Fig. 4.5: The diagram depicts the environments (indoor and outdoor) of experiments in this study.

periment used independent variables of mixed design. The study used a design between subjects to examine three main variables: *Conditions* (FSS, SFR, FSR, and NSW), *Stages* (Stage 1 and stage 2), and *Environments* (indoor and outdoor, Figure 4.5). Regarding *Conditions*, we analyzed the variations among the FSI modes in response to *RQ2* relative to the baseline. *Stages* were manipulated to involve two distinct creativity tasks, allowing evaluation of their impacts within the groups to address *RQ3*.Furthermore, *Environments* were manipulated by introducing indoor and outdoor settings, allowing comparison of their effects between the groups to address *RQ4*.

4.4.2 Participants

Sixty-four university students and staff members (22 women, 42 men) aged 20 − 41 (mean = 25.12, SD = 4.92, median = 23) were recruited. All participants had no body injury, no history of cardiovascular injury (heart attack or stroke), no acute severe fatigue, no lightheadedness, dizziness, or nausea while walking. The nationality of the participants was as follows: Japanese (n = 35), Chinese (n = 18), Indian (n = 5), Indonesian (n = 1), Thai (n = 1), Swiss (n = 1), Sri Lankan (n = 1), Korean (n = 1), Malaysian (n = 1). Each participant was paid 2000 yen (Japanese currency).

4.4.3 Procedure

Participants were required to sign an informed consent form. Then, they were introduced to the procedure of this study. Participants were randomly assigned to groups experiencing four conditions, alternating between indoors and outdoors (Figure 4.5). The procedure for this experiment includes three parts.

Part one: The researchers collected background information, including gender, age, frequency of divergent daily thinking, and walking experience. Participants were required to complete a pre-test questionnaire to measure attention and bodily awareness. Subsequently, the participants tested the functionality of headphones, watches, and smartphones, adjusting the volume of the headphones to a comfortable level.

Part two: The participants formally participated in the experiment, in which they performed creative tasks while walking and engaged in divergent thinking. The experiment comprised two identical stages with a 3-minute break between. Each stage lasted for 5 minutes, divided into a 1-minute preparation phase for system responsiveness and participant self-adjustment, and a 4-minute period for completing the creative task. Participants were informed that the tempo cues of the headphones would prompt them to begin the creative task at the end of the first minute.

Part three: The participants were informed that the experiment had been completed and instructed to remove all equipment. Then, they were required to complete a post-test questionnaire identical to the pre-task questionnaire. Following this, the participants conducted interviews to collect information on their user experience throughout the process.

4.4.4 Metrics

As mentioned above, walking creativity is accompanied by the regulation of attention and body awareness (Oppezzo and Schwartz, 2014), changes in physiological and behavioral states (Jylhä et al., 2012; Tajadura-Jiménez et al., 2018), and the performance of divergent thinking (Oppezzo and Schwartz, 2014). Therefore, we used the following methods to measure the interventions effects of WalkMe during training.

First, to evaluate *attention and body awareness regulation*, we used the Multidimensional Assessment of Interoceptive Awareness (*MAIA*) (Machorrinho et al., 2019) to understand multidimensional changes in the subjective experience of users during training. This was measured on a 5-pt Likert scale ranging from 1 to 5. The questionnaire comprises 20 items divided into four scales: Non-Distracting (ND), Attention Regulation (AR), Self-Regulation (SR), and Body Listening (BL). Then, we use the Measure of Attention Focus (*MAF*) (Atchley, 2011) to understand the state of attention focus during training. It is measured on a 10-pt Likert scale ranging from 1 to 10. It comprises 6 items: Body Sensations (BS), Task Relevant Thoughts (TRT), Self-Talk (ST), Task Relevant External Cues (TREC), Task Irrelevant Thoughts (TIT) and External Distractions (ED). All questionnaires were completed on Google Sheets on-line.

Second, to assess the performance of divergent thinking, we employed the Divergent Association Task (*DAT*) proposed by Olson et al. (2021). This task serves as a robust metric for evaluating the levels of creativity exhibited by users during the walking process. The *DAT* requires participants to generate ten words in 4 minutes, with an emphasis on maximizing the diversity of these words in terms of their meanings and applications. Participants are encouraged to explore the full spectrum of meanings and uses associated with each word. The *DAT* presents several advantages, particularly in the use of computational algorithms to score task responses, as opposed to traditional manual scoring methods. This aligns with the overarching goal of our study, which is to eliminate potential biases associated with manual scoring methods and enhance the reliability and efficiency of the evaluation process.

Third, to evaluate *changes in physiological and behavioral states* during training, we used a smart watch equipped with sensors that uses the WalkMe system to automatically record the user's *movement trajectories* of heart rate and cadence. Heart rate data provides insight into physiological responses, while fine-grained tracking of motion trajectories provides detailed behavioral analysis. These metrics are recorded with second-by-second granularity, ensuring a nuanced exploration of temporal dynamics and interactions between physiological and behavioral aspects, thus adding depth to our assessment of intervention effects. Furthermore, previous studies have suggested that changes in heart rate and cadence while walking may contribute to manifestations of divergent thinking (Kuo and Yeh, 2016; Keller et al., 2017). To this end, this study further explored the correlation analysis on changes in heart rate and cadence and the performance of divergent thinking.

Finally, to understand the subjective experiences of users during training, we conducted *semi-structured interviews*. The interview process was conducted by two experienced experimenters. The interview questions were designed to encompass three key aspects related to walking creativity. (1) Participants were asked about their state of attention and body self-awareness. This question involved exploring whether attention was interrupted and if participants employed physical self-regulation strategies during activities and whether they found them challenging. (2) Participants were asked questions about changes in their physiological and behavioral states. The questions in this domain were designed to determine whether participants felt physically comfortable and how objectively responded to the environment and tasks. (3) Participants were asked about their performance in creativity. This question investigates their performance at different stages in the process of divergent thinking, particularly focusing on the continuity of divergent thinking and the subjective feelings when entering divergent thinking.

4.5 Results

In this section, we present the results of both quantitative and qualitative analyses. For quantitative data analysis, we examined the performance of walking creativity under four conditions (i.e., Footstep-centered Sound Stimulation (FSS), Sound-centered Footstep Regulation (SFR), Footstep Sound Interactions Randomly (FSR), and No Sound while Walking, (NSW)) using the Statistical Package for the Social Sciences (SPSS). The significance level was set at $\alpha = 0.05$. For qualitative data analysis, we used an in-depth text analysis approach on interview data to explore and comprehend the user experiences articulated by participants during the walking creativity experiment.

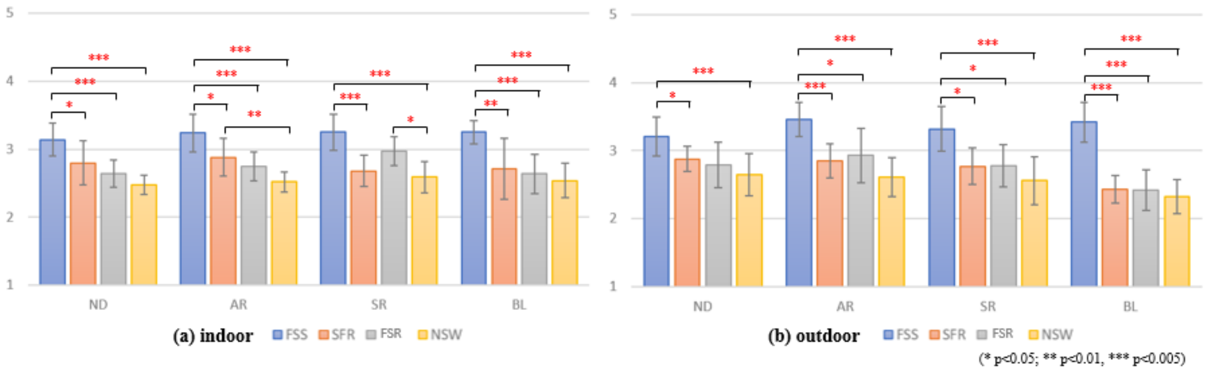


Fig. 4.6: Significant differences in post-test scores of participants were observed for Non-distracting (ND), Attention Regulation (AR), Self-regulation (SR), and Body Listening (BL) from the Multidimensional Assessment of Interoceptive Awareness scale. Indoor (a) and outdoor (b) each contain 4 conditions and were analyzed separately.

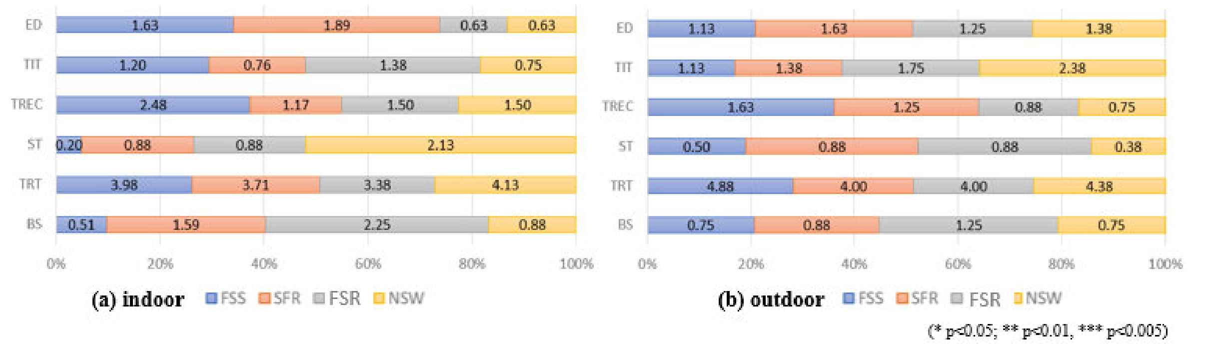


Fig. 4.7: The proportion for each condition across six items were distributed for investigating attention focus in Body Sensations (BS), Task Relevant Thoughts (TRT), Self-Talk (ST), Task Relevant External Cues (TREC), Task Irrelevant Thoughts (TIT), and External Distractions (ED) from the Measure of Attention Focus scale. Indoor (a) and outdoor (b) each contain 4 conditions and were analyzed separately.

4.5.1 Attention and Body Awareness Regulation

First, we conducted between-groups comparisons of *Conditions* and *Environments* on the MAIA using repeated measures analysis of variance and multiple post hoc comparisons using SPSS. Second, we conducted between-groups comparisons of *Conditions* and *Environments* on the MAF using categorical statistics and multiple post hoc comparisons using Excel and SPSS.

Multidimensional Assessment of Interoceptive Awareness (MAIA). The results are presented in Figure 4.6. Significant differences were observed in the pre- and post-tests for all groups.

Conditions × *Environments.* On NW, FSS showed significant differences compared to others indoors, while outdoors, there were significant differences (M = 3.21, SD = 0.29, p <0.005) between FSS and SFR, and significant differences (p <0.05) between FSS and NSW. In AR, both indoors and outdoors, FSS exhibited significant differences compared to others; indoors, SFR also showed significant differences (M = 2.88, SD = 0.28, p <0.01) compared to NSW. In SR, indoors, there were significant differences (M = 3.25, SD = 0.27, p <0.005) between FSS and SFR, and significant differences (p <0.005) between FSS and NSW, and FSR showed significant differences (M = 2.97, SD = 0.21, p <0.05) compared to NSW; outdoors, FSS demonstrated significant differences compared to others. In BL, both indoors and outdoors, FSS exhibited significant differences compared to others. Comparisons between the corresponding conditions of the indoor and outdoor groups did not show significant differences. The results indicate that attention and body awareness training under the FSS condition produces a significant performance compared to other interventions.

Measure of Attention Focus (MAF). The results are depicted in Figure 4.7. We calculated the proportion distribution for each condition across six items focusing on attention focus, both indoors and outdoors.

Conditions × Environments. Indoors, FSS demonstrated significant performance in TREC (24.8%) and TRT (39.8%); SFR led in ED (16.3%); FSR exhibited significance in TIT (13.8%) and BS (22.5%); while NSW significantly surpassed other groups in ST (21.3%). Outdoors, FSS and SFR showed similar trends; FSR was significant in BS (12.5%); and NSW significantly surpassed other groups in TIT (23.8%) and ST (43.8%). After post hoc test, only under ST conditions did FSS show a significant difference (p <0.01) compared to NSW. The results indicate that the dimensions of attention focus of FSS and SFR show a stable trend both indoors and outdoors, while FSR and NSW demonstrate unstable performance.

4.5.2 The Performance of Divergent Thinking

We conducted between-groups comparisons of *Conditions*, *Stages*, and *Environments* on the DAT (Figure 4.8) using repeated measures analysis of variance and post hoc multiple comparisons using SPSS.

Conditions × Stages × Environments. Indoors, during stage 1, there was a significant difference (p <0.05) between FSS (M = 79.85, SD = 3.39) and NSW (M = 69.34, SD = 10.82); in stage 2, the significant difference (p <0.005) between FSS (M = 86.15, SD = 2.47) and NSW (M = 67.81, SD = 11.85) persisted, with FSS outperformed SFR

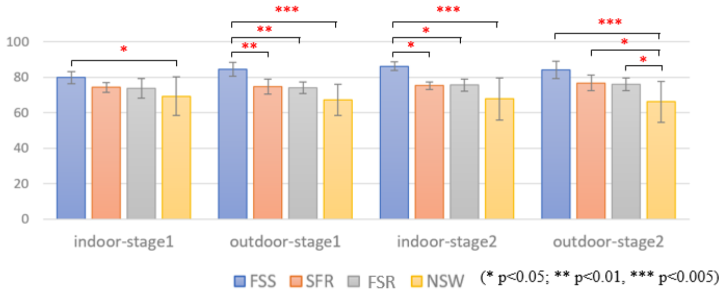
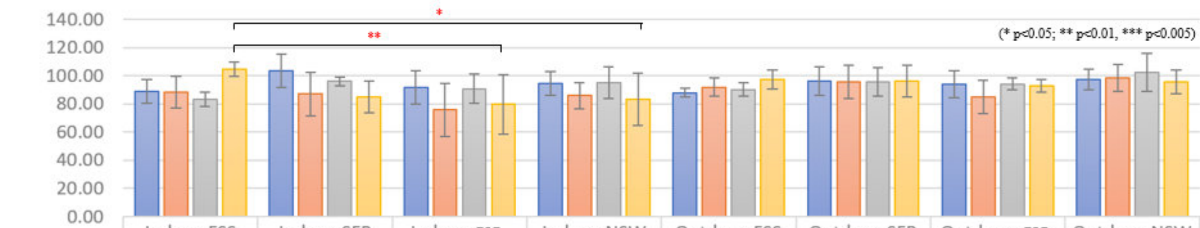


Fig. 4.8: Significant differences in post-test scores of participants were observed for the performance of divergent thinking from the Divergent Association Task scale. Four conditions (2 - indoor and outdoor × 2 - stage 1 and stage 2) were analyzed.



	Indoor-FSS	Indoor-SFR	Indoor-FSR	Indoor-NSW	Outdoor-FSS	Outdoor-SFR	Outdoor- FSR	Outdoor-NSW
HR-Stage 1	88.86	103.66	91.82	94.43	87.99	96.06	94.14	97.44
Ca-Stage 1	88.40	87.03	75.83	86.04	91.94	95.80	85.07	98.56
HR-Stage 2	83.32	95.96	90.89	94.96	90.24	95.58	94.17	102.32
Ca-Stage 2	104.58	85.22	79.79	83.32	97.15	96.23	92.85	95.63

Fig. 4.9: Significant differences in heart rate and cadence of participants were counted and observed while walking creativity. Eight conditions (2 - indoor and outdoor × 4 - FSS, SFR, FSR, and NSW) were analyzed.

(M = 75.31, SD = 2.09) and FSR (M = 75.61, SD = 3.47). Outdoors, during stage 1, FSS exhibited significant differences (M = 84.49, SD = 3.89) from the other three groups; in stage 2, the significant difference (p <0.005) between FSS (M = 84.14, SD = 4.83) and NSW (M = 66.11, SD = 11.47) was pronounced and additionally SFR (M = 76.81, SD = 4.42) and FSR (M = 76.14, SD = 3.62) showed significant differences compared to NSW. The post hoc test did not reveal significant differences when considering environments and stages as variables. The findings demonstrate that FSS shows significant creativity in different environments and stages, and variations in environment and short-term creative tasks do not lead to significant differences in creative performance.

4.5.3 Correlation Analysis on Heart Rate, Cadence, and DT

First, we analyze the changes in heart rate and cadence of users under different conditions (Figure 4.9). Data were analyzed from subjects' 4-minute quasi-task. Through the Shapiro-Wilk test, we observed that all conditions exhibited a normal distribution. Indoors, during stage 1 (FSS), the heart rate was lowest (88.86), while the cadence was highest (88.40). This trend persisted in stage 2. Outdoors, during stage 1 (FSS), the heart rate was the lowest (87.99), while the cadence of NSW was highest (98.56); in stage 2, we observed that FSS had the lowest heart rate (90.24) and simultaneously the highest cadence (97.15). Subsequently, a post hoc test was conducted. Indoors, significant differences were found in the cadence data of FSS (M = 104.58, SD = 5.03) during stage 2 compared to FSR (M = 79.79, SD = 20.99) and NSW (M = 83.32, SD = 18.46). However, no significant differences were observed in heart rate and cadence outdoors. The results indicate that indoors the heart rate and cadence data of FSS are more stable and exhibit similar trends. On the contrary, there is a lack of consistency in the outdoors.

Second, we conducted correlation analyses (Table 4.3) regarding heart rate, cadence, and divergent thinking, within the Pearson correlation coefficient, using SPSS to assess significance.

Heart rate × divergent thinking. Indoors, in stage 2 of FSS and SFR, there are a significant positive correlation between heart rate and divergent thinking, with correlation coefficients of 0.978 (p <0.01) and 0.984 (p <0.01), respectively. Outdoors, in stage 2 of the FSR, a positive correlation is also observed between heart rate and divergent thinking (r = 0.967, p <0.01). The results indicate that the positive correlation between heart rate and divergent thinking reveals a direct influence of heart rate on divergent thinking in the given conditions, suggesting potential for intervention. It should be noted that in stage 1, the correlation analysis between heart rate and divergent thinking for all conditions did not reach significance, implying the possible interference of other factors in their relationship.

Cadence × divergent thinking. Indoors, in stage 2 of FSS, a significant positive correlation is only found between cadence and divergent thinking (r = 0.955, p <0.01). Outdoors, in both stages of the FSS, a positive correlation is observed between cadence and divergent thinking, with correlation coefficients of 0.995 (p <0.01) and 0.852 (p <0.01), respectively. Furthermore, in stage 2 of the FSR, a positive correlation is found between cadence and divergent thinking (r = 0.964, p <0.01). The results suggest that, compared to other conditions, outdoors, FSS is more directly influenced by cadence, indicating its potential as a strong intervention condition.

Heart rate × Cadence × divergent thinking. Indoors, in stage 2 of FSS, there is

Table 4.3: The table shows the correlation analysis of significant differences in heart rate, cadence and divergent thinking (DAT) while walking creativity. Sixteen conditions (2 - indoor and outdoor × 4 - FSS, SFR, FSR, and NSW × 2 - heart rate and cadence) were analyzed. (*Notes:* * p <0.05 ** p <0.01.)

Conditions	**DAT-Stage 1**	**DAT-Stage 2**
Indoor-FSS-Heart rate	-0.060	0.978**
Indoor-FSS-Cadence	0.086	0.955**
Indoor-SFR-Heart rate	0.679	0.984**
Indoor-SFR-Cadence	0.339	-0.293
Indoor-FSR-Heart rate	0.159	0.088
Indoor-FSR-Cadence	-0.523	-0.118
Indoor-NSW-Heart rate	-0.015	-0.280
Indoor-NSW-Cadence	-0.015	-0.068
Outdoor-FSS-Heart rate	-0.319	0.125
Outdoor-FSS-Cadence	0.995**	0.852**
Outdoor-SFR-Heart rate	0.363	-0.017
Outdoor-SFR-Cadence	0.252	0.247
Outdoor-FSR-Heart rate	0.337	0.967**
Outdoor-FSR-Cadence	-0.449	0.964**
Outdoor-NSW-Heart rate	0.112	0.225
Outdoor-NSW-Cadence	0.376	0.007

a significant positive correlation between heart rate and cadence (r = 0.955, p <0.01). Outdoors, in stage 2 of the FSR, a significant positive correlation is observed between heart rate and cadence (r = 0.955, p <0.01). Both conditions show a significant positive correlation with their corresponding divergent thinking. In contrast, outdoors, in stage 1 of the SFR, despite a significant positive correlation between heart rate and cadence (r = 0.955, p <0.05), there is no significant correlation with the corresponding divergent thinking. The results suggest that the correlation between heart rate and cadence can positively impact divergent thinking under specific conditions, yet the reliability of this relationship remains to be explored.

4.5.4 Interviews

We conducted analysis between-group and within-group interviews to explore subjective user experiences in attention, body awareness, self-regulation, and divergent thinking during walking creativity under four conditions: i.e., Footstep-centered Sound Stimulation (FSS), Sound-centered Footstep Regulation (SFR), Footstep Sound Interactions Randomly (FSR), and No Sound while Walking, (NSW).

(1) Attention, body awareness, and self-regulation.

FSS. The study suggests that the FSS group, while walking, experienced a low sense of bodily awareness accompanied by a flow of information from the surroundings. Furthermore, sound helped concentrate attention, prevent distraction, and promote task-focused cognition. Indoors, the sound proved conducive to associative thinking. Although initial exposure to sound influenced attention and thinking, the impact gradually decreased during the adaptation process. Outside, participants showed sensitivity to changes in headphone sounds, where rhythms and ticking noises could potentially disrupt attention. Factors such as variations in walking distance, ambient noise, and social gaze also caused disturbances. However, in stage 2, participants gradually adapted to environmental disturbances, leading to a reduction in external attention.

SFR. The study suggests that the participants in the SFR group often found themselves entangled between focusing attention on sound or environment and divergent tasks, with a noticeable awareness of bodily sensations. Additionally, participants in the SFR group exhibited a sense of pressure during tasks. Indoors, participants emphasized the positive role of sound in aiding concentration in tasks. Participants also noted the positive role of sound in maintaining a calm and natural feeling, although at times it could evoke some anxiety. Adjusting the pace of walking based on sound could make them feel distracted, while walking fast heightened their awareness of bodily sensations. Outdoors, participants showed a strong attention to sound cues, the surroundings, and environmental changes. They engaged in purposeful thinking during environmental changes, but might experience hesitations in word generation, and environmental distractions could interrupt their thoughts.

FSR. The study suggests that the participants in the FSR group showed greater bodily regulation but often displayed distracted attention compared to the SFR group. Indoors, participants expressed concerns about the rhythm of sound. They believed that walking too fast could be a burden and that during periods of concentration they could gradually slow down, requiring alerting prompts. Although attention was better focused on thinking while walking, the speed of walking led to cognitive dispersion, preventing sustained focus on the task. Outdoors, participants displayed a degree of dispersed attention. Perceptions of surrounding elements, such as walking on acorns or the movements of people and animals, could interrupt thoughts. Rhythmic changes in sound affected walking speed, but also diverted attention toward adjusting walking pace rather than the task.

NSW. The study suggests that participants in the NSW group naturally maintained a dispersed and relaxed attention state, resulting in a subconscious or intentional lack of awareness about task attention and bodily self-regulation. Indoors, most participants perceived a sense of novelty while walking in new spaces. They consciously directed their attention to the surrounding landscape, accompanied by a freely adjusted walking pace. Although some participants found extended walks boring or fatiguing, there was generally a high acceptance of the duration of the walk. Outdoors, participants experienced relatively free and comfortable attention during the walking process. They noticed factors such as surrounding pedestrians, temperature and time constraints, but overall maintained a relaxed state during walking and thinking tasks.

(2) The performance of divergent thinking.

FSS. The study suggests that the FSS group demonstrates a divergent thinking pattern influenced by recent experiences, with scenes also evoking associations related to space and themes. Indoors, participants exhibited a divergent thinking process influenced by recent experiences and auditory stimuli, leading to a focused ideation that gradually narrowed its scope, such as focusing on scenes related to recent experiences (e.g., shopping). Interestingly, in the absence of specific cues, the occurrence of vocabulary was occasionally interrupted by novel, stimulating thoughts. Despite the presence of auditory stimuli, there was no significant impact on the association between vocabulary. Notably, outdoors, participants' observation of surrounding objects triggered associations with the scenery, and spontaneously generated vocabulary led to innovative thinking for different purposes. In response to situational cues, details gradually emerged, and associations were based on exclusion and prompts. This process included a cascade of sequential associations in response to random stimuli. Furthermore, auditory stimuli also influenced the divergent thinking process, allowing thoughts to expand freely from one concept to another.

SFR. The study suggests that the SFR group exhibits a divergent thinking pattern influenced by recent events, personal preferences, and internal dialogues, but lacks stimulation from the surrounding environment. Indoors, participants participated in a thought process organized along a timeline, focusing on recent and significant life events. Common aspects, such as personal desires and favorites, triggered organized and prioritized associations. In addition, this group showed a preference for random stimuli, resulting in diverse associations that often involve scenarios and deductive reasoning. Outdoors, the thinking process of the participants included memories of things happening in life and interesting events. Sound and internal dialogue played a crucial role in the divergent thinking process, guiding the sudden emergence of new associations during contemplation.

FSR. The study suggests that the FSR group's thinking tends to follow a non-linear jumping pattern, reflected in weak associations between vocabulary. Indoors, participants connected their thinking with their personal preferences and the surrounding environment. The audio signals from the headphones played a role in enhancing concentration and guiding the thought process along a linear path. Recent events triggered thoughtful, sequential vocabulary associations. Outdoors, participants demonstrated a tendency in divergent thinking to gradually expand the cognitive scope of familiar things. Under task requirements, they associated their preferred things and recent experiences with broader concepts.

NSW. The study suggests that the NSW group is influenced by personal interests, hobbies, and random stimuli. Although environmental stimuli can inspire their creativity, most indicated that they are often attracted by the environment and forget about the task. Indoors, participants demonstrated a unique pattern of jumping between related vocabulary, producing 2 to 3 thoughts before moving on to the next stimulus. The reaction process to random stimuli involved homophones, vocabulary, visual elements, and stories. Members of this group also favored and triggered associations through self-prompts related to recent scenes. Outdoors, participants exhibited the ability to expand from specific concepts to more general ones. The surroundings and recent experiences became crucial triggers for new thoughts.

4.6 Discussion

First, we review the design framework of the Footstep and Sound Interaction (FSI) system. Second, we discuss the role of FSI on walking creativity. Third, we present three implications for the system design of a walking creativity program. Finally, we discuss the limitations of this study and outline future work that deserves further investigation.

4.6.1 Revisiting Design Framework of FSI System

First, *rhythm detection design* is necessary. It not only enhances the system's understandability, but also stabilizes the data (Tan and Ren, 2023). By detecting the user's rhythm, the system can more accurately understand the user's behaviors and responses, thereby improving the system's flexibility and responsiveness. WalkMe's user studies demonstrate that the system can provide personalized services and feedback according to the dynamic needs of users, further confirming the importance of rhythm detection design in interactive systems. Additionally, during the creative process, users' attention and footsteps often exhibit specific rhythms and patterns. By detecting the user's rhythm, the system can more accurately capture the user's thought processes and moments of creativity, providing richer and deeper information for subsequent data analysis and exploration.

Second, we emphasize the effectiveness of *rhythm feedback design* in supporting various modes of footstep sound interactions. By integrating rhythm feedback, the system can better support real-time changes in user behavior and responses. During the walking creativity process, WalkMe's feedback design provides users with effective rhythm stimulation while also promoting users' rhythmic self-regulation. Furthermore, in this study, we underscore the importance of the rhythm loop formed between the feedback mechanism and the detection mechanism. The feedback mechanism interacts with the detection mechanism, jointly supporting the dynamic assessment of users' physiological and behavioral changes. For example, when users' attention is distracted or their footsteps are unstable, the stimulation mechanism can evaluate the user's state based on preset thresholds and provide the corresponding feedback to help users focus their attention (Tajadura-Jiménez et al., 2015, 2018). This design of the rhythm loop enables the system to better adapt to user needs and changes, enhancing the system's usability.

