Title	VRジムにおける周囲のアバターデザインがユーザーの行動と知覚に及ぼす影響
Author(s)	柯, 炳丞
Citation	
Issue Date	2025-12
Type	Thesis or Dissertation
Text version	ETD
URL	https://hdl.handle.net/10119/20315
Rights	
Description	Supervisor: 由井薗 隆也, 先端科学技術研究科, 博士

Japan Advanced Institute of Science and Technology

Doctoral Dissertation

The Effects of Surrounding Avatar Design on Users' Behavior and Perception in VR Gym

KE Bingcheng

Supervisor   YUIZONO Takaya

Graduate School of Advanced Science and Technology
Japan Advanced Institute of Science and Technology
(Knowledge Science)

December, 2025

Abstract

With the growing popularity of virtual reality (VR) technologies in fitness applications, such as VR gyms, understanding how virtual social environments influence users' physical and psychological responses during exercise has become increasingly important. This thesis investigates the impact of the visual attributes of surrounding avatars in a VR gym. Specifically, the dynamic features, such as exercise speed, and static features, such as body composition and exercise intensity, of surrounding avatars affect users' time perception, physical activity, and perceived exertion.

Two experimental studies were conducted. The first experiment investigated how the speed of exercise and intensity of surrounding avatars affect users' duration judgments and subjective feelings of time passage. The results indicated that when the surrounding avatars exercised at a faster exercise speed, participants perceived the duration of time as longer and felt that time passed more quickly. Additionally, high-intensity exercise led participants to perceive the passage of time as faster. The second experiment examined the effect of avatar exercise speed and body composition, such as normal and overweight, on users' physical performance and subjective exertion levels. The results show that the surrounding avatars exercised at a faster exercise speed, which can improve users' physical activity. The avatar with an overweight body composition helps people enhance their self-perception of fitness. Meanwhile, the surrounding avatars' exercise speed and body composition also have interaction effects that affect the user's participation in exercise. In conclusion, results from both studies demonstrated that dynamic attributes had a stronger and more consistent impact on users' performance and perception compared to static attributes. Static attributes rely more on people's realization of the static attribute in their experience.

Theoretically, this thesis contributes to the fields of human-computer interaction and social psychology by differentiating the effects of dynamic and static visual attributes in immersive virtual environments. Practically, it offers actionable insights for the design of future VR gyms, suggesting that surrounding avatar design can be strategically manipulated to enhance user engagement and support long-term exercise adherence.

Keywords: VR gym, Surrounding avatar, Avatar design, Time perception, Physical activity.

I

Acknowledgment

One of the most rewarding decisions I have ever made was to pursue my doctoral studies at the Japan Advanced Institute of Science and Technology (JAIST). As I complete this dissertation, I would like to express my heartfelt gratitude to all those who have supported, guided, and encouraged me throughout this journey.

First and foremost, I would like to extend my most profound appreciation to my supervisor, Professor Yuizono Takaya, for his unwavering support, insightful guidance, and continuous encouragement throughout my doctoral studies. His rigorous approach to research, patient mentorship, and forward-thinking perspective have profoundly shaped my academic development and inspired me to pursue research in this field further.

I am also sincerely grateful to Assistant Professor Wang Tzu-Yang, who provided crucial guidance in designing and conducting my experiments and offered continuous support as the leader of the CET team. His technical expertise, constructive feedback, and steady encouragement were instrumental to the successful completion of this research.

I would like to express my sincere gratitude to my external examiner, Professor Hiroyasu Ujike, for his valuable time, insightful comments, and constructive feedback during my dissertation defense. I am also grateful to my internal examiners, Professor Kim Eunyoung and Professor Kanai Hideaki, for their thoughtful evaluation and kind support during the final stage of my doctoral journey.

My heartfelt thanks also go to the faculty members and administrative staff at JAIST for creating a supportive and stimulating research environment. I am especially appreciative of the professors and committee members who participated in my dissertation defense; their valuable suggestions significantly contributed to the improvement of this work. I want to thank all the participants and volunteers who contributed their time and effort to my experiments.

Lastly, I am forever grateful to my family for their unwavering love and support. Most of all, I thank my wife for her patience, understanding, and encouragement throughout this journey. Her companionship has been my greatest strength, and I could not have reached this point without her.

To everyone who has accompanied me along the way, thank you.

Declaration of Publication

This dissertation includes parts of the work that have been published in the following papers:

1. Ke, B., Wang, T.-Y., Yuizono, T., & Kanai, H. (2024). *Workout at a virtual gym: Surrounding avatar's motion speed and exercise intensity effect on the user's time perception. PLOS ONE, 19*(12), e0311860.
   https://doi.org/10.1371/journal.pone.0311860
   (Extracted from Chapter 3)

2. Ke, B., Wang, T.-Y., & Yuizono, T. (2025). *The effect of surrounding avatars' speed and body composition on users' physical activity and exertion perception in VR GYM. Displays,* 103253.
   https://doi.org/10.1016/j.displa.2025.103253
   (Extracted from Chapter 4)

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Background

With the increasingly fast-paced lifestyle and growing work-related stress, the lack of physical exercise has emerged as a serious public health issue in recent years. The numerous previous studies indicate that physical activity significantly improves individual health [1]. The lack of physical activity and exercise is a complex problem that is affected by environmental, social, and personal psychological and physical factors. Regular exercise is regarded as an important strategy for enhancing overall health, reducing the risk of systemic diseases, and significantly lowering mortality rates [2]. However, despite the well-known benefits of regular exercise, based on data from the World Health Organisation (WHO) revealed that approximately 25% of adults and 80% of teenagers lack regular physical activity [1]. Regular exercise is often perceived as boring and difficult to maintain, and adherence to it as a habit may contribute to adults and students, after a long time of work or study, tending to avoid physical exercise and related behaviours. In contrast, individuals are more interested in leisure activities; for example, video games can provide entertainment that does not require movement while relaxing. Therefore, a need for a way to stimulate people to do more physical activity and enhance their motivation to cultivate the habit of regular exercise.

The reason most people can not maintain a long-term regular exercise is that negative exercise experiences which perceived during the process of exercising. For example, the high intensity of exercise in a gymnasium can lead to users having a state of hyperarousal, which induces people to perceive time distortion, in which time passes more slowly [3]. This perception of time dilation may reduce individuals' motivation to maintain regular exercise by intensifying their subjective experience of exercise duration and discomfort perception, which in turn undermines their anticipated

---

[1] https://www.who.int/news-room/fact-sheets/detail/physical-activity

benefits from physical activity [4]. At the same time, this time dilation also amplifies their perception of fatigue, which further affects individuals to give up exercising [5]. In addition to individuals' time distortion, while doing exercise, another reason is a lack of self-motivation, which is one of the important reasons why people can not adhere to participating in regular physical exercise. Since individuals usually tend to pursue immediate satisfaction rather than delayed satisfaction [6]. For example, people hope for quick feedback or improvement from the exercise, such as the body's appearance or exercise performance. However, such feedback or improvement typically requires a prolonged period of consistent exercise before noticeable results can be observed. Therefore, this uncertainty and vagueness of results from exercise contribute to individuals' decreased motivation to adhere to long-term exercise. Thus, there is an urgent need to identify approaches that can alleviate the challenges encountered during physical activity.