4.6.2 The Roles of FSI on Walking Creativity

Figure 4.10 maps the effects of the four FSI conditions (i.e., Footstep-centered Sound Stimulation (FSS), Sound-centered Footstep Regulation (SFR), Footstep Sound Interactions Randomly (FSR), and No Sound while Walking, (NSW)) on walking cre-

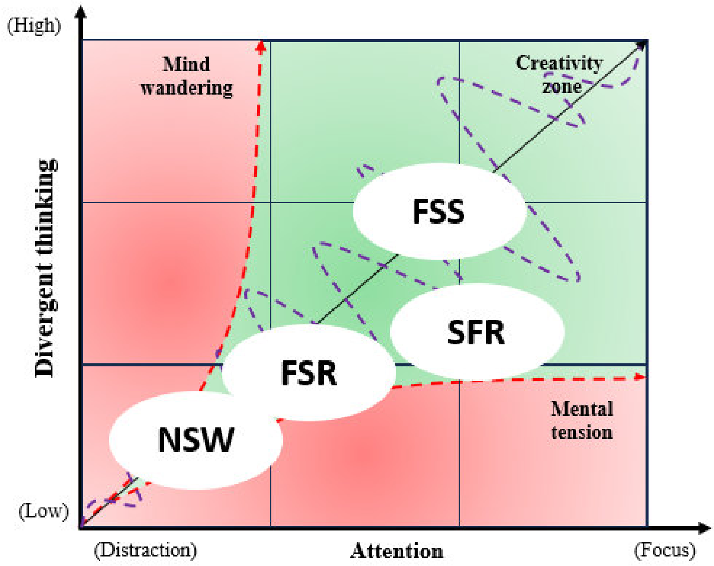


Fig. 4.10: The figure illustrates the high-level visualization of how the four conditions of footstep sound interactions (FSS, SFR, FSR, and NSW) influences attention performance and divergent thinking during walking creativity.

ativity. A foundational standpoint is that effective regulation of FSI plays a crucial role in enhancing attention regulation and creativity performance, and balancing both attention and creativity.

Regulating attention towards focus. Effective attention regulation to achieve focus requires mitigating the potential risks of cognitive tension and mind wandering. Our user study reveals that pedestrians often experience fluctuating attention states that alternate between distraction and focus while walking. Participants in the NSW and FSR groups frequently report being distracted, whereas those in the SFR and FSS groups demonstrate a commendable focus on attention (Figure 4.10). Distraction tends to occur more frequently, especially in unstructured and noisy environments (Torquati et al., 2017). Moreover, a potential concern arises from passively regulating attention towards focus, which may result in mental tension for users. This is evident from interviews where five participants in the SFR group mentioned feeling sustained tension and fatigue from continuously following the system's auditory cues. Conversely, actively regulating attention towards focus, as observed in the FSS group, also entails potential risks of mind wandering, particularly when the subject completes the task goal.

Enhancing divergent thinking. The key to improving divergent thinking lies in establishing a stable physiological and behavioral state to facilitate user focus. Our user study (Figure 4.10) indicates that participants in the FSS group show superior performance in divergent thinking, partially attributed to rhythmic auditory stimulation, which helps to maintain body comfort and awareness. This stable state facilitates guiding users' thoughts, directing their focus towards the current task. Conversely, being in an unstable state, as evidenced by the FSR group, often leads to divergent thinking, where thoughts deviate from the task at hand towards unrelated directions. Although in the SFR group, regulating behavior through rhythmic auditory cues maintains a certain degree of stability, it may also result in users engaging in mechanical following, consequently overlooking task requirements.

Balancing attention and creativity. The ideal FSI mode in balancing attention and creativity is an integrated framework that combines elements from both the FSS and the SFR modes. Our user study indicates that the FSS and SFR modes serve different regulatory roles (Figure 4.10). In the SFR mode, participants pay more attention to sound feedback. This increased attention can lead to increased focus on the present walking experience, consequently reducing the likelihood of attention distractions. In the FSS mode, participants receive sound feedback synchronized with their footsteps during random walking, creating a unique walking experience. Our user study suggests that this can stimulate their creativity. However, it is evident that both modes have room for improvement due to their respective limitations, such as mind wandering in the FSS mode and mental tension in the SFR mode. We posit the existence of an *middle way* that integrates the strengths of both modes while mitigating their respective weaknesses.

4.6.3 Design Implications

In this subsection, we present implications for the future design of FSI adapted to walking creativity.

Realizing a harmonies rhythm in data interactions. By highlighting the importance of achieving a harmonious rhythm in data interactions (Edensor, 2010; Amos, 2013; Maculewicz et al., 2016), our research suggests that such a harmony can significantly enhance the connection between attention and creativity, as well as foster resonance between users and the system. Our categorization of this harmonious rhythm into external and internal aspects provides a framework for understanding the nuanced dynamics at play. External harmony, which entails the coordination between the system's rhythm and the user's rhythm, highlights the need for interfaces to adapt seamlessly to users' pace and preferences. Internal harmony, on the other hand, emphasizes the integration of users' behavioral rhythm and cognitive rhythm, underscoring the importance of interface designs that facilitate cognitive flow and intuitive interaction. As users perceive the system as responsive and attuned to their needs, their trust in its capabilities deepens, leading to increased engagement and creative exploration. The integration of harmonious internal and external rhythms provides designers with new design guidelines and evaluation criteria as they consider incorporating rhythm as a design perspective.

Improving adaptive FSI for walking creativity. Our findings have identified an emerging *middle way*, wherein an adaptive FSI system is accompanied by two-way considerations. The adaptive FSI system emphasizes consideration and responsiveness to users' limitations during the interaction process, while preventing the system from entering a mechanized compliance state (Figure 4.10). It transcends the limitations of both the FSS and the SFR modes. Traditionally, the design of FSI systems has often leaned toward one-way adjustments, either exclusively catering to user preferences or responding only to system prompts (Altaf et al., 2015; Maculewicz et al., 2016). However, our study reveals a shift towards a more balanced/adaptive approach, wherein the system's adaptability is guided by dual considerations of both user input and system feedback. This *middle way* signifies a departure from rigid, predetermined interaction patterns toward a more dynamic and responsive system. By incorporating two-way considerations, designers can create FSI systems that seamlessly integrate user needs and environmental context, providing a more immersive and engaging walking experience.

Towards the creativity zone while walking. Based on our user study (Figure 4.10), we have identified three key implications. First, there is a need to fully stimulate users' abilities to attain optimal states of attention and bodily awareness. This involves designing systems capable of guiding users into a comfortable task zone, thereby avoiding excessive pressure or feelings of boredom. By providing appropriately challenging tasks and feedback, systems can help users maintain focus while remaining sensitive to their surroundings, thus fostering creative thinking. Second, it is imperative to fully exploit the potential of technology as a partner to users. This implies that systems should not merely serve as tools, but rather collaborate with users in an intelligent manner to offer support and inspiration. Third, attention should be paid to potential risks during the interaction process (Ren, 2016; Ren et al., 2019). This involves considering issues related to human limitations and impaired abilities, as well as problems arising from mechanistic interactions within the system. Designing systems with these considerations in mind involves addressing the physiological and psychological challenges users may face and implementing measures to mitigate these risks.

4.6.4 Limitations and Future Work

Upon reviewing this study, we acknowledge several limitations that provide valuable insights for future research efforts. (1) *Framework*: Although the current framework relies on mapping into existing FSI modes, it lacks uniformity and coherence, suggesting the potential for a more unified framework to enhance clarity and effectiveness. (2) *Evaluation*: The limitations of this study include the dependence on short-term experiments, restricted environmental conditions, and constraints related to the demographics of the participants and sample size. Future studies should employ more robust evaluation methods, such as longitudinal studies and comprehensive data analysis techniques, while also broadening the demographics of the participants to ensure the generalizability of the findings. (3) *Design practice*: The integration of existing frameworks in system design lacks cohesion. Moving forward, there is a need to develop a more cohesive framework adaptable to various everyday contexts, enhancing flexibility and usability across different scenarios. This approach could enable users to customize interactions, fostering a natural and adaptive user experience.

4.7 Conclusion

This study introduces a novel design framework and the development of the Footstep Sound Interaction (FSI) system with the goal of improving walking creativity. Through a user study, (1) we evaluated the user experience of the FSI system and compared three FSI modes with a walking-only condition, uncovering their effects on attention regulation, body awareness, and creativity. (2) We further investigate the impact of these modes on creativity in both indoor and outdoor settings, emphasizing the role of rhythm in fostering creativity and exploring the relationship between external auditory stimuli and internal attention regulation. (3) Finally, we presented the development of design principles for FSI systems aimed at promoting walking creativity.

Our findings not only contribute to the design of interactive systems to promote walking creativity but also advance empirical research, system development, and the formulation of design guidelines in this field. WalkMe's integration with mobile technology holds promise to enhance creativity conveniently and effectively. By investigating the relationship between technology-supported walking and creativity, our study opens new avenues for future research and practice in this domain.

Chapter 5

Study 2: Enhancing Running Meditation

This chapter introduces a study that investigates two-way adaptation in interactions between humans and computers. The study aims to explore the effects of adaptive sound system on running meditation. It includes two parts: (1) presenting the design framework and system development of RunMe, an adaptive sound system specifically designed for running meditation; (2) comparing the effects of the RunMe group with three other groups: non-adaptive sound, user favorite music and no sound groups.

This study serves as a micro-level exploration of our theoretical framework (i.e., FSIRA). It initiated the practical exploration of the FSIRA and developed the first generation of synergized interaction technology. The experimental results of this technology also validated the significance of two-way adaptation in achieving *synergized interactions* between our mind and body.

5.1 Introduction

Meditation has been widely recognized as a mindful practice that can improve mental health and well-being through attentional and body regulation (Larkey et al., 2009; Payne and Crane-Godreau, 2013; Niksirat et al., 2019). Although static meditation (e.g., Samatha, Vipassana, and Zazen practices) practices have been studied extensively, there is growing interest in the potential benefits of kinetic meditation (e.g., Tai Chi, Yoga, walking meditation) practices. With the development of interactive technology, many studies have explored kinetic meditation in sitting (Niksirat et al., 2017, 2019) or walking (Chen et al., 2015; Gromala et al., 2015) environments using virtual reality devices or mindfulness-based mobile applications. However, little study has been done on *running meditation*, which is a relatively new form of meditation practice.

The purpose of this paper is to focus on the design and evaluation of interactive technology to facilitate running meditation. The aim is to improve the understanding of runners actively involved in meditation practice, specifically in terms of their ability to regulate attention, be aware of their bodies, and cultivate mindfulness. We highlight the importance of the relationship between body awareness and attention focus for achieving the state of mindfulness during running meditation (Garg, 2012; Pustejovsky and Krishnaswamy, 2021; Claudia and Sas, 2021). This understanding serves as a valuable basis for creating interactive technology that is tailored to support this practice. Furthermore, we specifically explore the role of sounds in the running meditation experience, acknowledging their potential to enhance body perception and help runners direct their attention and awareness (Cochrane et al., 2020; Johansen et al., 2022).

To this end, there are three main challenges that must be addressed in designing and evaluating an adaptive sound system for running meditation. (1) *Stimulation*: Running meditation presents unique and challenging demands for stimulation technology, such as responding to changes in a runner's mental and physical performance in a mobile context. The stimulation mechanism during running meditation can be adjusted to changes in user awareness and behavior. For example, human attention goes through three stages: arousal, optimal focus, and stress zone in a task (Johnson and Proctor, 2004; Tang et al., 2015). Moreover, the stimulation mechanism can provide different feedback in various states. Technology can continuously monitor the user's state and provide real-time feedback for biological and behavioral stimulation (Niksirat et al., 2019). (2) *Regulation*: The regulation mechanism aims to maintain a dynamic balance in the meditative state of the user with the support of technology (Ren et al., 2019). Regulation technology can help the user adapt to biological and behavioral stimulation (i.e., heart rate and cadence). This requires choosing the appropriate technique to adjust and determine which stimulation is best suited for runners' self-regulation in a running environment. (3) *Data interactions*: Previous research has focused primarily on one-way adaptation, such as recommending suitable music based on footsteps (Headspace, 2022; Murgia et al., 2018). This study proposes a two-way adaptation approach (Ren et al., 2019) that emphasizes the dynamic balance between system stimuli and individual self-regulation. two-way adaptation in data interactions underscores the importance of maintaining stability and fluidity in the process of data interaction, especially in situations where users continuously need to harmonize with the system. This is evident in instances where the heart rate and cadence become unstable during running or when there are environmental disturbances and distractions.

Previous studies have explored interactive meditation supported by technology, integrating human sensory and bodily experiences with systems to regulate attention and maintain focus. For example, *Pause* (Niksirat et al., 2017; Cheng et al., 2016) encourages users to continuously touch a moving bubble with their fingers until it fills the screen, accompanied by a soothing ambient soundtrack for an immersive experience. *Sway* (Niksirat et al., 2019) detects slow and continuous body movements through the phone's gyroscope, providing audiovisual feedback to help users stay focused on the present moment. Some studies have also explored air- or tactile-based interactions integrated with physiological feedback to support interactive meditation (Claudia and Sas, 2020; Vasudevan et al., 2023). However, little study investigates the significance of sound and footstep interactions in mindfulness meditation. Although some studies have explored the positive effects of sound and footstep interactions in walking meditation (Chen et al., 2015; Cochrane et al., 2021), these studies focus primarily on one-way feedback (e.g., walking sonification (Hajinejad et al., 2016)), lacking in-depth exploration of two-way adaptive systems. In addition, running, as an acute and complex activity, introduces challenges such as instability of gait and heart rate, which frequently interfere with individual attention and mindfulness states (Havey, 2017; Brake et al., 2022). This contrasts starkly with the more peaceful environments when walking or sitting. The distinct nature of running poses new challenges to the applicability of sound and footstep interactions in running meditation.

In this study, we developed an adaptive sound system called RunMe. Our system presents the interaction mechanisms that provide a suitable sound stimulus according to the runners' biodata (e.g., heart rate) and behavioral data (e.g., cadence) for running meditation. Our system aims to provide adaptive real-time audio feedback to prompt users when distracted, rather than rigid tutorials (Niksirat et al., 2017, 2019). In our user study (N = 40), we investigated four conditions (see Section 5.4.1) to compare their impact on running meditation. The results of the study clearly indicate that our approach to design an adaptive sound system is more effective in supporting running meditation compared to the other conditions.

The contributions of this paper are threefold: (1) The development of RunMe represents an innovative step in the field of meditation technology, specifically tailored for running meditation. The study addresses a gap in existing technologies, which predominantly focus on sitting or walking meditation, by introducing a two-way adaptive sound system designed to enhance the running meditation experience. (2) The findings of this study highlight the superior performance of the RunMe group compared to other groups. RunMe not only excels in attention regulation and body awareness, but also demonstrates increased exercise motivation and mindfulness during running meditation. This underscores the potential of technology-supported interventions to positively impact both mental and physical aspects of wellness. (3) This study provides specific design implications for the development of a promising running meditation mechanism. It also aids future designers in reconceptualizing kinetic meditation practices, empowering them with a novel paradigm to construct innovative design practices.

5.2 Related Work

This section aims to help readers understand how technology supports meditation while running. First, we present a definition and mechanism of meditation practice. Second, since running meditation belongs to the category of kinetic meditation, we explain current studies of kinetic meditation using technology. Third, we introduce the concept of running meditation and explore the relationship between the biomechanics of running and mindfulness. Fourth, we investigate the interactions between sounds and footsteps for design.

5.2.1 Definition of Meditation

Drawing from the existing literature (Kabat-Zinn, 2018, 2023), we offer a comprehensive definition of meditation: a practice that involves mental training and the cultivation of a state of consciousness conducive to relaxation, heightened focus on attention and self-awareness. Meditation comprises various forms, with Concentrative Meditation (CE) being considered a popular method. This form of meditation requires practitioners to focus their attention on a specific object, such as sound, visual imagery, or body movements, and maintain this concentration for a period (Valentine and Sweet, 1999; Rao and Rao, 2017). For example, this study explores how users focus on their footsteps and the sounds provided by the system to help them maintain focus. CE involves two stages: the analytical phase and the placement phase (Gyatso, 2009). During the analytical phase, practitioners guide or restore their attention by reflecting on the meditation object, although a certain level of evaluative effort is still involved. Once practitioners achieve a sense of calmness, they gradually transition to the placement phase, the actual meditation stage. In this phase, practitioners experience a non-judgmental state of awareness, merely observing the flow of thoughts. If practitioners become distracted, they revert to the analytical phase to restore the meditative state.

In particular, distraction is a common challenge faced by people engaged in outdoor activities, often originating in a dynamic and stimulating environment. For example, factors such as natural sounds, changing landscapes, and unexpected events can divert the attention of practitioners from their meditative focus (Seuter et al., 2017). In these cases, the analytical phase serves as a valuable tool for practitioners to regain control over their attention and navigate interruptions effectively. Reflecting on the chosen meditation object during the analytical phase, individuals can reestablish a focused and centered state of mind, reinforcing the adaptability and resilience of concentrative meditation in running settings.

5.2.2 Technology Supports Kinetic Meditation

Kinetic meditation, which involves body movement with a focus on attention, has been recognized as a potential practice to improve mental health and well-being (Larkey et al., 2009). Kinetic meditation follows the same principles as static meditation, such as attention focus, mindfulness, and relaxation through body movement. There are numerous examples of this in traditional meditation practices, such as Tai Chi, Qigong, Yoga, or walking meditation (Schure et al., 2008; Davis et al., 2022). Increasingly, current studies suggest that kinetic meditation not only produces similar effects to static meditation, such as mindfulness (Schure et al., 2008; Curtis et al., 2011), relaxation (Niksirat et al., 2017; Kabir et al., 2018), stress reduction (Serpa et al., 2014; Hunt et al., 2018), and self-transcendence (Fiori et al., 2014; Malaver et al., 2022), it can also result in additional physiological and mental improvements, such as improved body awareness (Gibson, 2019; Chen et al., 2021a), creativity (Marson et al., 2021; Huang et al., 2023), skill training (Gray, 2020; Roychowdhury, 2021), and even the alleviation of pain (Venuturupalli et al., 2019; Yang et al., 2023). There has been a growing interest in using interactive technology to support kinetic meditation practices. For example, guidance-based instructions (Headspace, 2022) are presented as text, audio or video (e.g., Headspace (Headspace, 2022), Smiling Mind (SmilingMind, 2022), and Buddhify (Everywhere, 2022)) to guide users in meditation practice (Terzimehić et al., 2019).

In recent years, the embodied attention approach has emphasized the dynamic interaction between attention and body states. This approach highlights the importance of considering the body and its movements in the study of attention (Garg, 2012; Pustejovsky and Krishnaswamy, 2021). Many studies have explored the use of interactive systems that combine biofeedback and sounds to support mindfulness practices. For example, Dauden et al. (2021) developed an interactive system that uses heart rate variability as a measure of interoceptive awareness and provides real-time feedback through sounds to help users focus on their body sensations and attention processes (Claudia and Sas, 2021). The use of technology to support kinetic meditation practices is becoming an increasingly popular trend, specifically to improve interactions between body and mind by the mechanism design of *stimulation* and *regulation*.

Stimulation mechanism consists of detection and feedback technologies. By stimulating the human senses using sounds, users can improve their focus and body awareness during kinetic meditation (Niksirat et al., 2019). *Detection* technology can be used to monitor the physiological state of the user, such as skin conductance (Alawieh et al., 2019; Engelbregt et al., 2022), heart rate (Brown et al., 2021; Attar et al., 2021), breathing (Shih et al., 2019; Rahman et al., 2022), and pulse (Chen et al., 2021b), to adapt to the real-time response of the user. Detection technology can be combined with *feedback* technology. For example, utilizing biofeedback to assist users in regulating their physiological state to improve mindfulness meditation (Henchoz et al., 2021; Malaver et al., 2022). Notably, contemporary technologies have the capability to offer adaptive feedback by analyzing physiological data. This includes providing users with visual or audio representations of biological information (e.g., heart rate) via an application (Niksirat et al., 2019), as well as helping users regulate their state through sound commands or vibration feedback (Mahmoud et al., 2017). Adaptive stimulation can help users better control their physical state, enter a meditation state, and achieve physical and mental relaxation (Mahmoud et al., 2017; Niksirat et al., 2019).

Regulation mechanism can help users adjust their attention during meditation by synergistically enhancing each other through internal and external regulation mechanisms (Niksirat et al., 2017, 2019). The internal regulation mechanism can trigger a relaxation response by repeating a word, sound, breathing, or movement, thus achieving psychological relaxation and entering a state of mindfulness (Deepak, 2019; Amundsen et al., 2020). The external regulation mechanism can help users to better engage in internal self-regulation (Zev et al., 2020). For example, mindfulness-based mobile applications can monitor whether users are perform continuous, smooth, and rhythmic running exercises and help them adjust biological and behavioral data in real time while running (Kim et al., 2022). Through the combination of internal and external regulation, users can focus more effectively on the present moment, achieve psychological relaxation, and enter a state of mindfulness (Niksirat et al., 2019).

Studies consistently showed that stimulation or regulatory mechanisms can improve users' attention focus, body awareness, and mindfulness during kinetic meditation practices. These investigations emphasize the one-way design of interaction mechanisms, such as one-way rhythmic stimuli following music, to regulate one's gait (Headspace, 2022). This study advocates for the implementation of two-way adaptation (Ren et al., 2019) in the context of kinetic meditation and system adaptation. Despite a limited number of studies in the HCI community exploring this domain, for example, the attention regulation framework proposed by Niksirat et al. (2019), which guides the design of technology-supported interactive meditation, there is a notable gap in the exploration of this domain within the specific context of running. In particular, the intricacies of two-way adaptive interaction mechanism designs tailored for running meditation remain ununderstood. For example, the impact of body movements on attention focus and self-regulation in the context of running meditation has not yet been fully explored.

5.2.3 Understanding Meditation while Running

Running is one of the everyday physical and social activities. The rhythmic nature of running creates a connection between mind and body and helps runners to become aware of the present moment (Garrison et al., 2015; Mipham, 2012). Andy Puddicombe defines *mindful running* as the ability to run with clear intention, fully connected to body and mind, free from distraction and with an equal balance of focus and relaxation (Stieg, 2018). Similarly to walking meditation, meditation practice while running requires participants to focus their awareness at the moment (Bernier et al., 2009; Cochrane et al., 2021). When the mind of the runner wanders off and their pace becomes irregular, they are prompted to redirect their attention back to the present moment and to observe regularity in their rhythm and pace (Cathcart et al., 2014; Cochrane et al., 2021). This concept is not new; it is inspired by age-old regulation techniques, such as the use of Buddhist prayer beads and Tai Chi, where traditional mindfulness masters have used a variety of mediums for this purpose (Niksirat et al., 2019). To this end, we present a definition - "running meditation is a mindful exercise that combines running with heightened body awareness and focused attention, with the aim of harmonious integration of movement and focused awareness for holistic well-being."

Recent research has investigated the intricate connection between the biomechanics of running and mindfulness, shedding light on the interplay between physical and psychological factors that underlie the positive impact of running on mindfulness (Hollis et al., 2021; Ben et al., 2021). In particular, studies have revealed that running at moderate intensity, corresponding to a heart rate within the aerobic zone, has the potential to improve attention performance and elevate mood states (Yamamoto et al., 2023; Saddoud et al., 2023) - both pivotal components of mindfulness. Expanding the discourse to current advancements in physiological sensing technologies for exercise, it is noteworthy to consider how these technologies contribute to our understanding of the mind-body connection during running meditation. For example, wearable devices equipped with heart rate monitors and biofeedback mechanisms enable real-time tracking of physiological responses, offering valuable insights into the correlation between physiological states and mindfulness outcomes during running. Moreover, the rhythmic aspect of running has been explored as a facilitator of mindfulness, with running cadence, or the number of steps per minute, emerging as a significant factor (Ben et al., 2021; Havey, 2017). Studies suggest that manipulating running cadence can serve as a deliberate tool to induce a rhythmic stimulus, effectively regulating attention and breathing dynamics during running meditation (Burr et al., 2022). Beyond heart rate and cadence, the intricate interplay of biomechanical factors, such as the foot strike pattern and the running form, has surfaced in the discourse on running and mindfulness. These factors not only impact force distribution and injury prevention, but also contribute to the overall promotion of physical well-being and relaxation, a vital component of the holistic mindfulness experience.

Previous studies have shed light on the limited exploration of running meditation, despite its widespread adoption as a common daily exercise. The connection between running biomechanics and mindfulness is not well understood and this gap becomes more evident when considering the influence of technological interventions. Specifically, there is a scarcity of research on how mindfulness practices, such as focused attention on breathing, step cadence, or posture during running, affect biomechanical parameters. Furthermore, the impact of different mindfulness techniques, such as body scan meditation or mindful awareness of the surroundings, on running biomechanics remains largely unexplored. Although technologies have the potential to improve mindfulness and offer real-time biomechanical feedback, their specific effects on the intricate relationship between running biomechanics and mindfulness have not been thoroughly examined. Closing these gaps will lead to a more nuanced understanding of this relationship in both traditional and technologically mediated contexts.

5.2.4 Interactions between Sounds and Footsteps while Meditation

The use of sounds to facilitate kinetic meditation has generated growing interest (Cochrane et al., 2020, 2021), such as the impact of sounds on improving running performance (Lane et al., 2011; Edith and Leman, 2016) and reducing stress (Pieter et al., 2021). However, designing sounds that can provide real-time feedback during running and support kinetic meditation presents two challenging tasks. First, research emphasizes the need for adaptive sounds that align with each runner's unique characteristics. This enables the design of sounds to be tailored to individual preferences and running styles (Cornejo, 2021; Ballmann, 2021). Second, sounds offer real-time feedback to runners to optimize their performance, including pace, breathing, and posture, leading to optimal performance and meditative states (Ballmann, 2021). This requires accurate algorithms and sensors to capture and interpret the physical and physiological data of runners.

Although some studies have provided real-time feedback through sounds (Ettehadi et al., 2020; Niksirat et al., 2019), the system requires a high level of technical experience and is not user-friendly enough. Sound design should also consider potential interference factors that can arise during the use of sounds during running. For example, the study found that the use of fast-paced music during running increases the risk of injury because it encourages runners to exceed their physical limits (Phoenix and Bell, 2019). Thus, it is necessary to design sounds that balance the stimulating and relaxing effects of sounds while avoiding potential interference factors that can interfere with the physical and mental health of runners.

Based on previous studies in the interaction design between sounds and footsteps (Tajadura-Jiménez et al., 2015; Turchet et al., 2016), sounds can first be designed more finely and introspectively (e.g., natural environmental sounds) to adapt to the tranquility and introversion of meditation environments (Niksirat et al., 2017). This requires designers to reduce sound elements that can disturb meditation while maintaining interaction functionality. Second, the design of interactions between sounds and footsteps also faces challenges because footsteps during meditation can be very different from daily running (Cochrane et al., 2021; Bigliassi et al., 2020), which requires the development of new mechanisms of recognition and analysis of footsteps to adapt to this special scenario. The design of the interaction between sounds and footsteps can help users adjust their footsteps and running rhythm through adaptive feedback.

In summary, existing studies have investigated the interaction design between sound and footsteps. However, a critical examination of previous studies reveals a predominant focus on supporting meditation practices through interactions rooted primarily in finger, hand, or leg movements with sound systems (Niksirat et al., 2017, 2019). Remarkably lacking in this discourse is the attention given to investigating the potential and value of integrating footstep and sound interactions specifically tailored for running meditation. This omission underscores a significant gap in the research landscape, raising questions about the comprehensiveness and applicability of current findings in the broader context of running meditation practices.

5.3 RunMe: An Adaptive Sound System for Running Meditation

To investigate the proposed high-level interaction mechanism to support the design of running meditation technology, in this section, we describe the process for the design and development of RunMe: an adaptive sound system for running meditation in outdoor settings (Figure 5.1). RunMe aims to help runners achieve a mindful state in running by incorporating three aspects: adaptive stimuli, running regulation, and attention focus without judgement (Sas and Chopra, 2015; Zhu et al., 2017).

5.3.1 Design Framework of RunMe

The design of RunMe encompasses the interaction mechanisms (Figure 5.2) between (1) stimulation and (2) regulation using a smartwatch, earphones, and mobile phones, and (3) integration of the data interactions between the user data and the adaptive sound system.

Stimulation design. The *stimulation* mechanism (Figure 5.2a) is designed to synchronize with user's cadence and enhance interaction cycle. The purpose of this mechanism is to keep users focused on their body sensations and sensitive to the rhythm of the sounds they are experiencing. By resonating with the user's cadence, the stimulation mechanism helps create a harmonious connection between the user's physical

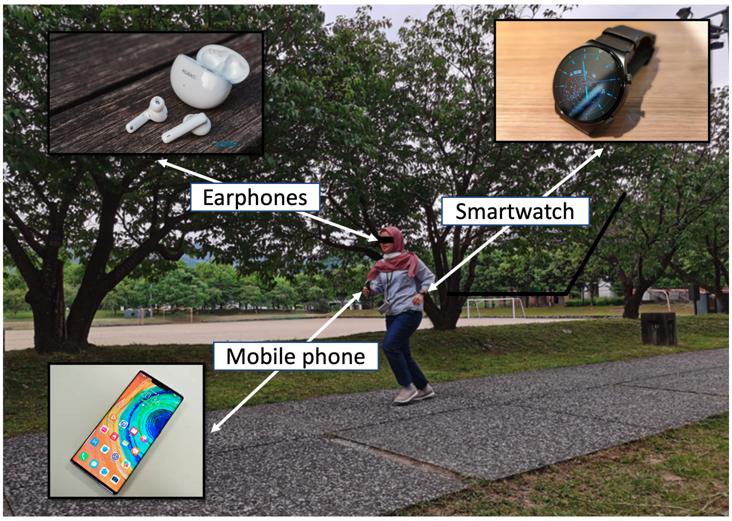


Fig. 5.1: The diagram depicts running meditation practice in outdoor using an adaptive sound system that integrates mobile phone, earphones, and smartwatch.

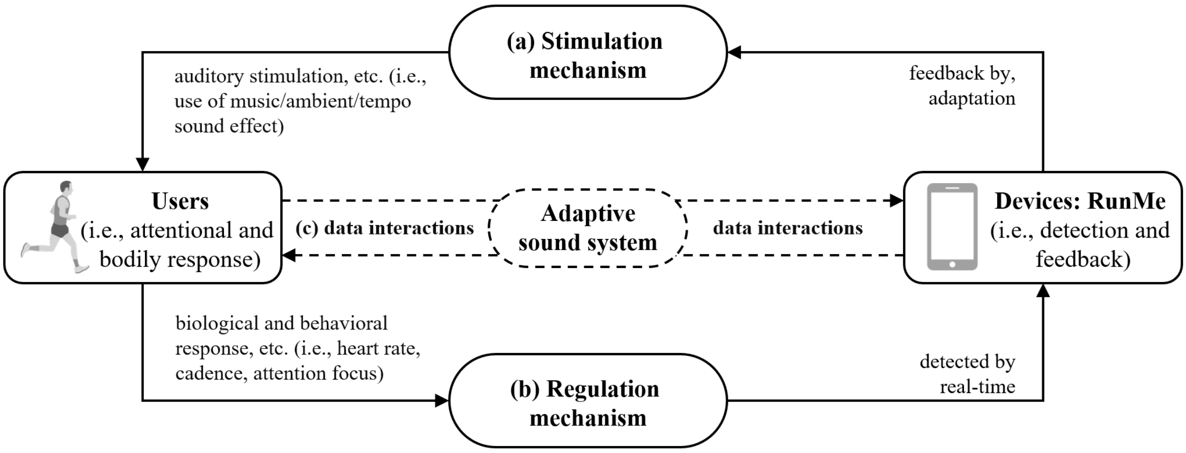


Fig. 5.2: A high-level design framework of the interaction mechanism in (a) stimulation design, (b) regulation design, and (c) integration of data interactions for running meditation.

movements and the rhythm of the sound. RunMe detects heart rate and cadence data using a smartwatch to regulate stimulation of the sounds which are transmitted via earphones. These devices vibrate and stimulate in a manner that aligns with the user's movement and music's beat.

The stimulation mechanism aims to provide proper soft stimuli, i.e., *ambient music*, *tempo sounds*, and *soft cues*. Ambient music*1 includes natural sounds such as chirping birds, flowing water, or rustling leaves. These sounds can create a calm and serene atmosphere, promoting relaxation and a sense of connection to nature during running

*1 https://noises.online/.

practice (Cochrane, 2019; Cochrane et al., 2020). Tempo sounds effects (i.e., beats) are recorded on the basis of MixPad Multitrack Recording Software, and designed to synchronize with the user's running cadence and provide a rhythmic audio backdrop. This can help runners maintain a consistent pace or align their movements with the beat of the music, sustaining them by enhancing their sense of rhythm and motivation (Cochrane et al., 2020; Dvorak and Eugenia, 2021). Soft cues*[2], that is, brown noise (e.g. the sound of a singing bowl being struck (Goldsby et al., 2017)), refer to gentle and subtle prompts or stimuli that help runners maintain focus and mindfulness. They serve as reminders to help runners remain attentive and prevent their thoughts from wandering. Auditory stimuli are designed on the basis of adaptive feedback, which is derived from the user's real-time responses. Audio with distinct rhythms (e.g., tempo) can help users focus on internal cues and improve body awareness (Jackson, 1995; Sheldon et al., 2015). The design strategy of the stimulation mechanism aims to use ambient music to eliminate judgmental disturbances, improve relaxation, and maintain immersion during running meditation. Furthermore, the strategy aims to help users regulate their attention throughout meditation practice (Csikszentmihalyi, 1990; Sheldon et al., 2015).

The design of adaptive stimulation provides real-time sounds synchronized with the user's rhythm during running activities. The integration of smartwatches and earphones implies that sounds are transmitted through earphones, in sync with user movements and the beat of the music. During this process, users are instructed to understand different sounds and adjust their running cadence accordingly. For instance, ambient music occurs throughout the running activity. Tempo, in contrast, appears in training sessions. Tempo integrates with ambient music and provides adaptive feedback in response to changes in the running data. Soft cues are presented in a gradually increasing manner when the user's running data exceed a threshold, at which time they receive reminders to adjust their cadence.

Regulation design. The *regulation* mechanism (Figure 5.2b) in this study aims to facilitate a state of mindfulness by regulating the attention and cadence of users while running. The regulation mechanism operates based on real-time heart rate and cadence data. This mechanism includes two elements: (1) Attention regulation: When the user's heart rate or cadence deviates from the specified range, the system intervenes to regulate the attention. RunMe adjusts the volume or switches to playing the tempo with ambient music, serving as cues for the user to adjust their pace and focus. This

*[2] https://mynoise.net/.

mechanism can be explained by the relaxation response principle, which refers to a state of deep rest and is the opposite of the fight-or-flight response (Benson et al., 1974; Peters et al., 1977). (2) Cadence regulation: Changes in heart rate and cadence are recorded by system. Volume variations and tempo changes in ambient music are used as external regulatory cues to help users adjust their cadence and maintain focus. The system provides flexible feedback, allowing users to regulate their subconscious cadence without judgmental awareness.

Users learn to understand the meaning of stimulation to regulate their running rhythm through four elements: (1) they learn the concept of relaxation response and its importance in achieving a state of mindfulness during running. (2) The specified heart rate and cadence ranges that indicate deviation from the desired state are explained. Guidance on interpreting volume variations and changes in tempo within ambient music as cues for adjusting pace and focus is provided. (3) Users are encouraged to develop awareness of their body sensations and functions, such as pace and breath, while participating in continuous and rhythmic running exercises. (4) Users draw inspiration from traditional mindfulness activities such as Buddhist prayer beads and Tai Chi, conditioning them to focus on the present moment through regular and unhurried movements.

Integration of data interactions. The *integration of the data interactions* (Figure 5.2c) in RunMe, involving cadence, heart rate, and sounds, is designed to enhance user self-regulation during running meditation. By utilizing the heart rate and cadence data collected from the smartwatch phone, RunMe dynamically adjusts the tempo and ambient music played through the earphones. This integrated feedback system consists of two components: "heart rate versus ambient music" and "cadence versus tempo sounds".

Based on our pilot studies and previous work (Gu et al., 2017; Prigent et al., 2022), we established a running meditation heart rate range of 100-170 beats per minute; this was further divided into three intervals within this range. Once the running exercise begins, the system initiates a 60-second preparation time, during which it assesses the user's heart rate. Based on heart rate detection, the system selects an appropriate speed for the ambient music to play. If the user's heart rate is too fast or too slow, the volume of ambient music is reduced, serving as a reminder for the user to adjust his/her pace and to maintain focus. Similarly, in the context of cadence, if the user's pace deviates from the desired range, the system responds by playing brown noise instead of ambient music. Ambient music serves as a rhythmic cue that aligns with the user's cadence.

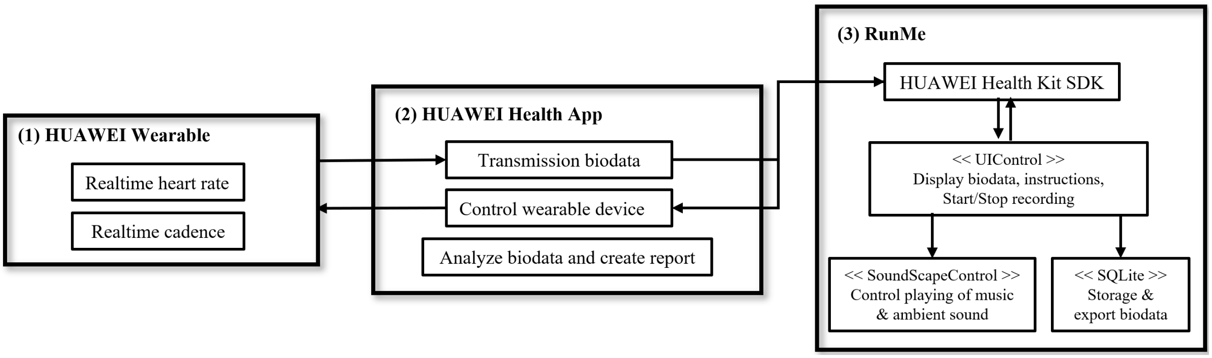


Fig. 5.3: The diagram depicts the architecture of RunMe.

This requires the user to remain attuned to their bodily sensations and sensitive to the rhythm of the music. By integrating data interactions, RunMe provides users with real-time feedback that helps them regulate their running experience. Adjustments in tempo, volume, and sounds serve as external cues. These cues guide users to align their cadence and heart rate within the desired ranges, promoting a state of mindfulness and improving the running meditation experience.

5.3.2 System Development of RunMe

In this section, we describe the technical development of RunMe, detailing both the architecture and the algorithms used for system operation and data interactions.

Architecture. Following Figure 5.3, the architecture of RunMe comprises three components: (1) a HUAWEI wearable smart watch to capture the users ' heart rate and cadence, (2) Huawei Health Kit, which is a android application responsible for transmission the users ' biodata in real-time and analyze biodata after running exercise; and (3) RunMe is the Android App which involved the HUAWEI Health Kit API and cover adjusting music & ambient music in real time according to the users ' biodata. Meanwhile, RunMe will show the suggestion and control the wearable device to start/stop recording biodata according to users ' real-time movement status.

Algorithms. We provide the algorithms of RunMe for monitoring and estimating data interactions during running meditation, which includes two parts as shown in Figure 5.4 First part - algorithm 4 shows data interactions of heart rate and ambient music. Second part - algorithm 5 shows data interactions of cadence and ambient music. Both algorithms support the user by providing adaptive sounds.

As shown in Figure 5.4a and algorithm 4, if the system detects a heart rate below

Algorithm 4 Heart rate (HR) monitor and estimation

```
while HR changes every 1 second do
  if HR < 100 OR HR > 170 then
    Stop running
    PrintMsg: HR too high/low, please retry;
  else if HR < HR1/HR2/HR3 − 20 OR HR > HR1/HR2/HR3 + 20 then
    Stop running
    PrintMsg: HR out of scope, please retry;
  else if HR < HR1/HR2/HR3 − 13 OR HR > HR1/HR2/HR3 + 13 OR HR <
  107 OR HR > 163 then
    PrintMsg: Detecting a significant change in HR, maintain your pace
    MusicFadeOut volume from 100% to 30%;
  else
    PrintMsg: Well done, keep your pace
    MusicFadeIn volume from 30% to 100%;
  end if
end while
```

Algorithm 5 Cadence (Ca) monitor and estimation

```
while Ca changes every 1 second do
  if Ca < Ca1/Ca2/Ca3 − 20 OR Ca > Ca1/Ca2/Ca3 + 20 then
    PrintMsg: Keep your pace following tempo
    Oceanwave noise CrossFadeOut and stop
    Brown noise CrossFadeIn and play;
  else
    PrintMsg: Well done, keep your pace
    Brown noise CrossFadeOut and stop
    Oceanwave noise CrossFadeIn and play;
  end if
end while
```

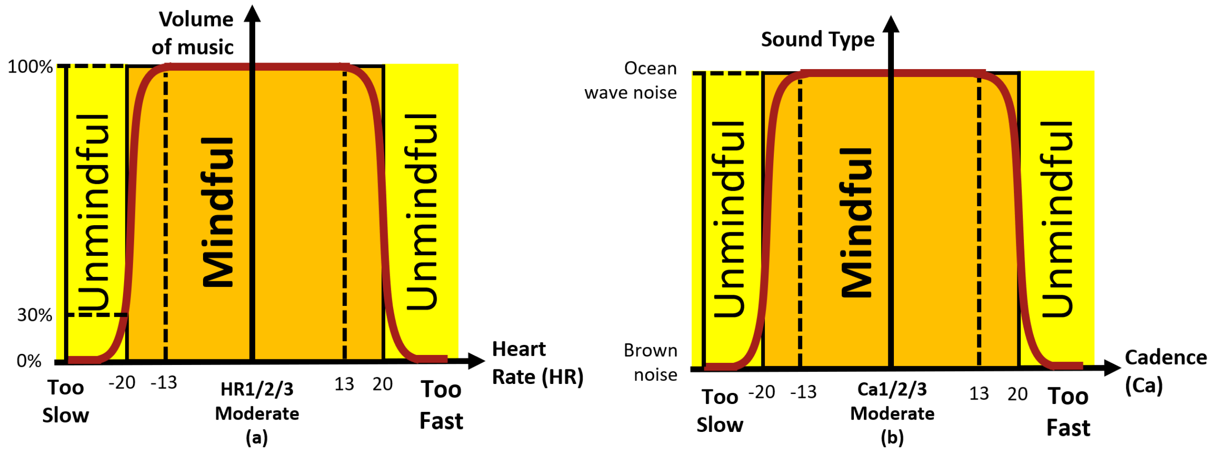


Fig. 5.4: The diagram depicts estimation of (a) heart rate versus volume of music, (b) cadence versus sound type. It aims to achieve data interactions (Niksirat et al., 2019) for maintaining regular running meditation using an adaptive sound system.

100 or above 170, it stops the output of all sounds and alerts the user about the excessively high or low heart rate, indicating a failed running attempt, prompting the system to restart. Upon entering the adaptive training phase, the system periodically monitors the user's heart rate and cadence within each session and provides adaptive feedback. At the beginning of each adaptive phase, the system uses (1) heart rate detection data (HR1, HR2, HR3) to determine the corresponding music BPM and the specified exercise HR range; (3) cadence detection data to determine the specified cadence range to play ocean wave noise or brown noise. Subsequently, the system continuously monitors heart rate (HR) and cadence (Ca) in real-time across different sessions to check if they deviate from the intended range. The ideal heart rate range is within positive and negative 20. If the detected heart rate exceeds this range, the test is stopped. To enhance the user experience, the system employs a buffering alert mechanism. When the heart rate range is within positive and negative 13, the system gradually reduces the volume of ambient music (oceanwave noise) from 100% to 30%, signaling significant heart rate fluctuations to the user. Once the user's heart rate returns to the ideal range, the system increases the ambient sounds volume from 30% to 100%.

As shown in Figure 5.4b and algorithm 5, the ideal cadence range is within positive and negative 20. When the system detects a cadence outside this range, it prompts the user to adjust their cadence to match the system's tempo sounds. At this point, ambient music gradually fades out, and soft cues (brown noise) begin playing. The ambient music gradually returns, and soft cues stop as soon as the user's cadence falls within the ideal

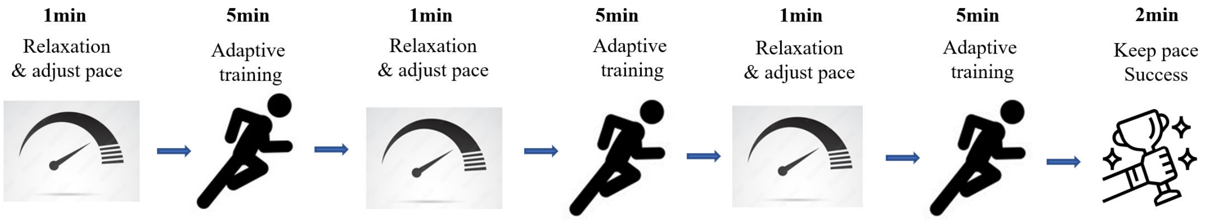


Fig. 5.5: The diagram depicts general workflow using RunMe to support running meditation.

range.

5.4 User Study

This study aims to investigate an adaptive sound system, i.e., RunMe, that has a positive effect on the experience of running meditation. We conducted a user study and evaluated the results using self-assessment methods. This study was approved by the Ethics Review Committee of the University.

5.4.1 Experiment Design

Figure 5.5 illustrates the timeline of the RunMe application supporting mindfulness training during running. Within this 20-minute period, there are three sessions dedicated to training and a buffer for stable data collection. Each session consists of a one-minute relaxation phase and a five-minute adaptive training phase. During the relaxation phase, the system monitors data without providing any feedback. The main purpose of the relaxation phase is to allow the subjects to stabilize their heart rate and adjust their rhythm. Due to limitations in the initial system response, the system initialization only takes 30 seconds in the first minute to record the user's heart rate and cadence data reliably.

Our goal was to explore the varying effectiveness of running meditation in four conditions, with a specific emphasis on evaluating the RunMe system. To accomplish this, we employed an experimental design between subjects, ensuring that each participant experienced only one condition, allowing for a robust assessment of the independent effects of each condition. Our focus was particularly directed at discerning differences in the effectiveness of the RunMe system, as described in Figure 5.6a. Next, we describe four conditions.

Adaptive sound system (RunMe). Utilizing this system, as shown in Figure 5.6a

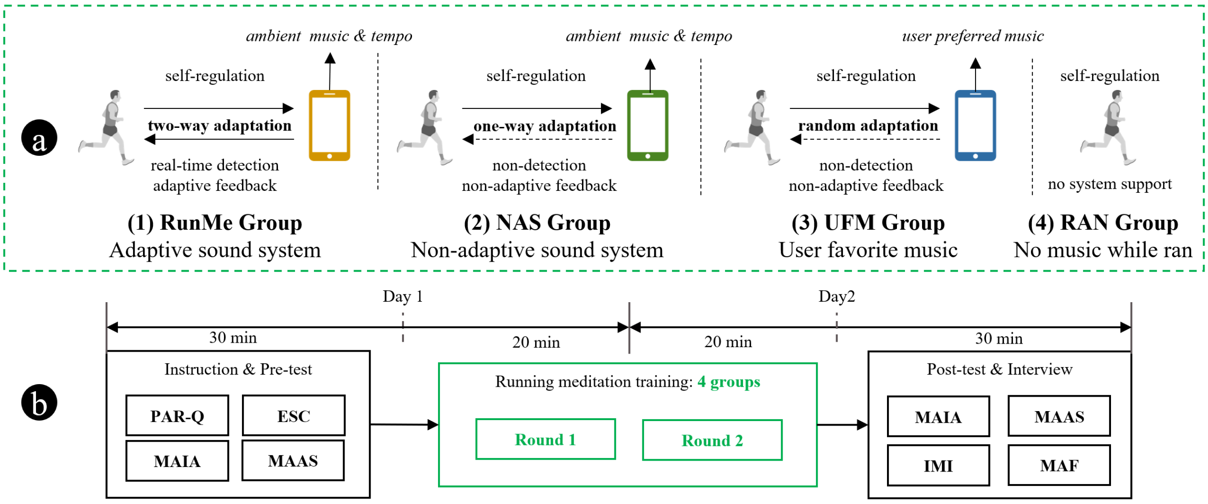


Fig. 5.6: The diagram depicts (a) differences in the grouping conditions of the user study; (b) experimental procedures and data collection methods.

- (1), users have the freedom to run while the system concurrently monitors real-time changes in their footsteps and heart rate. Specifically, RunMe facilitates seamless and two-way interactions, wherein users' physiological and behavioral data can be detected in real-time, providing adaptive auditory feedback, such as ambient music and tempo. The feedback is rhythmic to aids users in adjusting their footsteps, thereby maintaining a regular and rhythmic motion, ultimately assisting users in sustaining a continuous state of focus. During running, characterized by rhythmic patterns, users may experience disruptions in footsteps and heart rate as they reach a certain level of fatigue. RunMe has the capability to detect such variations in the user and adaptively adjust the feedback rhythm of the sound system. The system gradually aligns itself with the user's rhythm, prompting users to consciously modify their pace in order to progressively attain an optimal running state.

Non-adaptive sound system (NAS). As shown in Figure 5.6a - (2), users synchronized their running cadence with the rhythm emitted by the system in a conscious, one-way adaptation process. Simultaneously, the system neither collected user data nor delivered adaptive feedback.

User favorite music (UFM). In this condition, as shown in Figure 5.6a - (3), users listened to their favorite music from their daily playlists (e.g., classical, pop, or rock music) while running. Users were free to synchronize their footsteps with the beats in the music, but it was not mandatory. Notably, this system did not include a trial detection and feedback function.

No music while ran (RAN). As shown in Figure 5.6a - (4), users ran only without any music or sound and self-regulated their running cadence.

The RunMe, NAS and UFM groups were the experimental groups; the RAN group was the control group. The experiment consisted of 10 participants × 4 conditions × 2 repetitions = 80 trials.

5.4.2 Apparatus

As shown in Figure 5.1, a HUAWEI P50 smartphone (Android OS) was used to run our sound feedback system. The HUAWEI Watch GT 3 smartwatch and HUAWEI Freebuds 4i wireless earbuds were used to detect heart rate and cadence and provide audio feedback while running. We used Java to develop our application. The application is supported by the HUAWEI Health Kit API.

5.4.3 Participants

Forty university students and staff (12 women, 28 men) aged 20 − 44 (mean = 26, SD = 5.23, median = 25) were recruited. All participants had no body injury, no history of cardiovascular injury (heart attack or stroke), no acute severe fatigue, no lightheadedness, dizziness or nausea while running. Two of the participants had some experience in meditation practice (i.e., Zen - Japanese meditation), while the rest of the participants had never experienced meditation. No participants had experienced meditation while running. The nationality of the participants was as follows: Chinese (n = 17), Japanese (n = 13), Indian (n = 4), Indonesian (n = 3), Thai (n = 3). Each participant was paid 2000 yen (Japanese currency).

5.4.4 Procedure

The experiment procedure consisted of three parts: instructions and pre-test, running meditation training, and post-test (Figure 5.6b). Each participant completed the experiment over two consecutive days. The experiment was carried out between 1 pm and 6 pm each day.

Instructions and pre-test. Upon arrival, all participants were asked to complete the questionnaires of PAR-Q+ questionnaires (Warburton et al., 2011) and Exercise Stage of Change (ESC) (Zhu et al., 2014). These questionnaires were used to assess the suitability of the participants for running exercises and to collect background information related to running and mindfulness training. We report the results of ESC and PAR-Q + in Section 5.4.3. After passing the ESC and PAR-Q+ assessments, each participant received a study description and brief introduction to the experimental procedure. This included an explanation of the different conditions for each group and instructions (Headspace, 2022) on how to practice meditation while running. After signing the consent form, the study began. The first step was to set up the devices. Participants were asked to wear headphones, mobile phones, and smartwatches, with the control group only wearing smartwatches. Then, calibration tests were conducted for sound and physiological and behavioral data. The second step was that participants completed the Multidimensional Assessment of Interoceptive Awareness (MAIA) (Machorrinho et al., 2019) and the Mindful Attention Awareness Scale (MAAS) (MacKillop and Anderson, 2007; Claudia and Sas, 2021) forms to assess their level of body awareness and mindfulness before training.

Running meditation training. All participants had two rounds of 25 minutes of running meditation training. Participants in the RunMe and NAS groups were asked to watch an instruction video to learn how to use RunMe. Before each running session, users would perform a 5-minute slow jog to warm-up. The total duration (Figure 5.5) of the entire process using RunMe (i.e., the AS group) was 20 minutes. This included three sessions (18 minutes total) where each session consisted of 1 minute of adjustment time, approximately 5 minutes of music time, and a relaxation pace (warm-down) of 2 minutes at the end of the third session. The purpose of setting the preparation time was to allow the user to adjust his pace and restore heart-rate stability. The baselines of heart rate and cadence while running were set based on sports science standards (Brake et al., 2022; Adams et al., 2018), wireless watch detection standards (Fortmann et al., 2012; HUAWEI, 2022), and our pre-test data. As shown in Figure 5.6a, the NAS group, compared to the RunMe group, did not provide adaptive feedback through the RunMe system. The UFM group used a selection of the user's favorite music during running meditation training. The RAN group did the meditation practice while running without any sound system support.

Post-test. After training, participants were asked to complete the MAIA, MAAS, Measure of attention Focus (MAF) (Atchley, 2011), and Intrinsic Motivation Inventory (IMI) (McAuley et al., 1989; Mahmoud et al., 2017) questionnaires to assess their level of body awareness and mindfulness, attention strategies, and motor motivation. Furthermore, participants were asked to complete an interview to evaluate their subjective experience (e.g., attention focus, self-regulation, and mindfulness) during running meditation.

5.4.5 Metrics

The experiment collected subjective and objective user evaluations through questionnaires (i.e., IMI, MAIA, MAF, and MAAS) and semi-structured interviews with runners.

Questionnaires. (1) We used the *MAIA* (Machorrinho et al., 2019) to understand multidimensional changes in the users' subjective experience while performing running meditation. This was measured on a 5-pt Likert scale ranging from 1 to 5. The questionnaire comprises 37 items divided into eight scales: noticing, non-distracting, not-worrying, attention regulation, emotional awareness, self-regulation, body listening, and trusting. (2) We used the *MAAS* (MacKillop and Anderson, 2007; Claudia and Sas, 2021) which comprises 15 items to understand awareness of user mindfulness and attention while running under various conditions. This was measured on a 7-pt Likert scale ranging from 1 to 7. This is a standardized instrument widely used to assess state mindfulness (Brown and Ryan, 2003). (3) We used the *IMI* (McAuley et al., 1989; Mahmoud et al., 2017) to understand how embodied meditation affects user motivation while running. It is measured on a 7-pt Likert scale ranging from 1 to 7. It comprises 30 items divided into five scales: interest/enjoyment, perceived competence, effort/importance, pressure/tension, and value/usefulness. (4) We use the *MAF* (Atchley, 2011) to understand the state of attention focus while running meditation. It is measured on a 10-pt Likert scale ranging from 1 to 10. It comprises 6 items: body sensations, task relevant thoughts, self-talk, task relevant external cues, task irrelevant thoughts, and external distractions. Participants were asked to estimate the percentage of their attention assigned to each part during running meditation. The total of the six questions should be 100%. All questionnaires were completed in Google Sheets online.

Semi-structured interviews. To understand the rationale of each participant, we conducted a semi-structured interview on the user experience associated with attention and body awareness and mindfulness meditation while running in the four groups. The interview questions that we designed mainly include (1) Where your focus or attention was directed. Did it move? What triggered changes in your attention? (2) What is your body awareness like when you run? (3) What is the impact of sound and running on your overall experience? (4) When you experienced distractions, what strategies did you use to redirect your focus back to meditation? (5) Share your thoughts on the adaptive sound system.

5.5 Results

In this experiment, we assumed that RunMe can effectively support user attention and body regulation for mindfulness meditation while running. We present the results of the questionnaires and interviews between four conditions: adaptive sound system (RunMe), non-adaptive sound system (NAS), user favorite music (UFM), and no music while ran (RAN).