The rapid advancement of virtual reality (VR) technology has shown tremendous potential in various fields, particularly fitness and exercise. In recent society, people's life pace becoming increasingly faster, at the same time that contributes to the insufficiency of time and space for people's regular exercise, and also restricts people's exercise. Therefore, the rapid advancement of VR technology has shown tremendous potential advantages in various fields, particularly fitness and exercise. Therefore, the VR gym has provided a novel approach that can help individuals to relieve this problem, promote physical activity and encourage healthy behaviours. VR can provide immersion through computer-generated three-dimensional environments, enabling users to fully immerse themselves in the VR experience. It allows users to transition between diverse environments that are not easily realised in the real world, such as beaches or tropical rainforests. In the context of VR gyms, these advantages can help individuals to follow their own conditioning to adjust and costomize environmental parameters to create an optimal environment for the purpose of creating the most suitable exercise environment, which can increase the individual's exercise initiative and adherence. Additionally, this immersive exercise experience not only promotes physical activity [7] but also supports physical rehabilitation [8], making it a valuable tool in various exercise and healthcare applications. Consequently, an increasing number of individuals are gravitating towards VR gyms to replace conventional physical scenarios in daily life, owing to its manifold benefits, such as convenience and time saving. Therefore, a well-designed VR gym is crucial for enhancing users' enjoyment of exercise, improving training effectiveness, and promoting long-term adherence to exercise. Meanwhile, in VR, the avatar is a crucial component of the VR experience; it not only

serves as the visual representation of the user's digital body, but it also affects users' behavior. Therefore, in the design of VR gyms, exploring the impact of avatars is essential for optimising and enhancing users' experience.

In the field of VR, the avatar is a crucial part of the user's experience, especially in VR gyms. Avatars in VR are typically categorized into two main types: user-controlled and computer-controlled avatars. The user-controlled avatar is the user's virtual representation in VR, such as their digital representation of their body and identity. user through control the avatar that can enhance the user's immersive and interactive experience, even influence behaviour and perception [9]. The avatar is also a medium that connects users' physical and virtual bodies that enabling users to immerse themselves and interact naturally with the virtual objects. The user-controlled avatar, through the Proteus effect, shifts the user's behavior and psychological response [10]. The computer-controlled avatar is an avatar operated by pre-programmed algorithms, rather than by a user. The VR gyms and other scenarios were not independent environments and spaces; they were also social environments. Therefore, other users' avatars and computer-controlled avatars constitute the VR scenarios. Similarly, as a social environment, users exercise with surrounding avatars; their visual attributes may affect users' perceptions and overall experience. For the user's avatar, the Proteus effect has been widely investigated; however, the surrounding avatar was also important in the VR gym scenarios. Generally, the surrounding avatar can function as a co-existing exerciser in the VR gym. While exercising in the gym, it is not easy to focus only on one's own exercise. Previous research also indicated that the presence of another individual significantly increases users' motivation and perceived exertion during exercise in VR [11]. For example, the presence of another individual in the VR environment is necessary for aerobic exercise tasks such as cycling and running. Except for the aerobic exercise task, when a competitor's presence in VR has also been demonstrated to produce performance enhancement, particularly for users who reported having higher competitive motivation [12].

Time perception is really important for people's perceived exercise experience [13]. During exercise, individuals' time perception may affect exercise rhythm, endurance, perceived fatigue, and exercise performance [4]. For example, in high-intensity exercise, when people perceive high physical discomfort caused by high exercise intensity, it may lead to decreased exercise tolerance, premature termination of exercise, reduced engagement, and a lack of enthusiasm for sustaining maximal effort over extended periods [14]. Conversely, if users perceive time as shorter during exercise, that may help them increase endurance and adherence. Therefore, a better experience

3

during exercise must also have better time perception. Moreover, the presence of others, such as the surrounding avatar or other exercisers in the VR gym, may also affect the user's time perception, from both visual and social perspectives. Therefore, it is of great significance to study the adjustment mechanism of time perception in a virtual environment for optimizing the design of VR gyms, which aim to provide users with a better exercise experience, especially in terms of their time perception, and also enhance their exercise motivation.