5.5.1 Questionnaires

To analyze the results of questionnaires, we (1) tested the data using the Kolmogorov-Smirnov test and the homogeneity of variance using Levene's test, and (2) used Repeated Measures Analysis of Variance (RM-ANOVA) with Mauchly's test for data correction. Questionnaires were analyzed using a mixed methods approach, that is, 4 × 2 mixed ANOVA comparing time (within-subjects: pre-test vs. post-post) and intervention (between-subjects: RunMe group vs. NAS group vs. UFM group vs. RAN group). Post hoc comparisons were made using Bonferroni correction, and significance was established at $\alpha = 0.05$. Statistical analysis was performed using SPSS ver. 25 (SPSS, Chicago, IL, USA).

Interoceptive awareness. We found significant differences within four groups in terms of pre- and post-intervention measures (Table 4.1). Specifically, the RunMe group showed significant improvements in N (M = 4.15, SD = 0.13) and ND (M = 4.08, SD = 0.36), as well as AR (M = 4.08, SD = 0.19). The NAS Group also showed significant improvements in N (M = 3.88, SD = 0.27), ND (M = 3.50, SD = 0.27), and AR (M = 3.04, SD = 0.32). The UFM group demonstrated significant improvements in N (M = 3.67, SD = 0.33), ND (M = 3.47, SD = 0.26), AR (M = 3.50, SD = 0.29), and SR (M = 3.88, SD = 0.34). In addition, the RAN group did not show significant improvements.

Post hoc tests were performed to compare the differences between the groups (Figure 5.7). The results revealed that the RunMe group showed significantly higher improvements in N compared to the UFM group (p <0.005) and the RAN group (p <0.005). The NAS Group (p <0.005) and 3 (p <0.01) showed significantly greater improvements in N compared to the RAN group. The RunMe group (p <0.005) showed

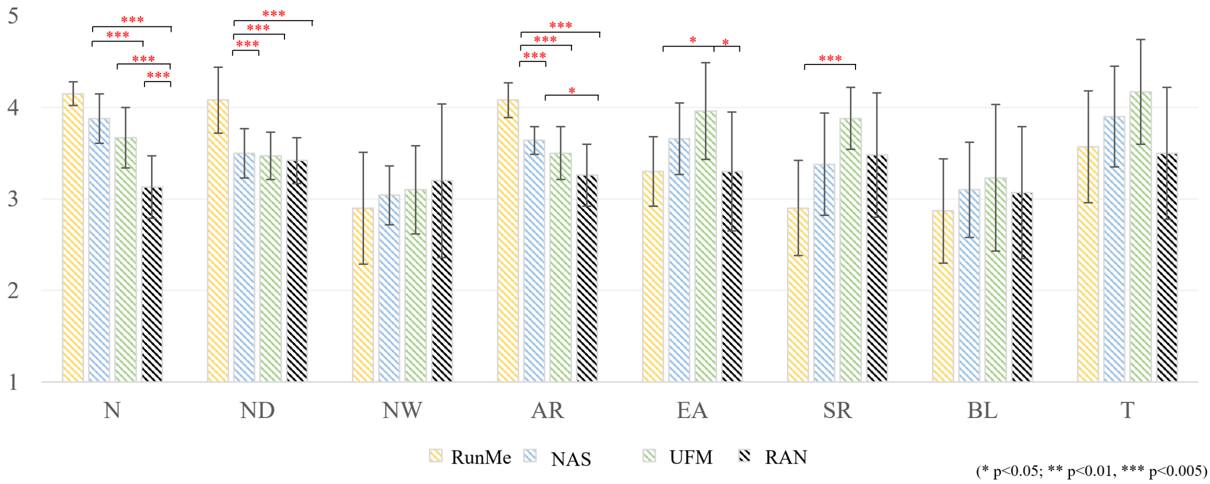


Fig. 5.7: Significant differences in post-test scores of participants were observed for Noticing (N), Non-distracting (ND), Not-worrying (NW), Attention Regulation (AR), Emotional Awareness (EA), Self-regulation (SR), Body Listening (BL), and Trusting (T) from the Multidimensional Assessment of Interoceptive Awareness scale.

significantly greater improvements in ND and AR compared to all other groups, while the NAS Group (p <0.05) showed significantly greater AR improvements compared to the RAN group. The UFM group (p <0.05) showed significantly greater improvements in EA compared to the RAN group, while no significant differences were found for NW, BL or T. Interestingly, there was an unexpected finding that the UFM group showed significantly higher improvements in EA (p <0.05) and SR (p <0.005) compared to the RunMe group. Through interviews during the post-test, we found that the reason for this result is that the sound based on user preferences brings more familiar stimuli to users. This familiarity makes them more focused and comfortable with emotional and body aspects, leading to increased active self-regulation. However, this does not mean that the UFM group is better than the RunMe group. Because running meditation is an overall experience, especially the impact of changes in attention regulation and body awareness on the state of mindfulness.

Mindful awareness. We found significant differences within four groups in terms of pre- and post-intervention measures. Specifically, all groups showed significant improvements in mindfulness during running meditation (Table 4.1). Post hoc tests (Figure 5.8) were performed to compare the differences between the groups. The results revealed that the RunMe group (M = 5.13, SD = 0.24, p <0.005) demonstrated significantly greater improvements in mindfulness compared to the other three groups. The NAS Group (M = 4.41, SD = 0.31, p <0.05) showed significantly greater improvements in

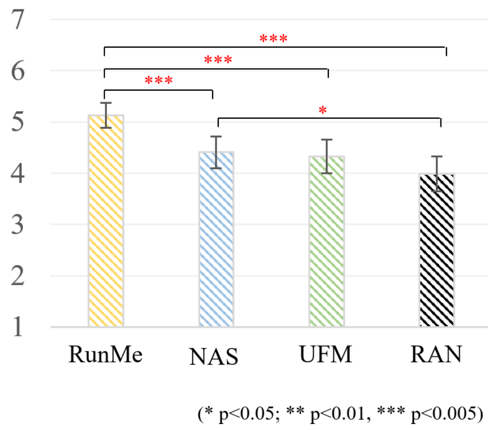


Fig. 5.8: Significant differences in post-test scores of participants were observed in performance of mindfulness from the Mindful Attention Awareness Scale.

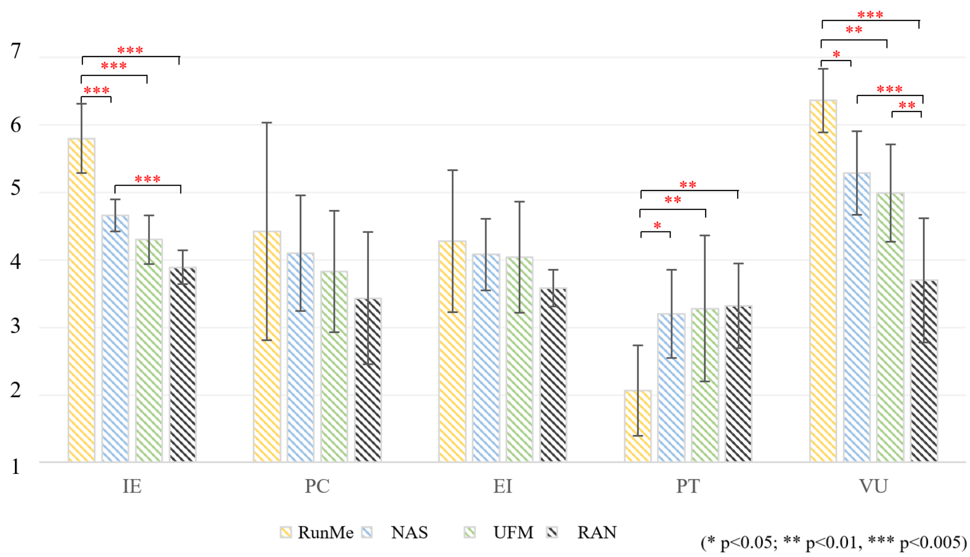


Fig. 5.9: Significant differences in post-test scores of participants were observed in Interest/Enjoyment (IE), Perceived Competence (PC), Effort/Importance (EI), Pressure/Tension (PT), and Value/Usefulness (VU) from the Intrinsic Motivation Inventory scale.

mindfulness compared to the RAN group. Interestingly, the UFM group did not show any significance compared to other groups. This point can be referred to the evaluation of Interoceptive Awareness in Section 5.5.1. Familiar/favorite music can promote the user's emotions and self-regulation, but it does not have a positive effect on the state of mindfulness, especially in a running environment. Overall, the results of the post hoc test showed that the RunMe group was significantly better than the other groups in enhancing the mindfulness state.

Intrinsic motivation. Post hoc tests were then conducted to compare differences between groups (Figure 5.9). The results revealed that the RunMe group showed sig-

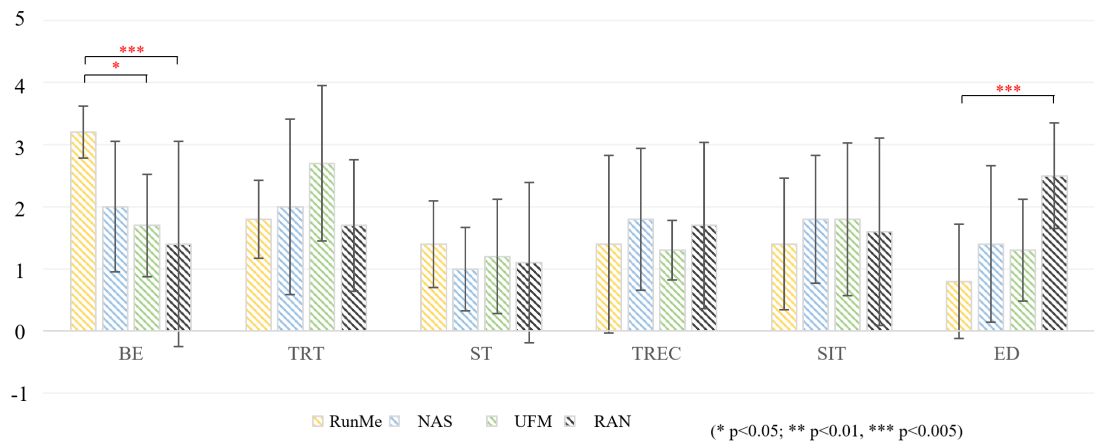


Fig. 5.10: Significant differences in post-test scores of participants were observed in Body Sensations (BS), Task Relevant Thoughts (TRT), Self-Talk (ST), Task Relevant External Cues (TREC), Task Irrelevant Thoughts (TIT), and External Distractions (ED) from the Measure of Attention Focus scale - short form.

nificantly greater improvements in IE (M = 5.80, SD = 0.51, p <0.005) and VU (M = 6.36, SD = 0.47, p <0.05) compared to the other three groups. Additionally, the NAS Group (p <0.005) demonstrated significantly greater improvements in IE (M = 4.66, SD = 0.24) and VU (M = 5.29, SD = 0.62) compared to the RAN group (Table 4.2). The UFM group (p <0.005) showed significantly greater improvements in VU (M = 4.99, SD = 0.72) compared to the RAN group. In particular, there was an unexpected finding that the NAS Group (M = 3.20, SD = 0.65, p <0.05), the UFM group (M = 3.28, SD = 1.08, p <0.01), and the RAN group (M = 3.32, SD = 0.63, p <0.005) showed significantly greater improvements in PT compared to the RunMe group (M = 2.06, SD = 0.67). We interviewed the RunMe group and 3 participants pointed out that the tempo in an adaptive sound system made them feel stressed. They mentioned that they did not initially adapt to the tempo, resulting in disordered steps and emotional oppression.

Attention focus. We counted the proportion of each category and found that the RunMe group (32%) was significantly higher than other groups in terms of BS. The UFM group (27%) was significantly higher than other groups in TRT, while the RAN group (25%) was significantly higher in ED than other groups. When we conducted group comparisons (Figure 5.10), we found that the RunMe group (M = 3.20, SD = 0.43) showed significant differences compared to the UFM group (M = 1.70, SD = 0.82, p <0.05) and the RAN group (M = 1.40, SD = 1.65, p <0.005) in terms of BS. Additionally, the RAN group (M = 2.50, SD = 0.85, p <0.005) demonstrated significant differences compared to the RunMe group in terms of ED (Table 4.2). The latter is within our expectations. This is because there is no support from the sound system when outdoors, and the interference of environmental factors on the subjects is significant.

5.5.2 Interviews

We presented a subjective and integrative description based on data from the five questions in the interview outline (see Section 5.4.5). The content of the interview was fully transcribed and coded using a hybrid coding approach (Fereday and Muir-Cochrane, 2006), and meaning-based labels were created to analyze the interviews.

Attention awareness and self-regulation. All participants mentioned that running meditation helped them relax. Participants' attention fluctuated dynamically between music and environmental stimuli. Some participants reported thinking about other things while running, but most tried to stay focused on meditation. Some participants mentioned that the rhythm of the environment and music affected their attention. In this regard, the results are consistent with existing related research results. Participants can experience distraction during tasks. To refocus their attention on meditation, participants used different self-regulation strategies, such as adjusting the rhythm of running and breathing, self-suggestion, self-talk, and following the rhythm of the music. For instance, $\mathrm{P8}_{RunMe}$: *"There were several moments when I was distracted by the circumstances, especially because there were a lot of people around the field. But it just happened for a moment and I was able to get back on track again through self-regulation."* $\mathrm{P4}_{RAN}$: *"I adjusted my breathing and paid more attention to the music."* Participants believed that these strategies could help them focus their attention and better engage in the task. $\mathrm{P2}_{RunMe}$: *"I self-directed and refocused, telling myself, focus, focus, and focus."*

The participants also mentioned that the rhythm of the environment and music could also affect their attention. Some participants stated that they would choose appropriate music to help them stay focused and relaxed, while others preferred to immerse themselves in natural environments while running. $\mathrm{P5}_{UPM}$: *"I imagined myself walking in the countryside or running by the sea, depending on the type of music."* The participants mentioned that running meditation could help them relax and that practicing running meditation before or after tasks could help them better control their emotions and anxiety. Participants believed that running meditation could help them perform better tasks, better manage their emotions, and cope with stress in daily life.

Body awareness and self-regulation. Running meditation practice can help participants better perceive and understand their own body state. Participants can feel the sensation of the soles of their feet, the depth and rhythm of breathing, and changes in heart rate during running. This allows them to better understand their body state and reactions. Some participants believe that through running meditation practice, they can better feel the relaxed and tense state of their body. This enables them to more easily grasp changes in their body state, thus better managing emotions and coping with stress. P3$_{UPM}$: *"I felt peaceful and relaxed. It seemed like my body was talking to me."* Participants mentioned the relationship between body awareness and breathing. They believe that by deep breathing and adjusting the rhythm of breathing, they can better perceive their body state. This practice promotes relaxation and a calm state of mind. P6$_{UPM}$: *"I felt that my body lightened up with every deep breath."* P1$_{RunMe}$: *"Sometimes I thought about my situation of heart beats and speed of running."*

The participants also mentioned the relationship between body awareness and attention. Participants believe that through body awareness they can better concentrate and maintain focus. This enables them to better participate in the practice of running meditation. P2$_{NAS}$: *"I felt that when I ran rhythmically with the tempo, my attention will always observe the changes in my gait, which was like the body giving instructions to my consciousness."* Furthermore, the participants pointed out the importance of body awareness in the practice of running meditation. Participants believe that body awareness can help them better understand their body state and reactions. This understanding promotes the balance of body and mind, including the regulation of emotions and stress, and stimulates their thinking. P4$_{NAS}$: *"I rethought my laboratory work during those 20 minutes, and I was surprised to get several new ideas."*

The impact of sounds on running meditation. Most participants believe that sounds and running have a positive impact on the overall experience. Participants stated that sounds can help them relax and concentrate better during running, while enhancing the pleasure of running. They believe that sounds can make running more interesting and meaningful, thereby increasing their satisfaction and participation. P8$_{NAS}$: *"I felt like my running performance was well guided by the sound system, which kept me excited rather than fatigued. I think it is suitable for participants like me who do not exercise very much."* Participants mentioned that they like to listen to the sounds of natural environments, such as bird songs, wind, and water flow. These sounds help them better immerse themselves in exercise.

Some participants like to listen to music, believing that music can help them maintain rhythm and relax their mood. P10$_{RunMe}$: *"Guided by music, I could feel the breeze blowing on my face, and this comforted me."* Furthermore, participants believe that an adaptive sound system (RunMe) provides better stimulation and feedback for running meditation practice, thus improving user experience. The participants stated that RunMe can adjust the content and rhythm of music, sounds, and guide language according to their individual situation. This personalized approach helps them relax and focus more.

Participants believe that RunMe can improve the adaptability of running meditation practice, thus better meeting individual needs and expectations. P8$_{RunMe}$: *"Upon completing the task, a strong feeling appeared. The music understood me, allowing for a natural and unforced running experience. Additionally, the rhythm of the sound subconsciously influenced my steps. In essence, I discovered a newfound sense of freedom and unconscious discipline, an experience unlike any other."* Some participants mentioned that they use RunMe to help control breathing and running rhythm, thus better participating in running meditation practice. However, some participants also complained that the background sound was a bit complicated. P7$_{NAS}$: *"I could choose only one type of background music and it would be better without beats."*

5.5.3 Summary

Our user study suggests that the RunMe group outperformed other groups (the RAN, NAS, and UFM groups) in running meditation. The findings indicated that the RunMe group (1) demonstrated a superior ability to maintain attention focus during their meditation, remaining non-distracting and exhibiting a heightened awareness of their surroundings, (2) exhibited higher proficiency, potentially manifesting as elevated levels of meditation practices, (3) displayed greater interest and enjoyment, perceiving the system as more practical and valuable for their running meditation experience and training, (4) demonstrated a more proactive engagement with body sensations during running meditation, and experienced fewer external distractions.

5.6 Discussion

In the following subsections, we first revisit the design framework of RunMe. Second, we discuss the practical distinctions of this study compared to previous studies. Third, we present three implications for the system design of a running meditation program. Finally, we discuss the limitations of this study and outline three prospective areas that deserve further investigation within the field of running meditation.

5.6.1 Revisiting the Design Framework of RunMe

First, the stimulation mechanism is crucial, as it not only supports the technological detection of user data, but also provides adaptive feedback. Detection is both "conscious" and real-time, facilitating the real-time collection of user data changes in a dynamic environment. Particularly, when users experience distraction affecting the rhythm of their steps, the stimulation mechanism assesses the user's state based on preset thresholds and provides corresponding feedback. Threshold-based detection offers a new design space for digital experiences that provide feedback on changes in human behavior and attention. This design is proactive, yet it does not imply a weakening of the user's attention regulation abilities due to excessive technological dominance. In contrast to this concern, our results indicate that adaptive sound stimuli contribute to helping users eliminate distractions from the environment, enabling them to focus their attention on the rhythm of their own body.

Second, the regulation mechanism is equally essential as it not only defines the thresholds for technological detection, but also provides reference feedback for the stimulation mechanism. This mechanism focuses on the human constraints in running meditation, which are characterized by individual differences and unstable performance. This poses challenges for system design and implies potential risks, especially when outliers occur. Human regulation while meditation is generally classified into two types: conscious and unconscious regulation (Niksirat et al., 2019). In this regulation mechanism, users undergo stages of meditation training, transitioning from conscious regulation to unconscious regulation. This is in line with the techniques of concentrative meditation. Ideal meditation practices seek unconscious self-regulation, where there is no judgment of stimuli or feedback. This study has found that RunMe effectively supports users to achieve meditation training effects from conscious self-regulation to immersion in mindfulness.

5.6.2 Practical Distinctions of RunMe

This subsection presents the practical distinctions between our system and previous work for meditation practice.

RunMe vs. past interactive meditation system. The design of RunMe is reflected in its two-way adaptive interaction model, compared with popular running meditation technologies, such as Headspace (Headspace, 2022), which mainly adopt a one-way interaction model. This difference of design allows RunMe to cultivate a deeper symbiotic relationship between user and system, further enhancing interactive meditation during running. In contrast, traditional technology relies on user behavior data to provide adaptive feedback, but fails to achieve deep two-way interaction.

There are two types of existing Mindfulness-Based Mobile Applications (MBMAs): static and kinetic, but both have certain limitations. Static MBMAs require a relatively quiet environment, while kinetic MBMAs lack flexibility in adapting to users' different skill levels. Designed specifically for running meditation, RunMe compensates for the challenges of using a smartphone while addressing the limitations of one-way cell phone tracking. RunMe provides users with a unique opportunity to practice mindfulness while running, enabling a more personalized and satisfying experience.

Compared with existing frameworks such as Pause and Sway (Zhu et al., 2017; Niksirat et al., 2019), RunMe not only achieves real-time feedback but also identifies the inadequacy of supervising user real-time impact and subsequent reactions to technical feedback. RunMe is designed to coordinate users' self-awareness and actions, enabling a self-regulated experience by providing kinetic assistance, making up for the shortcomings of existing frameworks.

Traditional meditation techniques often ignore individual differences in interactive systems, while the advantage of RunMe is to consider each person's unique status and abilities. The system does not just guide users, but is guided by the inherent differences between users to meet their individual needs. This personalized attention provides "on-the-go" runners with real-time feedback and kinetic assistance, making their running experience more seamlessly integrated.

RunMe vs. traditional meditation. RunMe draws inspiration from the traditional definition and techniques of concentrative meditation, which involve maintaining focus during the analytical and placement phases (Gyatso, 2009). In a running environment, external distractions can cause the user's attention to scatter. Traditional meditation poses a challenge for users entering the concentrative training phases of analysis and placement, particularly for novice runners (Seuter et al., 2017). RunMe integrates rhythmic auditory cues to assist users in becoming more adept during the analytical phase. For instance, RunMe trains users to maintain a stable cadence, focus on the rhythm of sound, and engage in active self-regulation. RunMe extends traditional meditation training by encouraging users to maintain stability throughout the entire running process, encompassing both physical and mental focus. Our user study found that RunMe is user-friendly and natural, allowing individuals to attain adaptive mindfulness practices while running after just one experience. RunMe can serve as a training tool for daily running meditation.

5.6.3 Design Implications

To create better user experience and performance in running meditation training, reviewing this study, we provide three implications in designing running meditation systems.

Towards two-way adaptation in interactions. Our validation of RunMe underscores the significance of two-way adaptive system as a fundamental design principle. To achieve this principle, adaptive stimulation and regulation mechanisms are needed. Designers are urged to deep considerations of individual differences, encompassing psychological, physiological, and behavioral states. One emerging solution involves leveraging optimization algorithms, enabling the system to discern and comprehend user-specific characteristics more accurately (Howes et al., 2023) that facilitates the delivery of more adaptive feedback. Adaptive feedback ensures a personalized meditation experience by considering dynamic changes in user data, such as physical response, emotional state, and meditation depth. This approach maximizes effectiveness for each individual during the meditation session. In addition, the system of running meditation can seamlessly integrate adaptive data interactions to gain profound insights into the distinctions in individual psychological and behavioral states. This integration ensures that meditation experiences comprehensively consider the intricacies of users during their practice. The tailored feedback (e.g., sound, vibration, or visual feedback (Zhang et al., 2019) serves the purpose of seamlessly intertwining body movement and mindfulness, thereby augmenting the overall efficacy of the meditation experience.

Realizing a holistic self-regulation. Main components of meditation states include attention control, emotion regulation and self-awareness (Tang et al., 2015). Our study advocates an ideal state while meditation in which technology completely follows the dynamic data which produces stimuli. Properly designed, this can make the presence and use of technology virtually unnoticeable and maximize the meditative state as in classical meditation modes (e.g., Zazen). Existing interactive meditation systems are still based on technological detection and stimuli-driven self-regulation. In this process, users have to spend extra cognitive resources to follow the stimuli of technology, which makes users unable to fully devote themselves to self-regulation. Our case bridges this gap by integrating biodata and behavioral data to provide users with adaptive sounds stimuli.

Balancing body movement and self-awareness. Running meditation is an intertwined state of body and awareness, where the user's awareness is influenced by body movement while guiding behavior. To this end, designers are encouraged to embark on an extensive exploration of human physiology and biomechanics. For example, by vigilantly monitoring biological information such as heart rate, respiration, and muscle tension, the system can precisely capture the user's physical status. The integration of feedback with biometric information not only allows guidance for users to adjust posture and breathing depth but also ensures their comfort and safety throughout the running meditation session. Additionally, suboptimal/imbalance interaction between body movement and self-awareness can lead to user distraction or disturbances in body rhythms (Niksirat et al., 2019). Our user study demonstrated the positive impact of incorporating music rhythm, evident in distraction prevention, pace regulation, and heightened focus on the present moment. RunMe effectively address short-term distractions in running meditation.

5.6.4 Limitations and Future Work

There are still three directions worth exploring in future research.

Enhancing the effects of adaptive sound system. The current studies have highlighted that factors like frequency and duration play a significant role in eliciting emotional responses during meditation. Future work could concentrate on optimizing these sound parameters to enhance user engagement and improve overall outcomes. Investigating how the frequency and rhythm of sounds contribute to attentional training and examining their relationships with neural activity in specific brain regions would be particularly crucial.

Exploring the interplay between running and meditation. Although our study has primarily focused on the effects of running on mindfulness, leaving a significant gap in understanding how running influences meditation and the dynamic interdependence between running and meditation. Future studies aim to unravel the specific cognitive and physiological pathways that underlie *synergized interactions* (Ren et al., 2019) between running and meditation. This research direction will provide practical implications for developing interventions that harness the combined benefits of running and meditation for holistic well-being. It is essential to bridge this gap to inform optimized interventions that can contribute to the overall improvement of individuals' physical and mental health.

Paying attention to the long-term effects of running meditation. Although current evidence of our study is insufficient to fully support this perspective in short-term training, our hypothesis for the future is that prolonged use of RunMe by users can achieve this effect. However, designing for long-term attention changes requires consideration of the enduring effects of rhythmic feedback on both physical and mental stimulation, necessitating the maintenance of a delicate balance between the two. Drawing inspiration from traditional meditation practices, future designs may explore traditional and rhythmic kinetic meditation practices such as Tai Chi and Qigong (Niksirat et al., 2017). This exploration aims to balance characteristics of awareness and movement qualities, thereby extending users' running performance and mindfulness effects for long-term training and daily use.

5.7 Conclusion

This paper introduces RunMe, an adaptive sound system, and demonstrates its efficacy in the context of running meditation. The interaction mechanism used in RunMe demonstrates successful self-regulation during running meditation. This mechanism uses lightweight mobile devices for stimulation and regulation. Furthermore, the data-driven interaction design significantly improves the user's meditation experience and effectiveness by helping to maintain concentration and relaxation. The findings of this study suggest that the system is successful in facilitating adaptive states of mindfulness. This is achieved by effectively balancing body movements and attention awareness, thus enhancing the overall effectiveness of meditation.

This study offers theoretical and design guidance for future designers who want to facilitate meditation practices. RunMe provides users with a dedicated space for meditation training that minimizes distractions commonly encountered in daily life. By seamlessly integrating into users' daily routines, RunMe enables individuals to engage in meditation practices more effectively. The setup of RunMe promotes intentional and focused kinetic meditation, which involves physical movement. The findings of this study are valuable for researchers interested in designing adaptive kinetic meditation practices and developing interaction mechanisms. In addition, the study provides guidance on incorporating meditation into various domains, such as sports health and psychotherapy, by suggesting effective approaches to implementation.

Chapter 6

Study 3: Enhancing Synergized Game Design

This chapter introduces a study aims to explore the effects of our framework of *synergized interactions* on game design in the context of education and HCI. It includes two parts: (1) presenting the teaching framework of synergized game design; (2) conducting a course to investigate the effects of the teaching framework on guiding students' engagement of synergized game design.

This study serves as a macro-level exploration of our theoretical framework (i.e., FSIRA). It goes beyond Study 1 and Study 2, which focused on *synergized interactions* between individual users and devices, by concentrating on *synergized interactions* between multiple users and between users and devices. This study provides preliminary support for the potential and significance of our theoretical framework in more complex interaction environments.

6.1 Introduction

During the past two decades, the positive impact of games in education has been a highly regarded area of interest, with a focus on exploring the potential of game-based learning and educational games (Prensky, 2003; Plass et al., 2015; Noemí and Máximo, 2014; Gui et al., 2023). These studies focus on the use of games as powerful educational tools such as the ability to improve students' motivation (Vos et al., 2011; Yu et al., 2021) and overall learning experience (Cheng and Annetta, 2012; Videnovik et al., 2020), and foster meaningful learning outcomes (De Freitas, 2018; Cheung and Ng, 2021). However, despite the many studies on the efficacy of games in enhancing various aspects of education, there remains a noticeable gap in understanding how students' engagement with games can be leveraged to cultivate their own game design capability. Although numerous studies have highlighted the benefits of playing games, little attention has been paid to the potential for students to become active creators of games within the educational context.

This study aims to address this gap by proposing a novel teaching framework designed to specifically enhance the capacity of students to design games. Building on the foundational knowledge established by previous research on game design teaching methodologies for both entertaining and serious purposes (e.g., training) (Amory and Seagram, 2003; Homer et al., 2020), this study seeks to shift the focus to fostering students' game thinking alongside reflective design. This change in perspective is inspired by the theory of *synergized interactions* (Ren, 2016). *Synergized interactions* emphasize the full utilization of the potential of both parties involved in an interaction by gradually adjusting the resources of each other (Ren, 2016). This concept helps us to rethink game design education by (1) focusing on extending students' game design abilities in the classroom and (2) reflecting on the goals of game design teaching when instructors are designing their courses.

To achieve this goal, this study proposes a Synergized Game Design Teaching Framework (SGDTF), which integrates concepts of *synergized interactions* within rhythm game design teaching. The purpose of the SGDTF is to enhance student engagement and promote reflective design practice. We conducted a 32-hour workshop over a two-week period in a university classroom, recruiting 30 students, including undergraduate and graduate students. We examined the student engagement and self-reflection abilities of game design as they engaged in the classroom. We also further reflect on the role of the SGDTF and its implications for future game design and teaching.

The contributions of this study are three-fold. First, we introduce a systematic teaching framework, the SGDTF. It offers a fresh perspective shift in the field of game design education, moving from a focus on the educational significance brought by tools to enhancing participants' game design abilities. Second, we conducted an empirical study in a university classroom. The study identified the effectiveness of the SGDTF in fostering students' engagement and reflective game design skills. This also underpins the framework's potential for sustained research in game design education. Third, we present an advanced reflection and understanding on future game design education. It underscores the extension of objectives, advocating not only for the educational goals of game design, but also for a return to human capability. This insight also provides inspiration for future game design educators and designers.

6.2 Related Work

Three main areas of related work influence our work in investigating a novel game design education: (1) understanding the rhythm game and game design, (2) the frameworks and challenges in game design education, and (3) approaching *synergized interactions* to rhythm game design.

6.2.1 Understanding Rhythm Game and Game Design

As a subtype of action games, rhythm games initially aimed to challenge the sense of rhythm of players, providing entertainment and enjoyment through interactive rhythmic experiences (Costello, 2018). With the continuous development of the gaming industry, the concept of rhythm games design has expanded and evolved. Rhythm is no longer merely a form of entertainment, but is recognized as a quality of design (Costello, 2018, 2020b; Tan and Ren, 2023), integrated into various genres of game design, including action-adventure, puzzle and even strategy games.

The potential application areas of rhythm games have also received widespread attention and exploration. For example, studies indicate that the design of rhythm-based sports training systems can help athletes improve their performance (Aftimichuk and Poleacova, 2020; Priasmara et al., 2021). In the medical field, some researchers are exploring the use of rhythm games as rehabilitation tools to help patients recover muscle function and motor coordination (Bégel et al., 2017; Prahm et al., 2019). In the realm of cognitive training in childhood, educators are applying rhythm games to facilitate children's learning and development processes, fostering attention, memory, and logical thinking skills (Javan et al., 2011; Choi et al., 2022). With increasing recognition of the potential value of rhythm games, the design principles of rhythm games have begun to shift from merely entertainment to more serious goals (Shen et al., 2009; Caserman et al., 2020). This paradigm shift also presents new opportunities and challenges for game design education.

6.2.2 Current Frameworks and Challenges in Game Design Education

In the field of game design education, previous research has focused on three main areas. First, scholars have viewed games as educational tools with the aim of improving student learning through game design education (Utoyo, 2018; Videnovik et al., 2020). This approach not only allows students to apply classroom knowledge in practice, but also fosters their interest and motivation in learning. Second, previous studies have explored the motivations, experiences, and learning outcomes of the students during the game design process (Domínguez et al., 2013; Yu et al., 2021). By analyzing students' psychological states and behaviors in game design activities, researchers seek to understand how to stimulate students' creativity and problem-solving abilities. Third, some studies have emphasized gamified interactions between teachers and students in classrooms to better facilitate game design education (Villagrasa et al., 2014; Hitchens and Tulloch, 2018). By establishing a positive interactive teaching environment, instructors can guide students more effectively, ignite their learning interests, and provide the necessary support and guidance.

In addition, several frameworks have been explored and proposed in the field of game design education. For example, a study has highlighted a content-centric framework that aims to understand and teach game design in higher education, as well as strategies to conceptualize games and organize the development process (Larsen, 2018). Furthermore, other research has identified design frameworks for educational games to support teacher instruction (Holmes and Gee, 2016; Yamani, 2021), student engagement and performance (Jan-Paul and Sara, 2011), and enhancement and understanding of learning content (Wang et al., 2011). However, these frameworks remain predominantly macroscopic and lack specific guidance to support students' game design processes. Moreover, existing frameworks inadequately address the correlation between game essence and students' capability, specifically how guiding students in game design and the process of game teaching influence students' design abilities. Therefore, the motivation of this paper lies in exploring new teaching frameworks to support the development of students' game design abilities.

6.2.3 Approaching *Synergized Interactions* to Rhythm Game Design

As a powerful concept, *synergized interactions* (Ren, 2016; Ren et al., 2019) can enable frameworks and design reflections across different domains. However, there are challenges in the field of game design education (see Sections 6.2.1 and 6.2.2), particularly in rhythm game design. Currently, there is a lack of a systematic teaching framework to guide students in rhythm game design in the classroom. Therefore, see Figure 6.1, this study aims to inject new ways of thinking and methodologies into rhythm game design

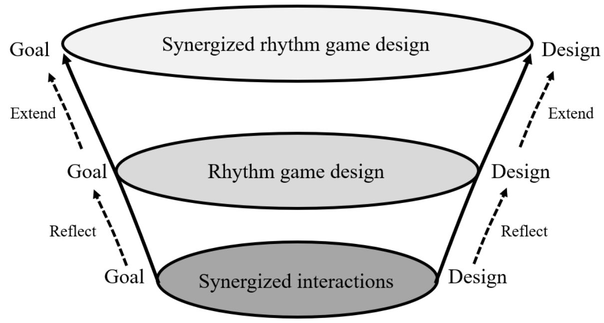


Fig. 6.1: A high-level diagram of approaching *synergized interactions* to rhythm game design.

education by introducing the concept of *synergized interactions*. Through reflection on current teaching objectives and designs in the education of rhythm games, we propose a new teaching framework to promote *synergized interactions* in rhythm game design. The significance of this framework lies not only in addressing existing issues in game design education but also in advancing rhythm game design and enhancing students' engagement and reflective abilities.

6.3 Framework

In this section, we propose a Synergized Game Design Teaching Framework (SGDTF) by integrating the concept of *synergized interactions* and game design. The structure of the SGDTF (Figure 6.2) includes three phases: (a) setting goals, (b) defining components, and (c) framing patterns within four stages (concept design, interaction design, mechanism design, and prototype design). These phases and stages are inspired by previous frameworks for game design (Schell, 2008; O'Shea and Freeman, 2019). The purpose of the *three phases* is to inspire designers to engage in reflective design with respect to synergized game design; the purpose of the *four stages* is to guide designers through staged engagement through teacher instruction in the classroom.

We have defined and elaborated the elements for each phase (see Sections 6.3.1, 6.3.2, and 6.3.3). By integrating rhythm game design as a case study, these elements are spread over four stages in three phases to effectively involve designers in synergized rhythm game design teaching. Specifically, in the *concept design* stage, designers are guided to understand and reflect on the goals of rhythm game. In the *interaction design* stage, designers need to define specific components to support the interactive experience of the rhythm game. In the *mechanism design* stage, designers further develop patterns for rhythm game design. Furthermore, these three stages collectively support

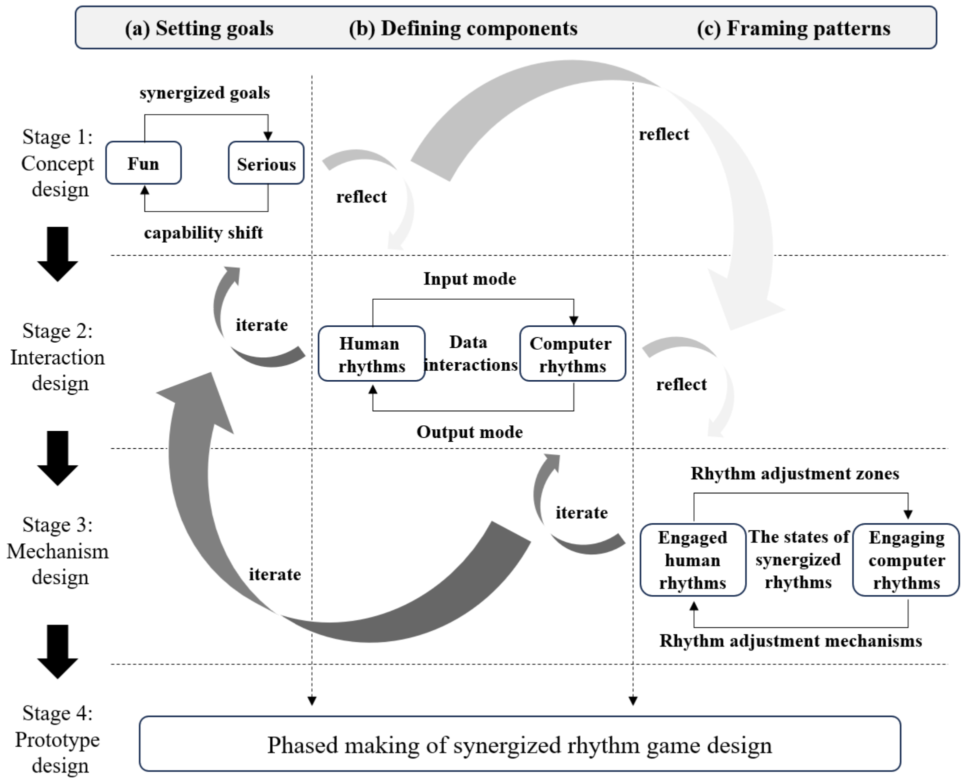


Fig. 6.2: A teaching framework for synergized game design that include three steps: (a) setting goals, (b) defining components, and (c) framing patterns within four stages of design of concept, interaction, mechanism, and prototype.

the *prototype design* of a synergized rhythm game. Reflection and iteration are present between stage designs throughout the design process. Our framework, the SGDTF, can (1) explore how phases and elements in each stage facilitate student engagement and reflective design, and (2) assess student phased improvements by examining iterations in each stage. It allows educators to gain insight into the learning process and provide targeted feedback and guidance to designers.

6.3.1 Setting Goals

In the phase of *setting goals* (Figure 6.2a), inspired by the concept of *synergized interactions* (Ren, 2016), we present a new perspective on rhythm game design, namely the setting of synergized goals between fun and serious goals, accompanied by the goal of capability shift.

Synergized goals between fun and serious. Unlike the traditional goals of game design, which generally focus on fun or serious purposes (Ratan and Ritterfeld, 2009;

Iten and Petko, 2016), our framework guides designers to reflect on the goals of their designs. Our intention is to explore how to balance the entertainment value (fun) with educational or developmental goals (serious) within the context of rhythm games. In addition, designers are asked to consider how to integrate elements of fun, challenge, and learning outcomes to create synergized goals. This principle inspires designers to approach game design from a holistic perspective.

Capability shift. In the realm of rhythm game design, designers explore the positive impact of games on human capability. This encompasses the development of cognitive, motor, emotional, and social dimensions (Ren et al., 2019). This principle guides designers in examining how games facilitate the progression of player abilities over time. The goal of conceptual design is to create a balance between game design and the enhancement of human capability. This contrasts with classical gaming models, which focus on the equilibrium between skill and challenge (Fullagar et al., 2013; Fong et al., 2015), emphasizing player interaction experiences. Our framework underscores the alignment between game dynamics and human capability, highlighting mutual reinforcement of abilities.

6.3.2 Defining Components

In the phase of *defining components* (Figure 6.2b), based on the perspective of rhythm in interaction design (Costello, 2018; Tan and Ren, 2023), we propose three elements to guide the design of game interaction: (1) defining human rhythm and computer rhythms; (2) designing modes for rhythm input and output; (3) ensuring rhythmic data interaction.

Human and computer rhythms. In the interaction of rhythm games, designers need to define human rhythms and computer rhythms (Tan and Ren, 2023). They explore the intricate interplay between human rhythmic input and computer-generated rhythms within the gaming environment. This principle will guide designers in defining specific types of rhythms and their expected effects. Our aim is to reveal the complexity of synchronization between these two rhythmic elements and to elucidate their profound impact on the gameplay and the player experience.

Rhythmic input and output modes. Students initially identify various interaction modes in which players rhythmically engage with the game, including tapping, sliding, and sound input, among others (Schell, 2008). Subsequently, they need to define output modalities (including visual, auditory, and tactile feedback channels (Johnson et al., 2017; Pycia and Troyan, 2023)) to provide feedback to the player effectively. Additionally, this principle will guide designers around key considerations regarding accessibility factors and design adjustments, with the aim of accommodating the diverse preferences and needs of players in terms of input and output modalities.

Rhythmic data interactions. Once the rhythmic interaction and its modes are defined, designers need to explore how to utilize rhythm data (including player performance metrics and game events (Schell, 2008)) to drive game dynamics. This involves understanding the role of data visualization and interpretation in improving player feedback and engagement. Designers must grasp the general principles of data interaction, extending to methods of leveraging rhythm data to achieve personalized gaming experiences and dynamically adapt to challenges. This principle supports designers in refining the construction of general components for collaborative rhythm game development.

6.3.3 Framing Patterns

In the phase of *framing patterns* (Figure 6.2c), inspired by the mechanisms of *synergized interactions* (Ren et al., 2019), we present three elements to construct game patterns: (1) defining the states of synergized rhythms; (2) setting the zone for rhythm adjustment; (3) designing mechanisms for rhythm adjustment.

The states of synergized rhythms. Designers need to define the different states or stages within synergized rhythms, such as immersion, flow, challenge, and reflection (Schell, 2008; Costello, 2018). These definitions provide a comprehensive framework for game design, helping to understand the dynamic journey that players undergo during gameplay. Support for this principle allows designers to investigate how transitions between these states affect the overall rhythm-gaming experience and player engagement. For example, a game design may carefully balance different states to ensure that players consistently feel challenged and satisfied throughout the gameplay, maintaining excitement and interest during smooth transitions between states. Furthermore, understanding the interaction between these states can assist designers in better adjusting the difficulty and rhythm of the game to meet the diverse needs and preferences of the players, thus enhancing the attractiveness and sustainability of the game.

Rhythm adjustment zones. Designers need to identify zones within the game where players can adjust their rhythmic performance or strategies, such as difficulty levels, rhythm variations, or gameplay modifiers (Schell, 2008; Costello, 2018). The design of these adjustment zones aims to meet the needs of players with different skill levels and

Fig. 6.3: The figure shows environment of synergized game design workshop in the classroom.

preferences while striking a delicate balance between providing challenges and opportunities for player adaptation and mastery. The setting of these ranges aims to elucidate how these zones enhance the engagement and satisfaction of players with different skill levels and gameplay styles.

Rhythm adjustment mechanisms. Based on the definition of synergized rhythm states and adjustment zones, designers need to further refine rhythm adjustment mechanisms. This principle guides designers to explore specific game mechanisms and systems that facilitate rhythmic adjustments, such as adaptive difficulty algorithms, practice modes, or in-game tutorials (Schell, 2008; Costello, 2018). Moreover, it is necessary to consider the effectiveness of different adjustment mechanisms in supporting player learning and progression. Designers should also consider how player feedback and data analysis can improve rhythmic adjustment mechanisms over time.

6.4 Evaluation in the Classroom

Based on our framework, we designed and conducted a synergized rhythm game design workshop in the university classroom (Figure 6.3). Our aim was to assess the impact of this framework on student engagement and self-reflective abilities.

6.4.1 Participants

The workshop attracted 30 undergraduate and graduate participants from a university in southeastern China, between 20 and 27, including 12 females and 18 males. All of them were enrolled in the School of Arts and Design, with backgrounds in indus-

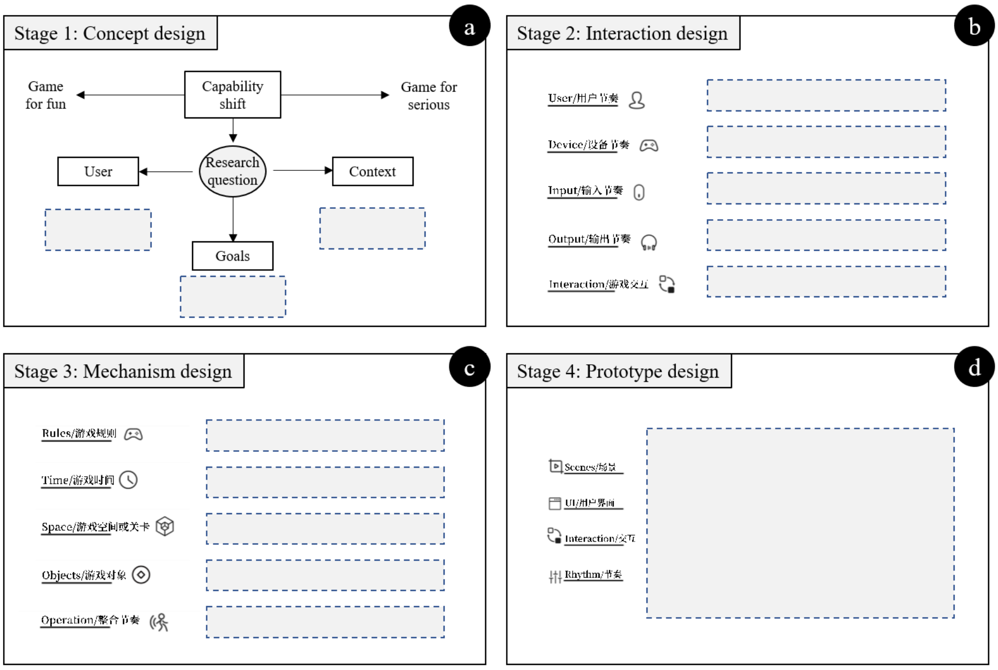


Fig. 6.4: The figure shows materials for teaching in synergized game design workshop, which is accompanied by corresponding four stages - (a) concept design, (b) interaction design, (c) mechanism design, and (d) prototype design.

trial design, digital media design, fashion design, graphic design, and possessed certain foundational design knowledge. All participants had previous experience with video games, with 13 being frequent players (playing on average once per day). Their voluntary participation in the workshop stemmed from their interest in game design. We intentionally selected these participants with a certain level of expertise to ensure their understanding and active participation in discussions, thus enhancing the credibility and generalizability of the study findings.

6.4.2 Materials for Teaching

In each of the four stages of the course, we have designed the corresponding documents (Figure 6.4) to help students quickly engage in classroom instruction in each stage based on the SGDTF. Figure 6.4a presents the conceptual design stage, guiding students to refine the goals of game design by defining users and scenarios as serious or entertainment oriented. Figure 6.4b illustrates the interaction design stage, guiding students in determining the rhythm of interaction between players during gameplay and the interaction modes after group discussions. Figure 6.4c illustrates the mechanics design stage where students are required to finalize specific content of the game, such

Fig. 6.5: The figure shows four stages of design of (a) concept, (b) interaction, (c) mechanism, and (d) prototype while students design synergized game in the classroom.

as objects and spaces of the game. Figure 6.4d provides a white board for each group to initially present prototype designs through hand-drawn sketches. In addition, this document offers four dimensions to help students continuously consider how to present their prototypes in a reasonable way.

6.4.3 Procedure

We have devised a teaching procedure based on previous game design frameworks (Crawford et al., 1984; Schell, 2008). It comprises four sequential stages, concept design, interaction design, mechanism design, and prototype design. All students are guided to engage in synergized game design during these stages in the classroom (Figure 6.3). Before starting the course, they are grouped into teams of 3 to 5 participants.

Stage 1: concept design. Students should establish the goals of game design based on the SGDTF outlined in Section 6.3.1. The consideration of synergized goals and capability shift can guide students in further clarifying target users, contexts, and specific questions and design goals. At this stage, students begin brainstorming in groups and produce conceptual design documents (Figure 6.5a).

Stage 2: interaction design. Students need to define human rhythms and computer rhythms, input and output modes, as well as data interaction modes based on the

SGDTF outlined in Section 6.3.2. They begin to understand materials and practical design based on design goals in Stage 1. In this stage, students begin learning about the components of rhythm games and produce interaction design documents (Figure 6.5b).

Stage 3: mechanism design. Students need to design the zones of rhythm adjustment and interaction mechanisms based on the SGDTF outlined in Section 6.2.2. The design of a game mechanism includes the definitions of the rules, time, space, and objects of the game, as well as the modes of operation of adjustment. In this stage, students have refined the primary patterns of game design and produced mechanism design documents (Figure 6.5c).

Stage 4: prototype design. Students begin to use digital tools and integrate materials (e.g., paper prototypes) to create game prototypes. Designs from stages 1-3 will be presented in the prototype. Prototyping design includes the creation of scenes, user interfaces, interactions, and rhythms. Students enhance their understanding through continuous design iterations and intra-group testing to validate game interaction and experience. In this stage, students strengthen their understanding between conceptual and prototype design and produce prototype design documents (Figure 6.5d).

6.4.4 Metrics and Data Analysis

We evaluated students' engagement and self-reflective abilities when they engage within the synergized game design workshop. For each assessment indicator, we used a mixed method approach, incorporating both quantitative and qualitative methods to collect subjective evaluations of the course from students. All quantitative data was collected on Google Sheets online. All qualitative data were collected by two researchers offline.

(1) Quantitative analysis.

Measuring student engagement. The Student Engagement Questionnaire (SEQ, (McNaught et al., 2006; Kember and Leung, 2009)) was used to assess student participation in the classroom. The questionnaire comprises 5 dimensions, of which I selected 4 dimensions (i.e., intellectual, student-student relationship, teacher-student relationship, and working together) containing 22 questions. The responses of students were measured on a 5-point Likert scale ranging from 1 to 5. Each participant was asked to complete pre-test and post-test before and after the course. By collecting responses to the SEQ, educators can gain insight into students' subjective attitudes toward various aspects of the course, such as critical thinking, creative thinking, adaptability, interpersonal skills and groupwork, and communication skills, and the relevance of engagement across various dimensions.

Measuring reflective design. The Rumination-Reflection Questionnaire (RRQ, (Trapnell and Campbell, 1999)) was used to assess students' self-reflective abilities regarding game design in the classroom. The questionnaire consists of two dimensions: Rumination and Reflection. We employed 12 questions under the theme of reflection as a scale. The responses were measured on a 5-point Likert scale ranging from 1 to 5. Each student completed the questionnaire both before and after the course. By collecting responses to the RRQ, educators can gain insights into students' subjective attitudes toward their own abilities in the course.

We examined the performance of quantitative analysis using the Statistical Package for the Social Sciences, SPSS ver. 25 (SPSS, Chicago, IL, USA). We (1) tested the data using the Kolmogorov-Smirnov test and the homogeneity of variance using Levene's test, (2) we used Repeated Measures Analysis of Variance (RM-ANOVA) with Mauchly's test for data correction, and (3) we used paired t-tests to analyze and compare performance between the pre-test and post-test evaluations. The significance level was established at $\alpha = 0.05$.

(2) Qualitative analysis.

During the workshops, students were asked to provide feedback after each stage, such as what they learned from the workshop, any challenges encountered at that stage, how they made design decisions, and the extent of engagement and collaboration among groups. We also observed their self-reflection in the workshop, including the questions they raised, the discussions held, the difficulties encountered, and their ideas and iteration processes in design. To further reflect on the workshop's process and outcomes, we conducted a follow-up interview with each group of student engagement and self-reflection of game design. The interview outline comprised 9 closed-ended multiple-choice questions on the satisfaction and experiences of student engagement in the classroom, along with 7 open-ended questions on student reflections at different stages, how groups engaged in collaboration and design, and encountered challenges in iterating prototypes.

All participating students also provided written feedback. The duration of each interview was approximately 30 minutes. The interview process was conducted by two experienced experimenters. The experimenters classified and organized the interview materials using thematic analysis within a hybrid coding approach

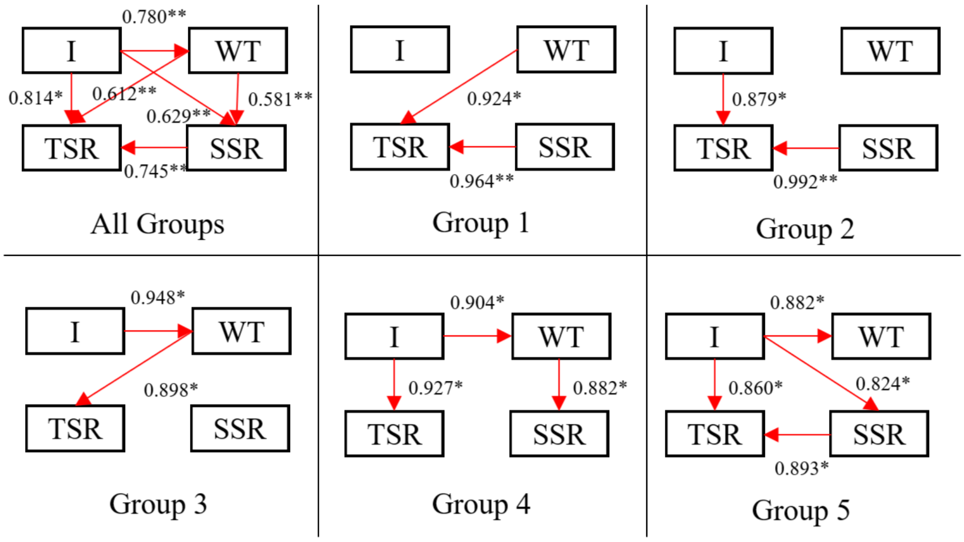


Fig. 6.6: The figure illustrates the overall and group-specific relevance of student engagement across four dimensions (i.e., Intellectual - I, Student-student Relationship - SSR, Teacher-student Relationship - TSR, and Working Together - WT) in the classroom from the Student Engagement Questionnaire (McNaught et al., 2006; Kember and Leung, 2009) (* <0.01; ** <0.05).

(Fereday and Muir-Cochrane, 2006). Two interviewers conducted the coding and analysis of the transcripts, which underwent two rounds of review to ensure rigor of the data. Permission was obtained to record the content of the interview.

6.5 Results

This section shows findings on student engagement and reflective design in the classroom based on quantitative and qualitative analysis.

6.5.1 Quantitative Analysis

(1) The SEQ for measuring student engagement. Figure 6.6 illustrates the overall and group-specific relevance of student engagement across Intellectual (I), Student-student Relationship (SSR), Teacher-student Relationship (TSR), and Working Together (WT). Significant positive correlations were observed among all groups. This indicates that the course design effectively enhanced student engagement not only in individual capacities but also in collaboration between students. Additionally, the study found significant differences in group-specific relevance of student engagement across the four dimensions. Specifically, in group 1, both WT (r = 0.924, p <0.05) and SSR (r

= 0.964, p <0.001) showed significant positive correlations with TSR, while in group 2, I (r = 0.879, p <0.05) and SSR (r = 0.992, p <0.001)) exhibited significant positive correlations with TSR. Furthermore, in group 3, significant positive correlations (r = 0.948, p <0.05) were observed between I and WT, as well as a similar trend (r = 0.898, p <0.05) between WT and TSR. In group 4, significant positive correlations were found between I and both TSR (r = 0.904, p <0.05) and WT (r = 0.927, p <0.05), with a similar trend (r = 0.882, p <0.05) between WT and SSR. Finally, in group 5, significant positive correlations were observed between I and the other dimensions, along with a similar trend (r = 0.893, p <0.05) between SSR and TSR. In summary, groups 1, 2, and 3 exhibited weaker correlations among the dimensions of student engagement within the groups, whereas the other groups demonstrated stronger correlations.