Except for the user's time perception, meanwhile, the physical performance and perceived exertion were also directly related to the users' experience and social interaction during exercise in the VR gym. Generally, people's perceived exertion should correspond to the exercise intensity and difficulty, and correspondingly appropriate level of physical activity. However, in the physical gyms, it is quite difficult to pay attention only to their exercise and neglect all other exercisers that can distract attention during exercise. Previous research studies have shown that exercise with other people often induces social comparisons that significantly affect physical activities [15]. People tend to unconsciously compare their own abilities with those of others to determine their physical level. At the same time, in VR exercise research, the visual representation of the surrounding environment is considered an important factor affecting users' physical performance. Overall, no matter whether in a physical or VR gym, the social factors and the presence of others have a significant impact on users' physical performance and perceived exertion. Therefore, investigating the surrounding avatars in VR gyms is necessary. Through modifying the visual attributes of surrounding avatars, our study tries to explore the right ways to enhance users' exercise experience, which is a crucial approach to increasing their exercise motivation and promoting long-term adherence to physical activity.

Therefore, this thesis primarily explores how the visual representation of the surrounding avatar in VR gyms affects users' time perception, physical performance, and perceived exertion. This thesis categorises avatar characteristics into two main types: dynamic and static attributes. Dynamic attributes include exercise speed, such as squatting speed and running speed, while static attributes encompass the exercise intensity experienced by the avatar, like the weight and size of dumbbells, body composition, such as normal and overweight body composition. This thesis focuses on how users perceive dynamic and static visual stimuli presented through HMDs to explore ways to optimise the design of surrounding avatars and enhance the exercise experience. Specifically, we will investigate whether avatars with different dynamic and static characteristics influence users' physical

4

performance, time perception, and subjective exercise experience. The goal of this research is to provide a scientific basis for future VR gym design and propose optimisation strategies for avatar visual attributes to enhance users' immersion, exercise motivation, and long-term exercise adherence.

1.2 Research gaps

Although the VR exercise and VR gyms have attracted increasing attention, most of the previous research has primarily examined the effects of avatar design on users' avatars on their exercise experience and motivation. Research on surrounding avatar design remains limited, with only a few studies focusing on the surrounding avatar's design. Most of research about the surrounding avatar only focus on avatar's exist or not, not the design of the surrounding avatar's dynamic and static attribute. From previous research, the users' avatars can significantly affect users' time perception. Meanwhile, in exercise, the exercise intensity and exercise speed were also important points in people's time perception. However, the extent to which the dynamic and static attributes of surrounding avatars affect users' time perception has not been sufficiently investigated.

- **Research gap1 :** The effects of surrounding avatars' design on dynamic and static attributes on users' time perception remain unclear.

Similarly, previous studies have suggested that people tend to compare with others to evaluate their own ability and adjust their performance. Meanwhile, in exercise contexts, the exercise speed and body composition were two aspects to expressed the ability and performance. However, the extent to which the dynamic and static attributes of surrounding avatars affect users' physical activity and exertion perception has not been sufficiently investigated.

- **Research gap2 :** The effects of surrounding avatars' design on dynamic and static attributes on users' physical activity and perceived exertion have still been insufficiently investigated.

5

1.3 Research objectives

The main research objective (MRO) of this study is to investigate the surrounding avatars in VR gyms, particularly how the visual attributes influence users' perception and behaviour. This thesis mainly focuses on the two aspects of the surrounding avatars' visual attributes, which are separated into dynamic and static attributes. With the growing integration of VR in various applications, understanding how the surrounding avatars' attributes influence the user experience is crucial. This thesis aims to bridge the gap between avatar design and the user's experience, providing valuable insights for optimising VR gyms.

The specific research objectives (SRO) are detailed as follows:

- **SRO-1:** To investigate the surrounding avatars' visual attributes on users' time perception, including duration judgment and feeling of time passage. SRO-1 will be achieved by pursuing two specific research objectives:

  - **SRO-1-1:** To investigate the surrounding avatar's dynamic visual attribute (exercise speed) on users' time perception.

  - **SRO-1-2:** To investigate the surrounding avatar's static visual attribute (exercise intensity) on users' time perception.

- **SRO-2:** To investigate the surrounding avatar visual attributes on users' physical activity and perceived exertion. SRO-2 will be achieved by pursuing two specific research objectives:

  - **SRO-2-1:** To investigate the surrounding avatar's dynamic visual attribute (exercise speed) on users' physical activity and perceived exertion.