(2) The RRQ for measuring reflective design. The RRQ assessed students' reflections as they engaged in the synergized game design. Overall statistical analysis revealed significant differences (t = -13.852, p <0.05) between pre-test (M = 2.72, SD = 0.20) and post-test (M = 4.14, SD = 0.44). Figure 6.7 illustrates significant differences in reflective design across all five groups in this classroom. Specifically, the significance values for the pre-test and post-test comparisons were as follows: for group 1, t = -8.511, p = 0.01 (pre-test: M = 2.73, SD = 0.09; post-test: M = 3.90, SD = 0.34); for group 2, t = -4.071, p = 0.015 (pre-test: M = 2.72, SD = 0.26; post-test: M = 4.12, SD = 0.57); for group 3, t = -14.754, p = 0.000 (pre-test: M = 2.65, SD = 0.21; post-test: M = 4.28, SD = 0.31); for group 4, t = -6.668, p = 0.003 (pre-test: M = 2.60, SD = 0.14; post-test: M = 4.22, SD = 0.45); for group 5, t = -5.257, p = 0.003 (pre-test: M = 2.86, SD = 0.20; post-test: M = 4.17, SD = 0.54). These findings suggest that the course design effectively facilitated a deeper level of reflection and engagement among students as they progressed from the pre-test to the post-test.

6.5.2 Quantitative Analysis.

(1) Findings on student engagement.

Based on closed-ended questions from the interview outline, this study found that student engagement experiences included satisfaction ratings of 4 or more of more 95% of participants on a 5-point Likert scale ranging from 1 to 5, across the four stages (i.e., concept design, interaction design, mechanism design, and prototype design) of teaching in the classroom. 70% of the participants identified the concept design stage as the most challenging, followed by 30% who found the interaction design and mechanism design

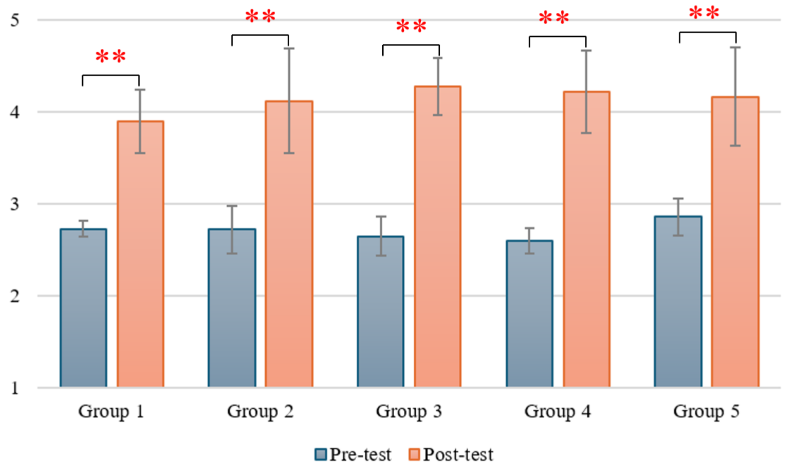


Fig. 6.7: Significant differences between pre-test and post-test scores of participants were observed for the performance of self reflection in the classroom from the Rumination-Reflection Questionnaire (Trapnell and Campbell, 1999). Five groups were analyzed.

stages challenging, with no participants mentioning difficulty in the prototype stage. In addition, all students recognized the importance of setting goals and highlighted reflections on the design process in four stages. 95% of the participants perceived an improvement in their game design abilities after the course, while the rest did not.

(2) Findings on reflective design.

We further explore findings on reflective design within four stages in the classroom from the open-ended questions in the interview.

Paying attention to concept design. Students across all groups emphasized the importance of discussing and reflecting on design concepts with group members, highlighting a commitment to teamwork and reflective thinking. Two groups (groups 1 & 4) of students highlighted the importance of completing tasks within their skill sets, demonstrating a clear awareness of their own proficiency levels. These students recognized the necessity of aligning design goals with their abilities to avoid pursuing unrealistic objectives. Additionally, some students emphasized the significance of defining clear objectives for each stage of the design process, ensuring a structured approach and preventing ambiguity. During brainstorming sessions within groups, three groups (groups 2, 4 & 5) emphasized the importance of considering real-life issues and societal needs, reflecting on the deficiencies and rationality of their designs to ensure practical applicability. It is noteworthy that 70% of students perceive concept design as challenging, primarily due to two factors: (1) excessive divergent thinking hinders their ability to concentrate on addressing specific design issues; (2) the lack of guidance from leadership groups results in a lack of clear direction during the design process.

Continual reflection from concept to prototype. Through user interviews, the study found that students gained new insights into the design process at different stages. Initially, many students had grand visions, but over time, they gradually narrowed their focus, identified target audiences, and simplified their design concepts. In the early stages, the concept of ideas involved not only abstract views but also concrete elements such as mythology, mechanics, and classical music. Collaboration with group members and mentors facilitated progressive improvements in design. Students emphasized the importance of incremental design and took a comprehensive view of players and society. These reflections had a profound impact on the quality of prototypes. Through thorough reflection and optimization of game mechanics, students integrated game concepts more closely with target audiences. All groups of students highlighted activities such as data collection, surveys, and group discussions as playing a crucial role in guiding conceptual design and accelerating subsequent stages.

Deep collaboration in prototype design. In this stage, each group engaged in deep collaboration with clear division of tasks. Students actively participated in brainstorming, questioning the prototype, and striving to address challenges. They adjusted game difficulty and interaction based on user feedback. Two groups (groups 1 & 5) recognized deficiencies in user experience and improvements, leading them to make secondary modifications to the game prototype, further enhancing the design. Two groups (groups 3 & 5) gradually improved their games by removing redundant content, incorporating feedback from teachers and peers from other groups. The study findings revealed that through continual collaborative efforts in prototyping, all groups identified satisfactory improvement strategies. This perspective was positively confirmed in self-evaluations conducted after the course, particularly regarding (1) perceived difficulty in prototype design and (2) subjective experiences during this stage.

6.6 Discussion

This section first reexamines the theoretical and practical roles of our Teaching Framework (SGDTF) in the field of game-based design and teaching. Second, we also present the implications of this research for enhancing student engagement and reflective design for teaching game design in the classroom. Finally, we discuss the limitations of this study and highlight potential future work to guide researchers interested in engaging in game design teaching.

6.6.1 The Roles of SGDTF

Theoretical roles. First, the SGDTF integrates frontier concepts from human-computer interaction, particularly emphasizing synergized interaction, which underscores the critical engagement and self-reflection of designers/students throughout the game design process. This focus on nurturing human potential in teaching offers a fresh perspective on current game design instruction, distinguishing it from classroom teachings centered solely on game-based learning or digital educational game-related topics (Tadiboyina et al., 2023; Gui et al., 2023; Yachin and Barak, 2024).

Second, the SGDTF advocates for close collaboration between individuals and tools in classroom instruction. This collaboration isn't merely about giving or following instructions; rather, it is based on the active volition of both parties involved in the interaction. In addition, the SGDTF pays attention to unstable or harmful factors within interactions. For example, during the initial group brainstorming stage, disagreements or excessive viewpoints within the group may hinder consensus. The SGDTF calls for the solution of these conflicting issues to create a more conducive teaching environment for game design.

Practical roles. First, this study examined a novel pedagogical approach through the integration of synergized rhythm game design, using rhythm games as a case study (Costello, 2018). This innovative endeavor aimed to inspire the contemporary field of game design instruction, challenging existing teaching paradigms (Villagrasa et al., 2014; Hitchens and Tulloch, 2018) and expanding into new educational domains. Despite the unique characteristics and challenges inherent in rhythm games within game design, they represent a representative and widely applicable case study, offering valuable insights and experiences for pedagogical practice.

Second, the SGDTF provides a concrete framework for teaching synergized rhythm game design, comprising four stages and three phases. This framework not only offers students a clear learning path (Figure 6.2), but also serves as a structured tool to guide instructional practices for educators. In addition, corresponding instructional materials are provided for each stage, along with specific templates for each phase. These materials and templates provide actionable examples for future researchers, emphasizing the need for flexible and adaptable designs to accommodate diverse student populations and teaching objectives.

Third, this study conducted a comprehensive evaluation of the implementation of the framework, which yielded positive insights. Such holistic assessments, coupled with several favorable findings in Section 6.5, not only objectively assess the effectiveness of the framework, but also offer valuable lessons and guidance for future research and practice in the field of game design instruction.

6.6.2 Implications

(1) Implications for student engagement

Maintaining balance in the concepts of game design. Encouraging designers to balance the goals of their designs initiates a departure from the traditional binary of prioritizing either fun or seriousness. In essence, it prompts a reevaluation of the dichotomy between entertainment and educational objectives, advocating for a more harmonious integration (Figure 6.2). By embracing this approach, designers are encouraged to explore the interplay between fun and seriousness, aiming to create experiences that captivate players while also imparting valuable knowledge. This shift towards balance acknowledges that effective game design should not lean too heavily towards either end of the spectrum, but rather strive for an equilibrium where both fun and educational aspects are seamlessly intertwined, amplifying the overall impact and engagement of the gaming experience.

Focusing on uncertainty in the process of game design. In the realm of game design education, the presence of uncertain factors influencing the design process is widespread, such as variations in student skill levels (Bulut et al., 2022), diverse learning preferences (Kinzie and Joseph, 2008), and differences in instructional materials/tools (Tan et al., 2023). Recognizing these uncertainties can prompt active engagement from participants in the classroom. For instance, educators must design learning experiences that accommodate the diverse needs and abilities of students, fostering inclusivity and participation, and encouraging students to develop proactive coping skills and teamwork. Moreover, teaching should also encourage students to embrace ambiguity and take risks in the design process, enhancing their engagement and fostering a motivation to learn from uncertainty.

Encouraging openness in the outcomes of game design. Based on the data from interviews in Section 6.5.2, it was found that the prototyping phase posed minimal challenges for each group. Subsequent examination revealed that this was due to the curriculum's lack of restrictions on the outcomes of game design. This allows for openness when students engage in their respective roles within the groups. Each group selects the final prototype format (e.g., paper prototype, video, or interactive prototype) based on the professional skills of its members before creating the prototype. Subsequently, each student contributes their individual strengths towards a common goal. The study suggests that this approach can encourage the realization of the full potential of individuals, tools, and interactions in stimulating the design process.

(2) Implications for reflective design

Critical thinking in setting goals. The cultivation of critical thinking skills in goal setting is paramount in game design education, guiding designers to approach the final prototype design phase with precision and foresight. In this critical stage (Figure 6.5), students are challenged to adopt a rigorous and rational approach, beginning with comprehensive brainstorming sessions to assess target audiences and evaluate their own capability. Through introspection and consideration of societal needs, students identify design gaps and ensure a rational approach to goal setting(Patel, 2003). They are encouraged to scrutinize whether their designs can address real-world issues, necessitating a meticulous evaluation of their objectives within relevant domains. Moreover, students engage in an iterative process of refinement, drawing insights from instructor feedback and user input to continually improve their ideas. By prioritizing critical thinking, students not only navigate the complexities of rhythm game design but also cultivate the innovation and relevance needed to make impactful creations.

Rhythm analysis in defining components. The integration of rhythm analysis in defining components marks a pivotal advancement in game design education (Costello, 2018, 2020b; Tan and Ren, 2023). From this phase, three key elements emerge: understanding human-computer rhythms, designing diverse interaction modes, and leveraging rhythm data (Figure 6.2). Designers must grasp the intricate interplay between human rhythmic input and computer-generated rhythms to enhance gameplay and elevate player experiences. Additionally, proficiency in crafting dynamic interaction modes tailored to diverse player preferences is imperative. Mastery in leveraging rhythm data to personalize gaming experiences and drive engagement is also crucial. By embracing these insights, educators can effectively equip future designers with the analytical and creative prowess needed to create immersive and inclusive gaming experiences.

Holistic thinking in framing patterns. Paying attention to holistic thinking in framing patterns is vital to guide designers to make mechanism design. Drawing from *synergized interactions* (Ren, 2016), three key elements emerge to foster human holistic thinking in game design education: defining states of synergized rhythms, identifying rhythm adjustment zones, and designing adjustment mechanisms (Figure 6.2). Designers must define different states within synergized rhythms, ensuring a balanced player experience that maintains engagement and satisfaction. Additionally, identifying rhythm adjustment zones allows for accommodating diverse player skill levels and preferences while fostering player adaptation and mastery. Refining adjustment mechanisms based on these zones ensures effective player learning and progression.

6.6.3 Limitations and Future Work

Although theoretically comprehensive, the framework in Section 6.3 can encounter practical challenges such as addressing individual student differences and adapting to diverse teaching environments of game design. In addition, limitations may arise in the evaluation process, including sample size and representativeness, as well as the effectiveness of the evaluation tools. Future research should focus on improving and delving deeper into these aspects to improve the credibility and applicability of evaluation results.

6.7 Conclusion

In this study, we introduced the Synergized Rhythm Game Teaching Framework (SGDTF), a structured approach aimed at fostering student engagement and reflective design practices. Through both qualitative and quantitative analysis, we observed a significant improvement in student engagement, as well as their ability to critically evaluate and refine their designs. It is evident that the SGDTF serves not only as a pedagogical framework, but also as a catalyst for innovation and introspection within the realm of game design education. Looking ahead, educators and designers must take advantage of the lessons learned here and embrace a more comprehensive approach that empowers students not only to create compelling games, but also to reflect on their designs. This will contribute to the development of a more inspiring and innovative ecosystem in game design education, cultivating game designers with greater depth and foresight.

Chapter 7

Study 4: Extension in Education from a HEC Perspective

This chapter introduces a study that explores an extended investigation on digital heritage education from a human-engaged computing perspective It includes two parts: (1) presenting the teaching framework of digital heritage education in the classroom; (2) conducting a course to investigate the effects of the teaching framework on guiding students' understanding and design of intangible cultural heritage.

This study serves as a macro-level exploration to extend our theoretical framework toward human-engaged computing. This is the frontier work in the world in applying human-engaged computing theory to digital heritage education, where *synergized interactions* can be achieved between students and devices. It will stimulate research on the application of our framework to education field.

7.1 Introduction

In the context of Digital Heritage Education (DHE), students face multiple educational challenges that require attention (Lu et al., 2022; Tan et al., 2020a, 2019), including improving the effectiveness of the instructional relationship between educators and students, fostering effective group collaboration among students, and facilitating their learning through the effective use of digital tools. This study specifically investigates methods through which students can effectively collaborate with digital tools to enhance their understanding and design of Intangible Cultural Heritage (ICH) (Lu et al., 2022; Alivizatou-Barakou et al., 2017).

ICH encompasses complex knowledge that students often find difficult to grasp. According to an ICH practitioner, if students do not understand ICH, they will not be able to create successful and innovative ICH products (Kurin, 2004; Lu et al., 2022; Tan et al., 2019). Consequently, numerous researchers have developed various digital tools to help in the comprehension and design of ICH, such as tools to visualize ICH knowledge or to assist students in ICH design practices (Leow and Ch ’ ng, 2021; Gómez-Ruiz et al., 2021).

However, digital tools are often regarded as standalone components within the classroom teaching toolkit. Few studies have emphasized the importance of student collaboration with these tools to enhance their understanding and design of ICH. Although some heritage education frameworks have begun to examine the role of digital tools in the classroom (Bekele et al., 2018; Portalés et al., 2018; Cerreta et al., 2021), they often neglect how these tools can systematically support students, guiding them from acquiring a basic understanding of the ICH knowledge to creating innovative products based on that knowledge. Therefore, the interactions between students and digital tools need to be re-evaluated to more effectively support the comprehension and design of ICH.

Inspired by the cutting-edge theory of Human-Engaged Computing (HEC) (Ren, 2016; Ren et al., 2019), which emphasizes achieving “the right balance” between humans and computers in interactions , we propose that the principles of HEC can significantly improve the DHE classroom. By equally prioritizing human needs and technological potential, HEC can empower the DHE environment to fully leverage engagement, thereby improving the collaboration between students and digital tools in understanding and designing ICH.

The contributions of this study are threefold: (1) we introduce a framework (Figure 7.1) comprising three dimensions — *engaged students*, *engaging digital tools*, and *synergized engagement* — to facilitate phased collaboration between students and digital tools for understanding and designing Cantonese Porcelain (CP), grounded in HEC theory. (2) This framework has been validated through iterative implementations of a creative CP course over five years, supporting three distinct phases of the understanding and design of ICH in the DHE classroom. (3) We contribute an extended framework to rethink the applications of the HEC perspective in current DHE and contribute future research agendas into DHE classrooms. (4) This pioneering work is the first to apply HEC theory to DHE, potentially sparking further research into the application of HEC theory in educational contexts.

7.2 Related Work

7.2.1 Challenges on Student ' s DHE in Classroom

Despite the potential of digital tools, the significant challenges encountered by students remain in their application to the Digital Heritage Education (DHE) classroom (Lu et al., 2022; Pisoni et al., 2021; Pitura and Monika, 2018). First, the effectiveness of these tools in fostering a deep contextual understanding of ICH varies widely among students, often depending on prior exposure to digital learning environments and their intrinsic motivation. This variation highlights the need for customized educational approaches that can adapt to different learning styles and levels of digital literacy (Ye et al., 2022; Challenor and Ma, 2019).

A key issue is the lack of real-time feedback and personalized guidance in digital learning environments, unlike traditional classrooms, where instructors can immediately address misunderstandings (Lu et al., 2022; Pisoni et al., 2021; Pitura and Monika, 2018). This gap in interaction can hinder students ' comprehension and application of ICH knowledge. Enhancing digital tools with adaptive technologies and AI-driven feedback could mitigate these challenges and improve learning outcomes (Lu et al., 2022; Giakoumis, 2020). Moreover, the cultural and contextual sensitivity of ICH poses unique challenges for digital representation (Pisoni et al., 2021). The subtleties and nuances inherent in ICH elements may not be easily captured or conveyed through digital means, potentially leading to oversimplification or misinterpretation of cultural knowledge. Digital tool designers must work closely with ICH experts to ensure that these tools faithfully represent the cultural intricacies and values embedded in ICH (Lu et al., 2022).

Finally, the rapid evolution of digital technologies requires continuous updates and adaptations of educational tools and curricula (Pitura and Monika, 2018). Keeping up with technological advances requires significant investment in resources and ongoing professional development for educators. Institutions must prioritize these aspects to ensure that their digital heritage education programs remain relevant and effective (Pisoni et al., 2021).

Although digital tools hold promise for enhancing DHE, addressing these challenges is crucial to realize their full potential. By fostering integrated, adaptive, and culturally sensitive digital learning environments, educators can better support students in their journey from understanding to designing ICH. Future research should focus on developing comprehensive digital platforms, improving feedback mechanisms, and ensuring the cultural authenticity of digital representations of ICH.

7.2.2 Current Frameworks in DHE

As digital technologies have advanced, various frameworks have emerged that integrate technology into heritage education. One of the first is the Heritage Cycle (Thurley, 2005), which underscores the importance of understanding, valuing, preserving, and enjoying heritage to facilitate its sharing. However, while this cycle underscores the importance of engagement with heritage, it does not fully integrate digital tools, potentially limiting its applicability in contemporary educational contexts.

Another framework, known as the "Framework to Heritage Education", was created to improve heritage education through information technologies, allowing individuals to access and engage appropriately with their cultural heritage (Mendoza et al., 2015). This framework offers a more modern approach, but still faces challenges in ensuring that digital interactions are as effective as traditional methods. There is a need to critically assess how these technologies impact the depth and quality of heritage education.

A digital learning-based approach emphasizes the methodology of digital cultural heritage education, with the goal of developing the skills of educators in this field (Kim and Kim, 2017). Although this framework is forward-thinking, it assumes a level of digital literacy that may not be present in all educators. This gap can lead to disparities in the effectiveness with which digital tools are utilized in heritage education.

In addition, a framework is dedicated to the implementation of digital tools to safeguard and manage cultural heritage, offering standardized guidelines for the preservation and protection of digital ICH (Börjesson et al., 2020). This framework lacks guidelines for the effective integration of digital technologies, resulting in fragmented approaches that do not fully address the nuanced needs of cultural heritage education.

Research has explored the integration of virtual museums into the education of digital cultural heritage and has established guidelines for their effective implementation in educational contexts focusing on cultural heritage (Antonaci et al., 2013). Virtual museums offer innovative ways to engage learners, but their effectiveness can be limited by technological access and the potential for reduced tactile and sensory experiences compared to physical museums.

Several theoretical frameworks have been proposed to assist in the design of virtual environments (Ibrahim and Ali, 2018) or serious collaborative games intended to improve users' understanding of cultural heritage (Andreoli et al., 2017). These frameworks highlight the potential of interactive and immersive technologies in enhancing cultural heritage education. However, they also raise questions about the balance between entertainment and educational value, as well as the potential for digital divides among different user groups.

In general, current frameworks have demonstrated beneficial outcomes in steering digital heritage education across diverse domains. However, it is essential to highlight the dearth of research frameworks that explicitly examine the effective utilization of digital tools by students in classroom settings to understand and design ICH, as well as guiding students in transitioning from understanding ICH to actively designing it.

7.2.3 Human-Engaged Computing as a Perspective

Although DHE has received increasing attention from governments, organizations, institutions, researchers, and educators in recent years, there are some key issues that still deserve further exploration. For example, building a systematic guiding framework to bridge theories and practices in DHE classroom. Some HCI researchers have used HCI theoretical methods, such as scenario-based design, activity theory, and user-cantered design, to empower heritage education using emerging technologies. In the field of education, scholars of interdisciplinary education and technology-enhanced learning have begun to use popular educational models (e.g., STEAM education) and concepts (technology-enhanced learning) in the dissemination and education of cultural heritage aimed at improving the understanding and experience of learners of cultural heritage and even stimulating creative thinking.

Although existing exploration has achieved certain results, there are still problems worth exploring for future DHE. For example, to promote deep engagement of learners and fully stimulate the potential of technology in DHE, the HCI community has the responsibility to propose a more comprehensive framework to guide the design and evaluation of DHE. Although there are mature teaching models in the field of education that can serve as a guiding framework for HCI educators to design courses, these models ignore or lack a sense of how to create meaningful interactions where learners engage with digital technology to understand, learn and design cultural heritage.

Human-Engaged Computing (HEC) integrates technology and human capabilities to achieve deeper levels of understanding (Ren, 2016). It consists of three core components: (1) engaged humans, individuals whose skills are utilized and developed through

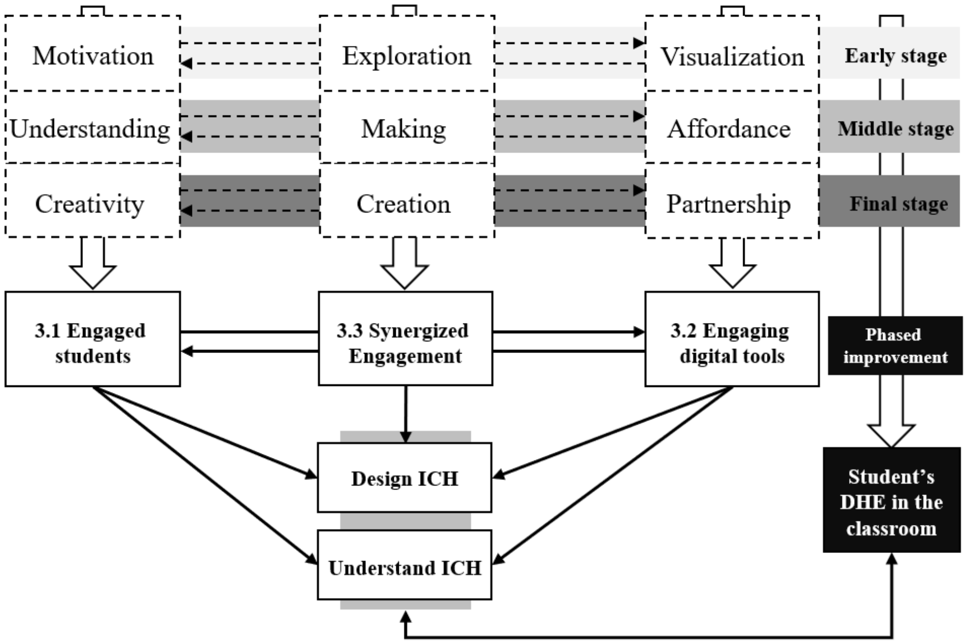


Fig. 7.1: A framework for students' digital heritage education in the classroom.

active participation, (2) engaging computers, which include hardware and software that involve and enhance human capabilities, and (3) *synergized interactions*, the seamless integration of human skills and technological capacities (Ren et al., 2019). HEC focuses on enhancing human abilities through active engagement and optimizing technology to facilitate meaningful collaboration with humans (Ren et al., 2019; Tan et al., 2023). The objective is to maintain a balanced approach that equally values human potential and technological capabilities. HEC is a holistic consideration to rethink the relationship between humans and computers. It has been explored and demonstrated the importance both theoretically and practically for stimulating human capabilities, designing potential tools, and creating meaningful interactions.

Our aim is to facilitate progressive collaboration and enhancement between students and digital tools. The HEC framework provides a guide for researchers and educators to reconsider the interaction between students and digital tools, while exploring the value of ICH, the capabilities of digital tools, the improvement of students' skills and the instructional design of DHE. This framework also underscores the importance of cultivating effective collaboration between students and digital tools, gradually unlocking their full potential to help students understand and design ICH.

7.3 Framework

Figure 7.1 depicts the framework for DHE within the classroom context, structured around three dimensions: *engaged students*, *engaging digital tools*, and *synergized engagement*, informed by the HEC framework (Ren et al., 2019). Each dimension includes three elements spanning early, middle, and final stages of the DHE classroom (Tan et al., 2019), facilitating incremental enhancements in understanding and designing ICH. Across these dimensions and stages, a total of nine elements are identified, guiding the progression from understanding to the design ICH.

Influenced by constructivist theory on motivation and learning creativity (Pavlović and Maksić, 2019; Neo and Neo, 2009), we define the elements of engaged students as motivation, understanding, and creativity. Based on the evolution of technology-supported roles in HCI (Ren, 2016; Farooq and Grudin, 2016), we characterize the elements of engaging computers as visualization, affordance, and partnership. Drawing insights from frameworks for technology-enhanced education (Ibrahim and Ali, 2018; Archambault and Barnett, 2010), we outline the process of synergized engagement as exploration, making, and creation. These elements are organized into three stages. Our framework seeks to (1) investigate the interplay of these components within each phase to enrich students ’ comprehension and design of ICH, and (2) assess student progress by evaluating developments at each stage.

Engaged Students. It strives to boost their motivation, comprehension, and creativity by actively participating in different phases. When students are motivated, they naturally take the initiative to learn and deepen their understanding of ICH. Once they grasp ICH knowledge thoroughly, their creativity can be fully activated when using digital tools to design innovative products. Unlike traditional approaches in digital heritage education where students passively absorb information, engaged students experience a comprehensive and phased process of enhancement that revolves around collaborative interactions with digital tools.

Engaging digital tools. The purpose of engaging digital tools is to maximize students ’ capabilities in visualization, affordance, and collaboration. In the DHE setting, these tools initially aid in visualizing various facets of ICH. Subsequently, students can leverage this visualization to comprehend how to creatively design products using digital tools. When students face challenges, digital tools serve as a means to facilitate collaboration and further enhance their understanding of ICH. Additionally, there is a focus on identifying potential limitations of tools to actively involve students in the

DHE classroom, guiding the development of more efficient digital tools.

Synergized engagement. It describes the dynamic collaboration between motivated students and interactive digital tools in the comprehension and design of Intangible Cultural Heritage (ICH). This approach unfolds through three key stages: exploration, fabrication, and creation, each fostering creativity throughout the learning process. Initially, students begin by exploring ICH knowledge. They then advance to crafting basic two-dimensional and three-dimensional models, utilizing their creativity to develop successful products by harnessing the full potential of digital tools.