  - **SRO-2-2:** To investigate the surrounding avatar's static visual attribute (body composition) on users' physical activity and perceived exertion.

In this thesis, two main experiments were conducted to investigate whether users in a VR gym are influenced by surrounding avatars' visual attributes, based on both dynamic and static, and whether this affects their time perception, physical activity and perceived exertion. The findings will not only deepen our understanding of the influence mechanism of surrounding

avatars' visual attributes but also provide theoretical support and practical guidance for the design of surrounding avatars in future VR gyms for designers and users.

1.4 Research significances

With the increasing number of users utilizing VR technology in sports and daily exercise, understanding how the visual attributes of surrounding avatars affect a user's exercise experience remains limited. Recent studies in VR exercise have primarily focused on user-controlled avatars, exploring their impact on immersion, self-awareness, and exercise behavior [16, 17]. However, in a physical gym, it is not only an exercise space but also a social environment. Users typically exercise alongside other individuals, and this social information may be important for the VR gym experience. Therefore, it is crucial to investigate how the design of surrounding avatars influences user behavior.

In this thesis, the surrounding avatars' design is categorised into dynamic and static attributes. The thesis investigates how these attributes, such as exercise speed and body composition, impact users' time perception, physical activity, and perceived exertion. This research addresses a gap in the VR gym field by exploring the surrounding avatars' effects on users' exercise behavior and physiological responses, from both theoretical and practical perspectives.

1.4.1 Theoretical significances

With the rapid development of VR technology, there is a growing interest in the behavioral and psychological aspects involved in immersive exercise experiences. Although previous studies have investigated the user's avatar design for the visual attribute while they are doing exercise, there is still a relative lack of research on how the surroundings affect user perception and behavior through social context. This thesis takes the design of surrounding avatars from their visual attributes as the starting point, combining social psychology and human-computer interaction theories, and investigates the two aspects of users' time perception and social comparison in the VR gym.

1.4.1.1 Expanded the understanding on the effects of surrounding avatar design on users' time perception

This thesis investigated, for the first time, the effect of surrounding avatar design from exercise speed (dynamic attribute) and exercise intensity (static attribute) on users' time perception while they did exercise in the VR gym. This research was the first to focus on the surrounding avatar, rather than the users' own controlled avatar. This thesis aims to bridge the research gap regarding the surrounding avatar design on the visual attribute of users' time perception. Meanwhile, it distinguishes the surrounding avatars' visual attributes into two main aspects: dynamic and static attributes, which affect the user's time perception.

1.4.1.2 Expanded the understanding on the effects of surrounding avatar design on social comparison theory

This thesis also extends how the surrounding avatar design influences social comparison theory in the VR gym. Through investigating the visual attributes of surrounding avatars in virtual gym environments, such as exercise speed and body composition, this research focuses on how these designs impact users' physical activity and fatigue perception through social comparison mechanisms. Social comparison theory considers that individuals evaluate their abilities and status by comparing themselves to others. In the virtual gym environment, users not only interact with their own avatars but also compare themselves to other surrounding avatars. This comparison can affect their exercise performance and experience. Through empirical research, this study focuses on how different avatar designs, like exercise speed and body composition, influence the social comparison process for users, and how these effects shape users' behavior and psychological responses in the VR gym.

1.4.2 Practical significances

Based on the proposed theoretical contributions, this thesis has equally practical significance, especially in the areas of VR gyms design and the surrounding avatar in VR gyms. With the widespread application of VR technology in the fields of sports and health, designing VR gym environments that are both immersive and motivating has become a pressing issue to address. To achieve this intention, designers need not only pay attention

to the method of interaction and visual attribute of surrounding avatars, but also should have a deeper understanding of the user's psychological reaction and behavioral change during the virtual movement process.

1.4.2.1 The surrounding avatar's effects on time perception

Specifically, VR gym designers could follow our findings on the effects of the surroundings avatar design to create a supportive surrounding avatar to help user improve their exercise experience while they are doing exercise in VR gyms. Especially when users exercise at relatively higher intensities, it often produces a sense of time distortion due to higher arousal and fatigue. When users want to alleviate the suffering from time distortion during exercise, the VR gym designer can design the surroundings according to the needs of users to adjust the visual attributes to help them relieve their bad experience from time distortion. That may help alleviate the subjective experience of time slowing down, reduce discomfort during exercise, and ultimately extend users' willingness to achieve their exercise goals. Although users' differences must be considered, this approach provides a promising strategy for optimizing user engagement and exercise experience in VR gyms.

1.4.2.2 The surrounding avatars' effects on physical activity and perceived exertion

In a traditional exercise setting, exercise was often perceived as boring, and it took a longer time to see the user's improvement. Therefore, based on the findings on surrounding avatar design in the VR gymthe future VR gym designer can provide users with additional support to help them enhance their exercise performance and adjust their perceived fatigue through the surrounding avatar design. Through the findings in this thesis, users can improve their exercise by strategically adjusting the surrounding avatars' design, thereby effectively improving their physical activity levels and adjusting their perception of fatigue. Based on these insights, VR gym designers can adopt targeted manipulation of the surrounding avatar's design on visual attributes to enhance users' exercise motivation, optimize exercise experiences, and extend users' engagement in VR gym.

1.5 Thesis structure

This thesis consists of six chapters, as shown below:

Chapter 1 Introduction:

In this chapter, I provide a detailed explanation of the research background for this thesis and explore the main challenges of users encounter during VR exercises, including difficulties in optimizing the exercise experience and the psychological changes. Additionally, this thesis examines the psychological mechanisms involved in VR gym exercise, including time perception, physical performance, and perceived exertion, and how the surrounding avatar affects perceptions. To address users' issues, I propose conceptual solutions that optimize user experience and enhance physical performance in VR gyms. Based on this content, this chapter will further define the core research subjects, research objectives, and expected outcomes. This research not only contributes to a deeper understanding of user experience mechanisms in VR exercise but also provides theoretical support and practical guidance for the future design and optimization of VR gyms.

Chapter 2 Literature Review:

This chapter presents a literature review based on the research content of this thesis, focusing on main areas such as virtual environments and avatars, core theories and influencing factors of time perception, and social comparison theory in exercise and virtual environments.

The first section examines exercise avatars in virtual environments, including their design, movement characteristics, and the impact of avatars on users' exercise performance, motivation, and psychological perception. Studies suggest that the appearance, movement patterns, and interaction modes of virtual avatars can significantly impact users' exercise behavior and experience.

The second section focuses on time perception, reviewing its fundamental theories and analyzing key factors that influence time perception in real-world settings. Additionally, this section highlights how exercise speed and intensity affect individuals' time perception, especially within the VR environment.

The third section introduces the basic concepts of social comparison theory. It examines its application in exercise scenarios, particularly how individuals compare themselves with others to adjust their exercise performance and motivation. Finally, this section examines social comparison in

virtual environments, focusing on how the presence and characteristics of virtual avatars in VR gyms or other virtual exercise scenarios impact users' exercise experiences and psychological states.

Chapter 3 The surrounding avatar effect on the user's time perception in VR gym:

This chapter introduces how the surrounding avatar's dynamic attribute, squat speed, and static attribute, the weight of the barbell, affect the user's time perception during exercise. It includes the research methodology, analysis results, and discussion.

Chapter 4 The surrounding avatar effect on the user's physical performance and perceived exertion in VR gym:

This chapter introduces, based on the social comparison effects, how the surrounding avatar's dynamic attributes, like running speed, and static attributes, like body composition, affect the user's physical performance and perceived exertion during exercise. It includes the research methodology, analysis results, and discussion.

Chapter 5 General discussion:

In this chapter, I mainly discuss the findings of the two experiments, focusing on the commonalities and differences between the dynamic and static features of the surrounding avatars in influencing users' time perception, exercise performance, and perceived fatigue. Based on these findings, this thesis proposes several recommendations for future virtual gym design, aiming to provide support and practical guidance for surrounding avatar design in VR gyms and to help build a more immersive, personalized, and efficient virtual exercise experience. It then describes the contribution to knowledge science and possible directions for future research.