Course (data)	**Digital tools**			**Outcomes**	**Probing method**
	independently developed tools	Open-source tools	Teaching aided tools		
1. 2018.11 2. 2019.04 3. 2020.04 4. 2020.11 5. 2021.04 6. 2021.11 7. 2022.06	CAI Web AR CAI Mini APP	Scratch Fusion 360 Micro bit Arduino	WeChat group Online classroom Online drive Online zoom	Game design Wearable design Lamp design AR game design Creative product	Database Survey Interview Focus group Exhibition Video Audio

Fig. 7.2: A five-year case study of engaging digital tools with students to understand and design Cantonese Porcelain in the classroom.

7.4 Evaluation of the Framework

To evaluate the validity and usefulness of the proposed framework, we designed and implemented creative design courses over five years (Figure 7.2). We tracked student engagement and improvement in understanding and designing ICH and conducted a critical review of the dimensions and elements of the framework we proposed. Our empirical research revealed that the framework effectively guided the creative design processes of the students, improving their engagement and skills in ICH design (Tan et al., 2019; Ji et al., 2020; Tan et al., 2021; Lu et al., 2022). The review also identified areas for improvement and guided future research.

7.4.1 Course Description

We designed and provided three types of digital tools (independently developed tools (Tan et al., 2019; Ji et al., 2020), open-source tools (Lu et al., 2019; Ji et al., 2021), and teaching aids for (Lu et al., 2019; Tan et al., 2021), Figure 7.3) to facilitate understanding and design of Cantonese Porcelain (CP, Figure 7.3a, (Lu et al., 2019)) based on previous courses. Figure 7.3 illustrates we held seven courses over five years, each with 30 students from various majors in the School of Art and Design. Each course was divided into six groups and included three instructors and three teaching assistants. The three types of digital tools are used in the course. More details can be seen in Figure 7.2. Each course lasted one month, with two classes per week, each 45 minutes long. Specific topics, such as lighting design for smart handcraft, were defined for each course. Figure 7.3b illustrates the course process and Figure 7.3c shows prototypes created on various themes. Three professional teachers evaluated the findings of the students.

7.4.2 Probing Method

To assess the validity and effectiveness of the framework, we used a mixed qualitative research approach with interviews and focus groups, referred to as *DfI* (that is, data from the interview) and *DfFG* (that is, data from the focus group), respectively. These methods were chosen to gain a comprehensive understanding of how participants perceive and experience the framework. The content of the interviews and focus groups was meticulously transcribed and analyzed using a hybrid coding method (Fereday and Muir-Cochrane, 2006), with descriptive labels applied to effectively interpret the qualitative data. The interviews collected student feedback on understanding and designing CP with digital tools, focusing on learning challenges, user experience, and impact of tools on creative design. Focus groups, involving CP inheritors and students, evaluated the design process and outcomes, providing diverse perspectives and insights into the framework's effectiveness and areas for improvement.

7.4.3 Findings

We examined the results of all the courses using the probing method Figure 7.2, covering five years of documentation. This identified insights gained from the initial, intermediate, and final phases of the courses, exploring the phased advancements as outlined in the proposed framework Figure 7.1. The findings highlight how the dimensions and elements of the framework helped students understand and design ICH using digital tools.

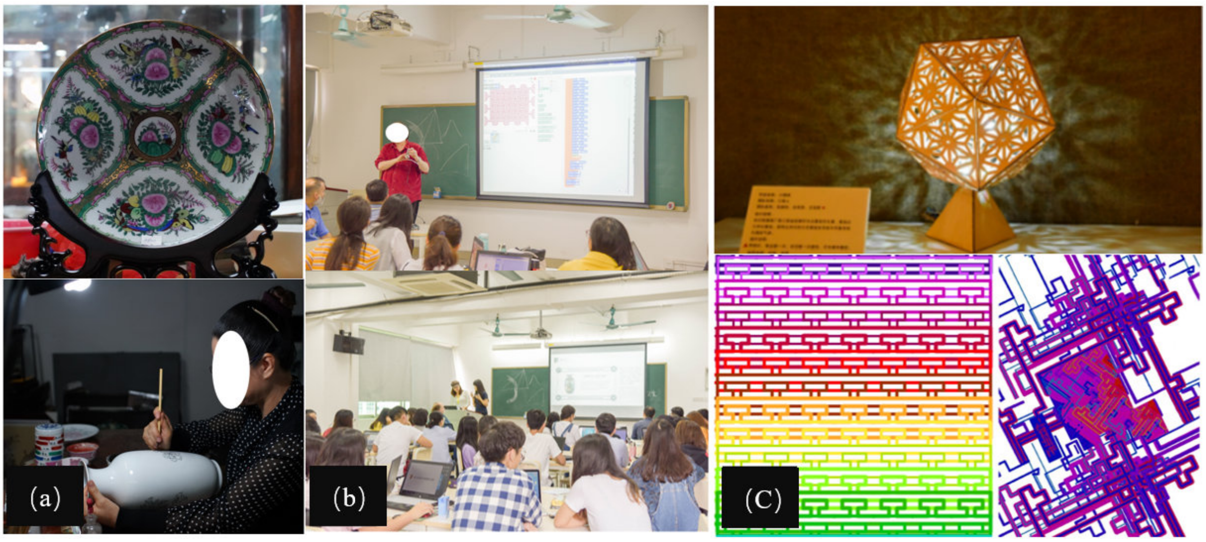


Fig. 7.3: Samples of (a) Cantonese Porcelain and CP's Making by Inheritor, (b) creative CP's design in the classroom, (c) CP's creative outcomes.

(1) Early stage: motivation, visualization, and exploration

During the early stages of the course, we found that the motivation of the students towards CP was higher than anticipated, with engagement levels significantly increasing in the latter stages (*DfI*). Collaboration with CP inheritors (*DfFG*) revealed key elements that differentiate CP from other Chinese heritages, such as the use of blue and white. However, the creative design of students often lacked core knowledge of CP. To address this issue, the CP inheritors suggested that students first be exposed to more examples and gain a deeper familiarity with CP.

Challenges of visualizing CP. One of the significant challenges in studying CP was visualization of the three-dimensional porcelain. Digitizing CP to recognize different patterns and colours is a complex and time-consuming, requiring extensive manual effort in photographing, modelling, and texturing. Despite our efforts, many aspects of CP, such as the inheritors' tacit knowledge, remain difficult to digitize. Future research will explore innovative approaches to digitize and preserve this tacit knowledge (*DfFG*), aiming to enhance understanding and preservation of CP ' s unique features.

Reframing design questions for exploration. Defining appropriate questions for conceptual design is a crucial challenge in the creative design process. Despite access to ample materials and easy-to-use tools, students found that defining design questions difficult, leading to considerable time spent on this stage. Some students suggested providing design themes to make their designs more purposeful, which proved effective encouraging critical thinking (*DfFG*). However, some students still struggled with problem definition, causing frustration and a desire to abandon the next production phase (*DfI*). To address this challenge, we need a more effective approach to problem definition beyond tool use and CP knowledge. Three groups noted spending significant time on problem definition, discussing CP elements and values with inheritors, brainstorming ideas, and evaluating feasibility with teachers (*DfI*, *DfFG*). Through time-consuming, this process significantly contributes to successful final creative outcomes.

(2) Middle stage: understanding, affordances, and making

Understanding CP. Poor visualization of CP can lead to misunderstandings of CP, especially for students without a background. Our interview found that physical products and recorded videos had visual impact but did not effectively convey knowledge to the public (*DfI*). Over half the students in the first class noted that while they had seen many pictures of CP, its historical background was often overlooked, leading to potential misunderstandings (*DfI*). For accurate and informed creative designs, students need a comprehensive understanding of CP, which requires constructing the original context of its content rather than merely copying during digitization (*DfFG*). Our findings indicate that while students may have a basic understanding of CP, there is a gap in adaptive creative design, particularly with specific tasks. For example, in designing lamps, balancing elements like the colour of the light and the shade is challenging (*DfI*). CP inheritors play a crucial role in enhancing students ' understanding and creative potential by identifying misunderstandings and providing critical guidance through classroom interactions (*DfFG*).

Creating affordances to bridge CP skills in creative design. The use of digital tools is crucial for connecting CP skills with creative design. Our CAI WebAR system has demonstrated the significant role of digital tools in accessing and understanding CP knowledge. However, leveraging digital tools does not mean incorporating all CP knowledge into one device (*DfFG*). Instead, we need to choose the most appropriate presentation methods for different types of the knowledge of CP and utilize various digital tools to maximize their advantages.. Throughout the course, we used various digital tools to help students understand and design CP. However, we found that students had varying degrees of understanding when using the same digital tools (*DfI*). Interviews revealed that a preliminary understanding of the CP ' s making process through the CAI Mini-APP before using CAI WebAR helped students better integrate the knowledge from both tools, enhancing their overall understanding (*DfI*). This suggests that students benefit from using different digital tools in a standardized order, which aids in understanding CP knowledge more effectively.

Defining a standard of making to balance tasks. A critical aspect of CP making is not merely reproducing its elements but presenting the core knowledge they contain (*DfFG*). To achieve this, we establish a standard of making when students use digital tools for CP creation. We ensure the authenticity and clarity of basic materials by involving a CP inheritor in compiling the CP database and teaching CP in the classroom. Our findings highlight the importance of students understanding CP ' s history and patterns before document creation (*DfI*). A clear grasp of CP ' s core knowledge helps students comprehend its relationship with creative design for specific products. Many students struggle with applying CP elements due to a lack of prior exposure to CP knowledge (*DfI*), hindering effective design. We propose defining a standard of making that ensures students grasp CP ' s core knowledge before applying it to specific tasks (*DfFG*). This approach deepen understanding of CP ' s unique features and enhance creative design skills. Our course underscores the importance of clear guidelines and structured learning for mastering CP element application (*DfI*), applicable to broader cultural heritage preservation efforts, fostering innovative digital tools for creative design.

(3) Final stage: creativity, partnership, and creation

Going beyond hands-on and becoming a partner. Our findings suggest that actively students as a partner in the creative design process enhances their learning experiences (*DfI*). To facilitate this, we employ three types of tools. One such tool is the CAI WebAR system, developed independently to overcome traditional classrooms limitations, allowing students to simulate CP pen-making using their mobile phones. This tool integrates physical CP plate simulation through left and right-hand interaction. Interviews revealed that many students appreciated this tool, as it stimulated hands-on work and made them feel as if they were truly creating CP (*DfI*). Some students even described the experience as " amazing ". Among the selected tools, open-source options require the most hands-on experience in the classroom, encouraging students to create designs based on them. For instance, Scratch, a visually appealing programming tool, reduces learning costs and boosts motivation to produce (*DfI*).

Enhancing students' creativity. Our findings emphasize the importance of enhancing students ' creativity in the course. However, many students questioned the use of digital tools over paper tools for CP ' s creative design of the CP, encountered challenges in rendering CP ' s elements in prototype (*DfI*). To address this issue, we encouraged students to think creatively about how their prototypes reflect CP's meanings (*DfFG*). Interviews revealed this approach's benefits, with students noting that designing lamps helped them understand CP by visualizing pattern application (*DfI*). They felt engaged in creative activities while grasping CP elements. However, achieving harmony between CP elements and integrated design is crucial (*DfFG*). Some works may not meet CP's creative design criteria according to its inheritor, underscoring the need for clear guidelines and structured learning to deepen understanding and enhance creative skills (*DfI*). Encouraging students to innovate while respecting CP's traditional elements fosters a comprehensive understanding and creative potential.

Value co-creation. Our findings underscore the importance of co-creation values in creative design in CP, achieved through collaborative efforts with digital tools (*DfFG*). Understanding CP's value is crucial for optimizing digital tool partnerships in designing CP outcomes. By using digital tools for CP creative design, more students can appreciate CP's value and stimulate their creativity. Interviews reveal a positive correlation between students' understanding of CP's value and the quality of their creative designs (*DfI*). As noted by some students, deeper knowledge of CP leads to more authentic and innovative designs (*DfI*). Evaluations by CP inheritors further emphasize the importance of applying CP knowledge in design, suggesting that understanding CP's value enhances students' ability to create meaningful and innovative designs (*DfFG*).

7.5 Discussion

Our study emphasizes the importance of digital tools in engaging students with Intangible Cultural Heritage (ICH), showing their effectiveness in fostering ICH preservation and enhancing student creativity. This section provides guidance for future researchers, designers, and educators in digital heritage education (DHE), addressing theoretical insights and future research directions.

7.5.1 Theoretical Implications for Future DHE

Our unique DHE framework offers a detailed design and evaluation model, differing from existing HCI and education frameworks (da Cruz Alves et al., 2021; Stephanidis et al., 2019; Ouyang and Jiao, 2021). It encourages rethinking educational research in areas such as creativity with computers, emerging tech skills, and AI in education, while improving current models. Over five years of empirical research, we refined our framework, providing practical recommendations for curriculum design and assessment. We identified key research questions on tool-related risks, impacts of interactions, and motivation of students in DHE, guiding future research and the development of innovative digital tools for cultural heritage education.

7.5.2 Implications for Future Agendas

ICH as a design source in the classroom. The wealth of experience and wisdom in ICH can greatly inspire designers to create culturally significant works (Tan et al., 2020b; Cerisola, 2019). Many designers seek inspiration from ICH museums and studios (Pistilli, 2018; Pagán et al., 2020), with luxury brands like PRADA collaborating with ICH inheritors for new product development. Young ICH inheritors are also redesigning ICH products to appeal to modern tastes, offering designers new opportunities to create works that resonate with contemporary audiences. Research should explore how designers can integrate ICH into their creative processes to produce modern interpretations of cultural heritage. In China, ICH education is gaining popularity in schools, aiming to enhance students ' creative abilities and cultural understanding (Ciolfi et al., 2015; Lu et al., 2022; Liu et al., 2023). Incorporating ICH elements into the curriculum and providing hands-on activities can help students appreciate and engage with ICH design, fostering a deeper connection to cultural heritage.

From participatory to engagement. Our creative design course emphasizes engagement design, involving students, digital tools teachers, and CP inheritors to maximize students ' creative thinking and problem-solving abilities (Permatasari and Cantoni, 2021; Cumbo and Selwyn, 2022). By actively involving students in the design process and decision-making, we enhance creative outcomes. Given their initial unfamiliarity with CP and digital tools, the course focuses on holistic growth and problem-solving skills. Encouraging students to explore their interests, experiment with ideas, and collaborate with peers fosters a sense of ownership and investment in the creative process.

Engaged students for group creativity. Engaged students should be viewed at the group level, as collaboration often outperforms individual effort. In the CP Creative Design course, students form groups to leverage their strengths and immerse themselves in tasks, fostering creativity (Ren et al., 2019; Tan et al., 2020b). However, group collaboration can encounter conflicts, requiring attention to cognitive connections among students. Promoting effective communication and idea-building helps maintain positive group dynamics. Creating a supportive, inclusive environment where individual differences are valued, and everyone can participate equally is essential. Encouraging multiple perspectives and incorporating feedback further enhances the group's creative process.

Fostering meaningful interactions in DHE. For students to fully benefit from digital tools in learning and designing ICH, they must engage in meaningful interactions that stimulate creativity. However, these tools can also pose challenges by disrupting learning rhythms or replacing the learning process (Ren et al., 2019). To address these issues, we suggest creating synergies between digital tools, interfaces, and human perception to motivate and engage students. This involves balancing student needs with the nature of digital tools, ensuring they do not impair existing abilities, providing real-time feedback, allowing freedom in participation, and fostering creativity. Digital tools should align with the learning objectives of DHE, complementing rather than replacing the learning process. Educators need to select tools that support learning goals and provide proper guidance on their use. Additionally, designing digital tools to encourage collaboration and interaction among students is crucial. Features that enable students to share work and give feedback can help them learn from each other and gain a deeper understanding of ICH.

7.6 Conclusion

In this study, we proposed a holistic framework to guide future digital heritage education and followed CP's creative design course for five years. The process involved course design, material preparation, course survey, and iteration. Our team had long-term cooperation and exchanges with CP inheritors and gained valuable first-hand information, including stakeholder feedback, the iterative trajectory of the course, the work of students in each course, and a holistic database of CP. We believe that the student will be the primary participants in the inheritance of ICH, and ICH's digital education will gradually be integrated into school curricula. Our work will inspire designers, educators, and researchers to rethink digital heritage education from framework, design, and practice perspectives, and it will also inspire other educational topics in the education and information technology community to reconsider the relationships between humans and computers and help educational or pedagogical research establish new research agendas.

Chapter 8

General Discussion

This chapter discusses four parts: (1) summary of studying *synergized interactions* in this dissertation; (2) general discussion of theoretical studies; (3) general discussion on empirical studies; (4) limitations and future work.

8.1 Summary of Studying *Synergized Interactions*

The study of *synergized interactions* in this dissertation (see Figure 8.1) explores the dynamic interaction between humans and computers. On one side, humans focus on meaningful interactions between their mind and body. On the other side, computers are explored in two modes: first, where computers understand humans, with the computer taking an active role while the human mind implicitly senses the computer's output; second, where humans understand computers, with the computer in a passive role, and humans making perceptual judgments upon sensing the computer's output, subsequently adjusting their body explicitly.

The key of this dissertation lies in achieving two macro goals: (1) the regulation of *synergized interactions* for humans, which requires a nuanced understanding of how to balance and integrate body, mind, senses, and perception; and (2) the dynamic adjustment of *synergized interactions* for computers, which involves creating systems that can seamlessly adapt to human inputs and states in real time.

The necessity for computers to adjust based on the real-time state of humans is paramount. Equally critical is the need for humans to dynamically regulate their interactions on the basis of continuous feedback from computers. This two-way adjustment ensures that *synergized interactions* occur in a seamless and harmonious zone. Such interactions not only maximize the potential of both humans and computers but also safeguard against the risk of one dominating or detracting from the other's capabilities and interests.

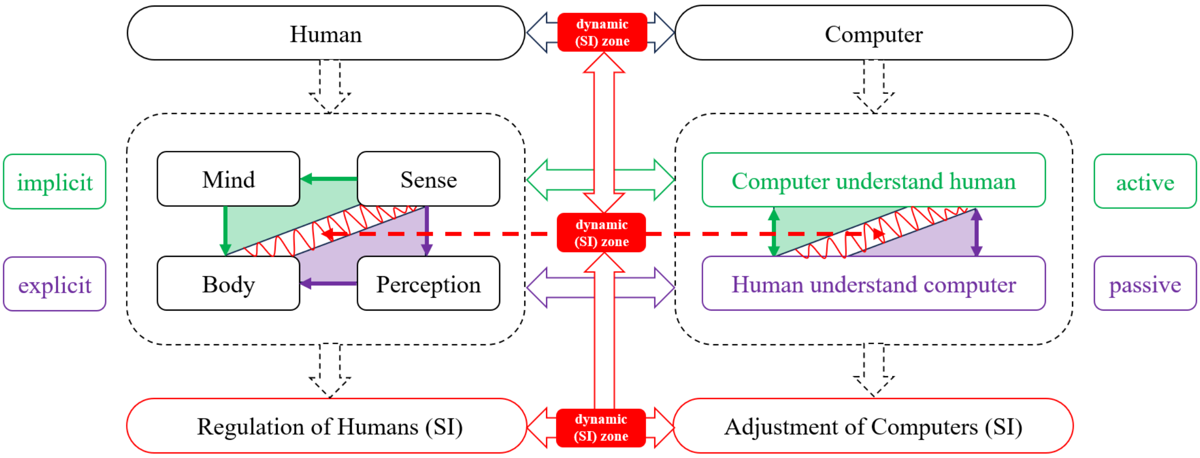


Fig. 8.1: The figure show a summary of studying *synergized interactions* in this dissertation.

8.2 Theoretical Studies

8.2.1 Perspectives

(1) Human perspective: augmenting human capabilities.

During the past four decades since Engelbart proposed the notion of augmenting intelligence in 1962, the HCI community has witnessed rapid development, intersecting with psychology, computer science, and design. However, Engelbart's vision has not garnered widespread attention within the HCI community during this period. Despite prolonged discussions and research on human-centered design and computing, interactive technologies aimed at enhancing human sensory and behavioral capabilities have been continuously developed in various fields and demographics (Rogers, 2022; Harrison et al., 2007; Bannon, 2011). However, these concepts and technologies still focus primarily on extending basic human abilities, without paying attention to human soft skills (e.g., creativity, mindfulness, and design) from an ideal perspective of human-computer relationships, namely *synergized interactions* (Ren, 2016).

It is evident that the rapid advancement of technology has greatly enhanced basic abilities, yet it has also brought about irreparable harm to the human psyche, manifesting in the alienation within human-computer relationships. Examples include the negative impact of streaming media on human emotions, privacy, ethics, consciousness, and value, among others (Bargh and Morsella, 2008; Acquisti et al., 2015). The initial motivation of this dissertation is to adopt the perspective of *synergized interactions* in the theory of Human-Engaged Computing (HEC) (Ren, 2016), with the aim of reducing the threats posed by technology to humans while promoting the enhancement of human soft skills. This perspective is a sobering reminder amidst the current fervent environment of relentless technological advancement (e.g., the revolution of super AI), inspiring all HCI/HEC researchers not to overlook the potential risks of technology and the sustainable development of humanity while pursuing technological progress.

(2) Computer perspective: designing synergized technologies.

With the widespread application of information and communication technology in our daily lives, there is a pressing need for more harmonious interaction between humans and computers, which requires the development of technologies that facilitate improved interaction (Bargh and Morsella, 2008; Acquisti et al., 2015). However, current HCI dynamics are primarily human-driven, with computers lacking initiative and autonomy, resulting in an imbalance in interaction (Bargh and Morsella, 2008; Acquisti et al., 2015). This disequilibrium not only poses various issues in health and social domains but also leads to dependence on computers, such as internet/gaming addiction. The fundamental reason behind this lies in the fact that computer operations remain predominantly directed by human volition, exhibiting a one-way nature.

In recent years, there has been extensive research into new interaction models and technologies between humans and computers, spurred by advancements in fields such as human-computer interfaces, artificial intelligence, and robotics (Bargh and Morsella, 2008; Acquisti et al., 2015). However, much of this research continues to be anthropocentric and one-way in nature. The development of balanced human-computer foundational technologies, termed synergized technologies, remains largely underexplored. The realization of synergized technologies aligns with the recent pursuit within the HCI community for seamless integration between humans and devices. Seamless integration involves computers not only serving as tools, but complementing human capabilities and perceptions, fostering a natural fusion between humans and computers (Bargh and Morsella, 2008; Acquisti et al., 2015). Across the entire HCI research landscape, the interaction between humans and computers has shifted from the traditional norm of human input and computer output towards a norm of mutual synergy, highlighting the evolving nature of this relationship.

(3) Interaction perspective: getting the "right balance".

Previous research in the field of Human-Computer Interaction (HCI) has revealed one of the reasons for the imbalance in interaction between humans and computers: inconsistency in actions between the two parties, directly impacting subsequent behaviors and task performance (Bargh and Morsella, 2008; Acquisti et al., 2015). This phenomenon primarily stems from the complexity of human actions during mutual interaction and response processes, resulting in mutual "ahead-of-time" or "delay", leading to gaps between actions on both sides (Bargh and Morsella, 2008; Acquisti et al., 2015).

Synergized interactions advocate for achieving the ideal relationship of getting the "right balance" according to Eastern philosophy when humans interact with computers (Ren, 2016). This relationship differs from traditional mechanical resource allocation demands (e.g., equilibrium) and emphasizes dynamic adaptation accompanied by suitable resource provisions for both interacting parties. This perspective aims to address the imbalance in interaction between humans and computers, improve their correlation, establish a more comfortable computing environment, and contribute to the overall societal well-being.

8.2.2 Methodology

(1) Paying attention to rhythm analysis in interactions.

Costello (2020b) emphasizes the importance of paying attention to rhythm in designing interactive systems. This attention to rhythm can help researchers and designers find the "groove" (Malone, 2022) or optimal state between humans and computers (Costello, 2018, 2021; Danielsen et al., 2023). Henri Lefebvre's rhythm analysis theory explains how social and biological rhythms can interfere with, harmonize, and regulate each other (Lefebvre, 2013). Human rhythm is entangled with computer rhythm in the ubiquitous computing world (Weiser, 1994; Frauenberger, 2019).

The asynchrony of rhythms between humans and computers poses a significant challenge in the field of HCI. We need to pay attention to how to effectively regulate the rhythm in interactions between humans and interactive systems, such as how to drive human and/or computer rhythms to maintain optimal states in interactive systems to better stimulate the potential of both sides of the interaction (Ren, 2016; Ren et al., 2019). Our emphasized vision suggests employing rhythm analysis to thoroughly examine the evolving states of interaction between both parties. Optimization of asynchrony of rhythms in HCI is crucial to achieving mutual understanding. Although humans exhibit highly intricate and diverse rhythmic patterns, computer rhythms tend to be fixed, predictable, and mechanical. This contrast may lead to instances of discordance and unnaturalness in interaction between humans and computers, consequently affecting interaction efficiency and user satisfaction. Therefore, in the design of HCI/HEC systems, it is imperative to acknowledge the differences in rhythm between users and computers, and to explore methods for harmonizing these disparities to enhance the interaction experience, performance, and stimulate the potential of both parties involved.

(2) Synergized interaction framework.

The core concept of a synergized interaction framework is built on rhythm analysis inspired by previous studies (Höök, 2010; Lefebvre, 2013; Costello, 2020b), emphasizing the significance of rhythm in human-computer interaction. By adjusting the rhythm of the interaction, a synergized interaction can be achieved. From a computational point of view, the framework provides a method to interpret and analyze the mathematical representation of enhanced human-computer adaptability, while proposing adjustment mechanisms for three adaptation modes to facilitate synergistic interaction.

Specifically, the framework comprises three parts: first, it elucidates the computational approach for synergistic interaction based on time and rhythm; second, it posits adjustment mechanisms tailored to three adaptation modes, namely situational awareness, cognitive adaptation, and affective adaptation, aiming to enhance synergy between humans and computers; third, it presents a universal interactive procedure adaptable to different interaction modes, thereby elucidating the computational manifestations of synergy. This framework holds theoretical significance, as well as practical application value. By citing relevant research and case studies, we can further validate the effectiveness and innovation of the framework, showcasing its potential and prospects in practical applications. Thus, from an academic standpoint, this framework not only enriches our understanding of HCI/HEC, but also provides valuable insights for the design and optimization of HCI/HEC systems.

8.3 Empirical Studies

8.3.1 Design

(1) Synergized interactions between human and computer.

Our empirical inquiry is motivated by the aspiration to foster synergistic interactions between humans and technology, achieved through a dual focus on (1) facilitating human engagement and (2) refining synergized technologies. In our investigation, Chapters 4 and 5 are dedicated to exploring the intricacies of designing synergized technologies that serve as enablers for enhancing users' soft skills within the fabric of their daily lives. These chapters investigate the intricate design strategies aimed at orchestrating seamless interactions, emphasizing the nuanced mapping of diverse interaction modes and the contemplation of reflective paradigms inherent within two-way interaction models. This meticulous approach ensures that technology not only augments, but harmonizes with human capabilities, amplifying the potential for holistic skill development.

In Chapter 6, our attention pivots towards the strategic design of human engagement, particularly within the dynamic realm of educational contexts, where fostering collaborative learning environments is paramount. Here, the focus is on nurturing students' teamwork prowess and nurturing their capacity for introspective analysis within the context of game design pedagogy. The design strategies delineated in this chapter illuminate the importance of cultivating intrinsic motivation for engagement, recognizing the iterative nature of developmental processes, and acknowledging the enduring impact of engagement experiences on long-term skill acquisition.

In Chapter 7, we attempt to utilize HEC theory as a lens to focus on synergized engagement between engaged students and engaging digital tools. This represents a novel integration of HCI and education, emphasizing how students progressively use digital tools for creative design, thereby bridging the gap between understanding and design. We emphasize the coherence and progression of students' learning by structuring teaching phases sequentially, enhancing their design capabilities and understanding. This approach encourages continuous reflection and adjustment, fostering adaptability. In addition, we explore the dynamic interactions between students and digital tools, illustrating their evolution and role in facilitating deeper engagement and more sophisticated design outcomes, thus expanding traditional boundaries of design education.

(2) Data interactions between human rhythms and computer rhythms.

Rhythm serves as a metric in the design of data interactions, intricately intertwining the interactions between humans and computers, as well as the interplay between the human body and mind. The focus of the two case designs in Chapters 4 and 5 centers on harnessing human data interactions with the support of wearable technologies. The rationale for the design mainly involves the examination of the mutual influence between human behavior rhythms, physiological rhythms, and creative rhythms. The tempo of technological outputs is tailored based on human thresholds across different domains, while also adapting in real-time based on human-generated data. Smooth operation of data interactions requires consideration of rhythm in both detection and feedback design. Detection often overlooked exists as a passive presence for humans, whereas feedback frequently entails proactive stimulation, which can lead to distraction and depletion of cognitive resources when users are engrossed in tasks. This insight suggests that future designs should pay more attention to passive feedback design, providing users with positive stimulation without causing interference.

8.3.2 System Development

(1) Development of one-way interaction modes.

Chapter 4 explores two common one-way interaction modes: one in which humans actively understand computers (passive) and another where computers actively understand humans (passive). From the perspective of rhythm, the former is computer-driven, where individuals actively follow the rhythm outputted by the computer to adjust their own rhythm; while the latter is human-driven, where computers autonomously detect changes in human rhythm and output adaptive rhythms. When developing, several challenges may arise: one challenge is ensuring that the rhythm outputted by the computer can be effectively understood and followed by humans. This involves understanding the physiological and behavioral rhythm changes in humans in order to design interaction methods that align with human habits and cognitive processes. Another challenge is how to accurately capture human rhythm changes and make corresponding adjustments.

In addressing these challenges, our study adopts the following development methods and techniques. First, a user study and testing is conducted to gain insight into user needs and preferences, thereby guiding interaction design. Second, advanced sensor technology and data analysis methods are utilized to accurately monitor and analyze human rhythms, allowing precise perception of human rhythms and adaptive adjustments. Finally, continuous user feedback and iteration are crucial to ensuring system performance and user experience, thus necessitating ongoing system optimization and updates.

(2) Development of two-way interaction modes.

The development of a two-way interaction mode represents an exploration of the latest practices in synergized technology. The development of this mode is presented in Chapter 5, which includes algorithms concurrently integrating the synergized interaction framework outlined in Chapter 3. The design and construction of an interactive model theoretical framework utilizing computational formulas is carried out.

To date, there has been no research, making this the first attempt. Interactions between humans and computers can be observed at each moment of action arranged in chronological order. During synergized rhythms, the rhythms between humans and computers are aligned, representing the optimal state of two-way interaction modes. However, achieving synergized rhythms requires adjustments to both human and computer rhythms. This necessitates accurate monitoring and analysis of human and computer rhythms, as well as ensuring that the system can dynamically adjust rhythms to achieve the optimal interaction state. This transformation of theoretical frameworks into practical and operational interactive models involves the design, implementation, and optimization of algorithms.

8.3.3 User Study

(1) Self-regulation in daily activities.

Chapters 4 and 5 focus on self-regulation between the body and mind of individuals in daily life activities (i.e., walking and running). User studies reveal two challenges: (1) Running, which is more vigorous compared to walking, may not be suitable for all users or difficult to maintain for some. In particular, with regard to mindfulness as a specific training objective, it requires users to maintain a consistent pace and heart rate. Users without running experience often struggle to maintain stable performance due to the difficulty in maintaining a steady pace and heart rate. (2) Completion of creative tasks while walking requires users to meet higher standards in attentional resources compared to maintaining mindfulness, that is, they need to engage additional resources for divergent thinking while maintaining focused attention. This poses a challenge for users with poor attentional self-regulation (e.g., attention-deficit/hyperactivity disorder). In summary, our studies have preliminarily explored these issues and advocated for the continuous development of more targeted synergized technologies to address these emerging and potential issues identified.

(2) Collaboration and reflection in the classroom.

Chapters 6 and 7 focus the attention of user study on collaboration and reflection among students in the classroom. The design of the course effectively guides students' phased engagement throughout the entire game design teaching process. However, two challenges persist in conducting user research: (1) There is a challenge of imbalance between commonality and individuality in student collaboration, involving the integration of students' backgrounds and experiences. Although individual differences are difficult to avoid, extreme cases should be avoided as much as possible when designing groups, such as grouping students from the same major together. This directly affects effective collaboration among students in the prototype design stage. (2) Individual reflection is often limited by engagement in early group discussions (i.e., brainstorming). There is a lack of sufficient open discussion among students and sustained reflection on a topic. This involves the under-use of tools and materials and excessive divergent thinking. We propose adopting a principle of diversity when grouping students, avoiding grouping those from the same major together as much as possible to ensure teams consist of members with different backgrounds and everyday experiences. We recommend introducing structured collaboration tools and methods, such as organizing regular group discussions or workshops, to facilitate open discussion and ongoing thematic reflection.

8.3.4 Evaluation

(1) Physiological data.

The collection of physiological data in Chapters 4 and 5 includes mainly cadence, heart rate, and brain waves. We developed a system to collect user cadence and heart rate (at a rate of once per second) based on smartphones and smartwatches. A refresh rate of once per second is quite high for collecting user cadence and heart rate, especially on devices such as smartphones and smartwatches. This frequency is sufficient to capture changes in users' physiological activities, such as variations in walking rhythm and heart rate. With a sampling rate of once per second, high-resolution data can be obtained, enabling more accurate and detailed analysis. However, it is essential to ensure that the system design can effectively handle and store such high-frequency data and can manage the complexity of data processing during analysis.

For the collection of brainwave data, we utilized existing equipment (MUSE 2) to collect single-channel data from the user's frontal lobe. The MUSE 2 is a consumer-grade EEG headband device, which may have a lower accuracy and signal-to-noise ratio compared to professional-grade neurophysiological research equipment. The collection and analysis of brainwave data require consideration of the complexity of data processing and interpretation. Our experiments revealed numerous uncertainties causing biases in data collection, such as the fit of the device to the forehead, users' emotions and gender, and variations in posture during movement. These factors directly contributed to the unusability of the data.

(2) Subjective reports.

The main methods for collecting subjective reports are primarily questionnaires and interviews. In terms of questionnaires, we especially emphasized the reliability and validity of the scales. This emphasis stemmed from the fact that participants in the experiments of Chapter 5 came from different countries, prompting the use of multilingual questionnaires for evaluation. It should be noted that the questionnaires in different languages were all derived from published versions in specific languages, and their reliability and validity have been verified. Through this approach, the study ensured the quality and consistency of the data collected in different language versions of the questionnaires. This method recognizes the importance of linguistic and cultural nuances in psychological evaluation, with the aim of maintaining the integrity of the measurement tools in different language environments and providing more empirically meaningful data for different groups of participants.

The interview guide was designed specifically for the research objectives. Although some templates from previous studies were referenced, specific questions were developed through discussions involving at least two qualitative researchers. The strength of this method lies in ensuring that the guide design aligns with the specific requirements of the research and allows for thorough exploration of the topics of interest. Through discussions among qualitative researchers, diverse professional opinions are obtained, thereby improving the quality and effectiveness of the interview guide.

8.4 Limitations and Future Work

8.4.1 Theoretical Studies

Synergized interactions is a concept rich in implications for HCI/HEC. Exploring this concept can be approached from various perspectives. This study provides one practical pathway, focusing on observing and creating ideal HCI relationships through rhythm analysis and modulation, where *synergized interactions* can be achieved. However, this is just one of many roads leading to Rome and, inevitably, the full scope of this concept may not be fully understood at the theoretical level.

- First, this study focuses on exploring *synergized interactions* through rhythm analysis and modulation, but synergized interaction is a multifaceted concept, and this study may not cover all aspects in full. Future work can employ various methods, such as combining quantitative experiments and qualitative analysis, to deepen the understanding of various aspects of *synergized interactions*.
- Second, the findings of this study may only be applicable to specific contexts and methods. Different contexts or interaction modes may yield different results and

caution should be exercised when applying these findings to other scenarios. Future work can conduct more refined and specific studies for different application contexts to explore specific mechanisms and effects of *synergized interactions*.

- Third, while rhythm analysis and modulation offer valuable insight into *synergized interactions*, they may not fully capture all the features of interaction dynamics. Other methods or approaches, such as qualitative observation or physiological measurement, may provide additional perspectives. Future work can develop new technological tools and algorithms to better achieve rhythm analysis and modulation, thereby promoting the realization and optimization of *synergized interactions*.
- Fourth, implementing rhythm analysis and modulation can face technical challenges, such as data collection, algorithm development, and system integration, which may affect the feasibility and effectiveness of the research. Future work can explore interdisciplinary collaboration, such as psychology, design, and engineering, to jointly explore the theory and practice of *synergized interactions*, promoting the development and innovation of the research field.

8.4.2 Empirical Studies

This doctoral dissertation primarily explores empirical research in two domains (that is, everyday life and education) with respect to *synergized interactions* that enhance human capability. As such, there are some limitations and future work at the empirical level.

- *Technological Constraints*: While the designed synergized technologies have shown positive results, there are limitations in their current state of development. The reliance on existing interaction systems and patterns suggests that the technologies are not yet fully optimized. The absence of advanced AI-driven personalized matching models limits the ability to achieve seamless detection and feedback in dynamic interaction processes. Future work should focus on incorporating artificial intelligence to develop and train personalized matching models. This would enable more dynamic and adaptive interaction processes, moving away from static, preset standards.
- *Generalizability and Applicability*: The case studies, especially in the education domain, may have limited generalizability due to the specific contexts in which they were conducted. Individual differences among participants, such as varying

skill levels and personal backgrounds, affect the applicability of the findings across different populations. Future work should include a wider range of contexts and diverse participant groups will help in assessing the generalizability and robustness of the findings. Implementing the technologies and frameworks in different educational settings and industries can provide deeper insights into their effectiveness and adaptability.

- *Evaluation Metrics*: The evaluation of synergized technologies and teaching frameworks might be constrained by the metrics and standards used, which may not capture all relevant aspects of effectiveness and user experience. Future work should develop more holistic evaluation metrics will help in better assessing the performance and impact of the synergized technologies and educational frameworks. Incorporating qualitative feedback and long-term impact studies could provide a richer understanding of user experiences and educational outcomes.
- *Personalization and Differentiation*: Addressing the individual differences among participants by developing more personalized and differentiated strategies will enhance the effectiveness of the teaching framework. Future studies should explore ways to customize the framework to better suit individual learning styles, skill levels, and personal backgrounds.

Chapter 9

General Conclusion

This chapter presents four parts: (1) main findings from Chapter 2 to Chapter 7; (2) main contributions from theoretical studies to empirical studies; (3) future agendas to guide researchers and designers in the HCI/HEC community; (4) final remarks to rethink the whole doctoral dissertation.

9.1 Main Findings

This subsection has succinctly summarized the findings of this doctoral dissertation, which are distributed across the following chapters.

- *Chapter 2* indicate that (1) rhythm, as a significant analytical approach, holds substantial importance for observing interaction states; (2) a promising hypothesis suggests that adjusting interaction rhythms can facilitate the transition towards synergized rhythms between human rhythms and computer rhythms, thus offering a practical approach for realizing this synergized interaction.
- *Chapter 3* contribute to the following aspects: (1) We define states of *synergized interactions* by adjusting interaction rhythms to achieve synergized rhythms; (2) We establish interaction protocols by proposing computational methods of rhythm adjustment to implement *synergized interactions*; (3) We design promising interaction mechanisms by identifying the interaction procedure and five design principles based on FSIRA.
- *Chapter 4* demonstrate that (1) The FSS mode demonstrated higher performance in body awareness and attention regulation in both indoor and outdoor environments; (2) the creativity scores of indoor participants were higher than those of outdoor participants; (3) The indoor FSS mode produced greater creativity compared to the indoor RFSI mode; (4) Participants in the indoor FSS mode showed a significant correlation between heart rate and cadence with creativity compared to other groups; etc.

- *Chapter 5* show that the RunMe group outperforms the other groups in attention regulation, body awareness, exercise motivation, and mindfulness. Importantly, RunMe allows users to engage in running meditation without specialized equipment, making it accessible for daily practice.
- *Chapter 6* indicate that (1) there has been a significant improvement in student engagement, with students demonstrating increased collaboration and active engagement in the creative process; (2) the reflective design abilities of students have been enhanced, allowing them to critically evaluate their own work and make informed decisions to improve rhythm game design.
- *Chapter 7* indicate that (1) the proposed framework effectively guides collaboration between students and digital tools in the understanding and design of Cantonese Porcelain (CP) based on HEC theory; (2) Validation through a five-year creative CP course demonstrates the framework's support for phased student understanding and design of ICH in DHE, marking a pioneering application of HEC theory in education.

9.2 Main Contributions

This dissertation aimed to investigate theoretical and empirical studies of *synergized interactions* to enhance human capacity employing a mixed-method approach. We identified (1) theoretical studies: synergized interaction framework based on rhythm perspective in Chapters 2 & 3, (2) empirical studies: synergized technologies to enhance walking creativity and running meditation in Chapters 4 & 5 and synergized teaching design to augment game design capabilities in the classroom in Chapter 6, and extended investigation to rethink theoretical and empirical studies of *synergized interactions* from a macro perspective (i.e., human-engaged computing) in the field of digital heritage education in Chapter 7.

9.3 Future Agendas

Above all, we advocate that future research of synergized interaction should consider further exploration on the following agendas.

- First, a more systematic and refined theoretical framework is needed to deepen our understanding of the multidimensional characteristics and underlying mechanisms of *synergized interactions*.

- Second, more empirical research should be conducted to validate and extend existing theoretical models and to explore the effects and factors influencing *synergized interactions* in different contexts.
- Third, synergized interaction technologies should not only consider the technical implementation of HCI/HEC, but also focus on user experience and social impact, in order to achieve harmonious development between technology and society.
- Finally, it is recommended to conduct long-term longitudinal studies to observe and analyze the long-term effects and potential issues of synergized interaction technologies in practical applications.

9.4 Final Remarks

Reflecting on the concept of *synergized interactions* based on whole doctoral research, I wish to leave three final remarks on questions that have been the focal points of my sustained inquiry and exploration. These remarks are the original motivation for the entire study and the cornerstone of future reflections on basic concepts in HCI/HEC.

(1) Can synergized interactions can be observed?

Existing examples mainly observe whether the *synergized interactions* have been achieved based on the outcome of the interaction (i.e., the whole is greater than the sum of its parts), which lacks a critical observation of the interaction process. As with the previous examples, the process of *synergized interactions* is complex and real-time, involving a large amount of data in interactions between humans and computers, which poses great challenges for observers to carry out their work. To this end, the HCI/HEC community has drawn on knowledge from other disciplines to reveal the process of interaction. For example, anthropological HCI/HEC scholars advocate observing the process of interaction from the perspective of events or actions, while phenomenological HCI/HEC scholars advocate observing the interaction experience from a first-person perspective. However, interaction is an activity between two or more objects, and previous methods have focused on the experience or performance of objects during the interaction process, with little research exploring how objects interact with each other. This makes it difficult for scholars to find effective methods to observe the operating mechanism of a larger vision.

(2) How to define the protocol of synergized interactions?

In general, *synergized interactions* require each entity to contribute its own efforts to achieve a common goal. On the one hand, the proportion of human and computer involvement in a task can affect the level of synergy achieved. For example, in a collaborative writing project, if human contributions are minimal, the result may lack creativity and originality, while if computer contributions are minimal, the result may lack accuracy and efficiency. However, task allocation between humans and computers can also affect the level of synergy achieved. For example, in a customer service environment, if computers handle simple queries and humans handle more complex issues, the overall service provided may be more efficient and effective. Therefore, *synergized interactions* can be achieved, which requires defining how each interacting entity should be allocated during the interaction process, which requires the development of protocols as a unified standard.

(3) How to guide designers to develop and evaluate synergized interaction technology?

Measurement of *synergized interactions* requires evaluating not only the results of synergy between multiple entities, but also the synergized mechanisms between them. Existing evaluation methods include (1) the use of performance metrics to assess the effectiveness and efficiency of collaborative work, and (2) using observational methods to assess the quality of interactions between entities. These methods may involve considering factors such as analyzing the communication patterns between entities, the level of engagement and engagement of each entity, and the level of coordination and cooperation displayed during the interaction process. Further research may be needed to clarify the detailed guidance of these considerations in the evaluation process.

Conclusion of this dissertation in general: (1) Existing concepts/theories (e.g., *synergized interactions*) are generally overgeneralized in the HCI/HEC community and there is a gap between theory and practice; (2) There are many approaches to explore and respond to the above three remarks of *synergized interactions* but there is currently a lack of practical exploration at the theoretical and empirical level; (3) This dissertation provides one of approaches and validate it through theoretical and empirical studies, where *synergized interactions* can be observed, achieved, and evaluated; (4) Future researchers and designers should maintain reflection on the use and extension of existing HCI/HEC concepts (e.g., *synergized interactions*).

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Publications

Many of the ideas and figures contained in this dissertation have been previously published in the following peer-reviewed publications:

1. Papers published or accepted

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- *Tan, P.*, Ren, X., Cheng, Z., & Ji, Y. (2023). A framework for students' digital heritage education in the classroom-a human-engaged computing perspective. *Education and Information Technologies*, 1-23. (*Chapter 7, JCI: Q1*)
- Lu, Z., *Tan, P.*, Ji, Y., & Ma, X. (2022, June). The crafts+ fabrication workshop: Engaging students with intangible cultural heritage-oriented creative design. *In Proceedings of the 2022 ACM Designing Interactive Systems Conference* (pp. 1071-1084). (*Chapter 7*, Top conference)

2. Papers under reviewed by academic journals

- *Tan, P.*, Zhu, X., Bi, T., & Ren, X. (2024). RunMe: An adaptive sound system for running meditation. *ACM Transactions on Computer-Human Interaction.* (*Chapter 5*)
- *Tan, P.*, Cheng, Z., & Ren, X. (2024). FSIRA: A Framework for Synergized Interactions through Rhythm Adjustment. *Human–Computer Interaction.* (*Chapter 3*)
- *Tan, P.*, Cheng, Z., & Ren, X. (2024). A investigation of synergized game teaching framework for student engagement and reflective design in the classroom. *Education and Information Technologies.* (*Chapter 6*)

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Appendix A

Measure of Attentional Focus (MAF)

What percentage of the time did you focus on each of the six categories?

Note. The sum of the percentages across all six categories must equal 100%. If you checked " No " for a category then you should select " 0 " for the % of that category.

1) Bodily sensations *(heart rate, breathing rate, muscles, fatigue, pain, sweating, cramps)*?
2) Task relevant thoughts *(strategies, goals, pace, injury concerns, thoughts about time)*?
3) Self-talk *(psyching up, for example, " I can do it ")*?
4) Task relevant external cues *(the time display, listening to the music & white noise)*?
5) Task irrelevant thoughts *(daydreaming, problem solving, planning, recalling memories, meditating)*?
6) External distractions *(sights and sounds in the environment)*?

Please make sure percentages chosen for the 6 categories add up to 100%; *Total% =*

Appendix B

Intrinsic Motivation Inventory (IMI)

For each of the following statements, please indicate how true it is for you, using the following scale:

1. Not at all true
   ......
4. Somewhat true
   ......
7. Very true

1) I enjoyed doing this activity very much.
2) This activity was fun to do.
3) I thought this was a boring activity.
4) This activity did not hold my attention at all.
5) I would describe this activity as very interesting.
6) I thought this activity was quite enjoyable.
7) While I was doing this activity, I was thinking about how much I enjoyed it.
8) I think I am pretty good at this activity.
9) I think I did pretty well at this activity, compared to other students.
10) After working at this activity for a while, I felt pretty competent.
11) I am satisfied with my performance at this task.
12) I am pretty skilled at this activity.
13) This was an activity that I couldn ’ t do very well.
14) I put a lot of effort into this.
15) I didn ’ t try very hard to do well at this activity.
16) I tried very hard on this activity.
17) It was important to me to do well at this task.
18) I didn ’ t put much energy into this.
19) I did not feel nervous at all while doing this.
20) I felt very tense while doing this activity.
21) I was very relaxed in doing these.
22) I was anxious while working on this task.
23) I felt pressured while doing these.
24) I believe this activity could be of some value to me.

25) I think that doing this activity is useful for improving my self-control ability.
26) I think this is important to do because it can improve my self-control ability.
27) I would be willing to do this again because it has some value to me.
28) I think doing this activity could help me to improve my self-control ability.
29) I believe doing this activity could be beneficial to me.
30) I think this is an important activity.

Appendix C

Multidimensional Assessment of Interoceptive Awareness (MAIA)

Below you will find a list of statements. Please indicate how often each statement applies to you generally in daily life.

1. Never

   ......

5. Always

1) When I am tense I notice where the tension is located in my body.
2) I notice when I am uncomfortable in my body.
3) I notice where in my body I am comfortable.
4) I notice changes in my breathing, such as whether it slows down or speeds up.
5) I ignore physical tension or discomfort until they become more severe.
6) I distract myself from sensations of discomfort.
7) When I feel pain or discomfort, I try to power through it.
8) I try to ignore pain.
9) I push feelings of discomfort away by focusing on something.
10) When I feel unpleasant body sensations, I occupy myself with something else so I don ' t have to feel them.
11) When I feel physical pain, I become upset.
12) I start to worry that something is wrong if I feel any discomfort.
13) I can notice an unpleasant body sensation without worrying about it.
14) I can stay calm and not worry when I have feelings of discomfort or pain.
15) When I am in discomfort or pain I can ' t get it out of my mind.
16) I can pay attention to my breath without being distracted by things happening around me.
17) When I am in conversation with someone, I can pay attention to my posture.
18) I can return awareness to my body if I am distracted.
19) I can refocus my attention from thinking to sensing my body.
20) I can maintain awareness of my whole body even when a part of me is in pain or discomfort.
21) I am able to consciously focus on my body as a whole.
22) I notice how my body changes when I am angry.

23) When something is wrong in my life I can feel it in my body.
24) I notice that my body feels different after a peaceful experience.
25) I notice that my breathing becomes free and easy when I feel comfortable.
26) I notice how my body changes when I feel happy / joyful.
27) When I feel overwhelmed I can find a calm place inside.
28) When I bring awareness to my body I feel a sense of calm.
29) I can use my breath to reduce tension.
30) When I am caught up in thoughts, I can calm my mind by focusing on my body/breathing.
31) I listen for information from my body about my emotional state.
32) When I am upset, I take time to explore how my body feels.
33) I listen to my body to inform me about what to do.
34) I am at home in my body.
35) I feel my body is a safe place.
36) I trust my body sensations.

Appendix D

The Mindful Attention Awareness Scale (MAAS)

Day-to-Day Experiences

Instructions: Below is a collection of statements about your everyday experience. Using the 1-6 scale below, please indicate how frequently or infrequently you currently have each experience. Please answer according to what really reflects your experience rather than what you think your experience should be. Please treat each item separately from every other item.

1. Almost Always
2. Very frequently
3. Somewhat frequently
4. Normal
5. Somewhat infrequently
6. Very infrequently
7. Almost never

1) I could be experiencing some emotion and not be conscious of it until some time later.
2) I break or spill things because of carelessness, not paying attention, or thinking of something else.
3) I find it difficult to stay focused on what ' s happening in the present.
4) I tend to walk quickly to get where I'm going without paying attention to what I experience along the way.
5) I tend not to notice feelings of physical tension or discomfort until they really grab my attention.
6) I forget a person ' s name almost as soon as I ' ve been told it for the first time.
7) It seems I am " running on automatic, " without much awareness of what I ' m doing.
8) I rush through activities without being really attentive to them.
9) I get so focused on the goal I want to achieve that I lose touch with what I ' m doing right now to get there.
10) I do jobs or tasks automatically, without being aware of what I'm doing.
11) I find myself listening to someone with one ear, doing something else at the same time.
12) I drive places on ' automatic pilot ' and then wonder why I went there.
13) I find myself preoccupied with the future or the past.
14) I find myself doing things without paying attention.
15) I snack without being aware that I ' m eating.

Appendix E

The Divergent Association Task (DAT)

Instructions

Please enter 10 words that are as different from each other as possible, in all meanings and uses of the words.

- Take the test (4minutes)

Rules

- Only single words in English.
- Only nouns (e.g., things, objects, concepts).
- No proper nouns (e.g., no specific people or places).
- No specialised vocabulary (e.g., no technical terms).
- Think of the words on your own (e.g., do not just look at objects in your surroundings).

Consent

Contribute your anonymous responses to our research?

- Yes
- No

Enter words

Demographics (optional)

- Age
- Sex
- Country

Bonus question (optional)

One hears about " morning types " and " evening types. " Which one of these types do you consider yourself to be?

- Definitely a morning type
- Rather more a morning type than an evening type
- Rather more an evening type than a morning type
- Definitely an evening type

Appendix F

The Student Engagement Questionnaire (SEQ)

Please indicate your level of agreement with the statements below. Please choose the one most appropriate response to each question.

1. Never

   ......

5. Always

1) I have developed my ability to make judgements about alternative perspectives.
2) I have become more willing to consider different points of view.
3) I have been encouraged to use my own initiative.
4) I have been challenged to come up with new ideas.
5) I feel that I can take responsibility for my own learning.
6) I have become more confident of my ability to pursue further learning.
7) During my time at university, I have learnt how to be more adaptable.
8) I have become more willing to change my views and accept new ideas.
9) I have improved my ability to use knowledge to solve problems in my field of study.
10) I am able to bring information and different ideas together to solve problems.
11) I have developed my ability to communicate effectively with others.
12) In my time at university I have improved my ability to convey ideas.
13) I have learnt to become an effective team or group member.
14) I feel confident in dealing with a wide range of people.
15) I feel confident in using computer applications when necessary.
16) I have learnt more about using computers for presenting information.
17) Our teaching staff use a variety of teaching methods.
18) Students are given the chance to participate in classes.
19) The teaching staff try hard to help us understand the course material.
20) The course design helps students understand the course content.
21) When I have difficulty with learning materials, I find the explanations provided by the teaching staff useful.
22) There is sufficient feedback on activities and assignments to ensure that we learn from the work we do.
23) The program uses a variety of assessment methods.
24) To do well in assessment in this program you need to have good analytical skills.

25) The assessment tested our understanding of key concepts in this program.
26) The communication between teaching staff and students is good.
27) I find teaching staff helpful when asked questions.
28) I manage to complete the requirements of the program without feeling unduly stressed.
29) The amount of work we are expected to do is quite reasonable.
30) I feel a strong sense of belonging to my class group.
31) I frequently work together with others in my classes.
32) I have frequently discussed ideas from courses with other students out-of-class.
33) I have found that discussing course material with other students outside classes has helped me to reach a better understanding of the material.
34) I can see how courses fitted together to make a coherent program of study for my major.
35) The program of study for my major was well integrated.

Appendix G

The Rumination-Reflection Questionnaire (RRQ)

Item order below corresponds to the recommended item administration order shown in the print version above: items 1-12 below are the Rumination scale items, and items 13-24 below are the Reflection scale items. The instruction text below is modified slightly from the print version to better accommodate online administration. In online surveys, we recommend administering the rumination and reflections items on different pages with non-identical page titles (e.g., " RMQ " and " RFQ " , for rumination and reflection pages, respectively.).

1. Never

   ......

5. Always

1) My attention is often focused on aspects of myself I wish I'd stop thinking about.
2) I always seem to be "re-hashing" in my mind recent things I've said or done.
3) Sometimes it is hard for me to shut off thoughts about myself.
4) Long after an argument or disagreement is over with, my thoughts keep going back to what happened.
5) I tend to "ruminate" or dwell over things that happen to me for a really long time afterward.
6) I don't waste time re-thinking things that are over and done with.
7) Often I'm playing back over in my mind how I acted in a past situation.
8) I often find myself re-evaluating something I've done.
9) I never ruminate or dwell on myself for very long.
10) It is easy for me to put unwanted thoughts out of my mind.
11) I often reflect on episodes in my life that I should no longer concern myself with.
12) I spend a great deal of time thinking back over my embarrassing or disappointing moments.
13) Philosophical or abstract thinking doesn't appeal to me that much.
14) I'm not really a meditative type of person.
15) love exploring my "inner" self.
16) My attitudes and feelings about things fascinate me.
17) I don't really care for introspective or self-reflective thinking.
18) I love analyzing why I do things.
19) People often say I'm a "deep", introspective type of person.
20) I don't care much for self-analysis.
21) I'm very self-inquisitive by nature.

22) I love to meditate on the nature and meaning of things.
23) I often love to look at my life in philosophical ways.
24) Contemplating myself isn't my idea of fun.