Chapter 6 Conclusion:

This chapter is mainly about the comprehensive summary of the surrounding avatar's dynamic and static features, as well as their effects on users' physical performance and time perception, and the reasons for these changes in users.

Chapter 2

Literature review

2.1 Exercise in VR

Over the past decade, exergames have been utilized to help individuals address the issue of physical inactivity. Since it has gained popularity worldwide, it can offer users an enjoyable and playful experience while also providing exercise. Exergames are games that combine physical exercise with gameplay, encouraging players to engage in physical activity as part of their gaming experience. Previous research has indicated that users playing a dance exergame can have an average heart rate almost as high as that of a common aerobic exercise [18]. Meanwhile, the exergame can help the average user significantly burn calories and also result in support for weight loss and improving users' fitness [19]. Moreover, the visual effects of exergames can also alleviate users' pain associated with exercise and enhance their motivation and physical performance [20]. Therefore, exergames are widely popular and one of the effective means to help people solve the problem of inactivity and improve their health habits through exercise.

The emergence of VR has opened up new possibilities for designing exergames with innovative interaction mechanisms with more immersive perception, such as the application of "PowerBEATS VR" (Fig. 2.1). VR is a field of computing, and its goal is to create a virtual world in which users are immersed and able to interact with virtual objects and environments. To achieve this purpose, specific devices are required to simulate the environment and provide feedback to the users, thereby making the experience as realistic as possible [21]. It generally refers to the creation of immersive and interactive virtual environments using computers and peripheral devices, such as HMDs and motion capture systems, allowing users to have an immersive experience. The immersive technology and system provide a physical perspective of sensory simulation, enabling interaction through the integration of multiple sensory channels, such as sight, hearing,

Figure 2.1: Exergame in VR: PowerBeats VR[1]

touch, smell, and taste [22]. At the same time, it provides a perception of presence, which means the user primarily considers themselves to exist in the virtual environment, while they do not exist in the physical world [23]. Additionally, VR can offer users a highly immersive experience by simulating various scenarios and providing unique experiences. Moreover, VR offers opportunities and possibilities that the physical world cannot easily replicate; a case in point is that users can select their virtual environment, such as walking on the beach or in a tropical rainforest. It is effortless to allow users to relax their minds and fully engage with the entire virtual environment through an immersive experience. Due to these advantages, VR is utilized in a variety of industries. For example, in the field of exercise, VR is not only used for sports training and movement correction, but also for simulation to help users improve competitive performance in exercise [24]. This wide range of cross-field applications also demonstrates the significant development potential and diverse adaptability of VR technology.

The application of VR in exercise should primarily focus on enhancing the user's motivation and physical performance during exercise, making the exercise process more pleasant and efficient. First, VR helps users increase

---

[1]The source of application PowerBeats VR: https://store.steampowered.com/app/810500/PowerBeatsVR/

participation and motivation in exercise. Banos et al. found that VR can help overweight children divert their attention away from unpleasant experiences and may enhance their enjoyment during exercise, thereby increasing their participation in sports [25]. Dolu and Camliguney also demonstrated that people perform better in the VR condition compared with the non-VR condition [26]. At the same time, Matsangidou et al. found that people who exercise in VR conditions perceive less pain and exercise time is longer [27]. Additionally, in VR, there are extra factors that can enhance the immersive experience, which may also boost people's motivation for exercise. For example, Shaw et al. added an extra factor in VR cycling, like wind, sound, and resistance, which results in higher motivation and interest in exercise [28]. Farrow et al. found that VR exergaming can effectively enhance the enjoyment of HIIT training and that using ghost mode to compete against previous exercise records can effectively increase exercise intensity [29]. Additionally, VR has demonstrated significant effects in enhancing exercise performance and endurance. For example, Hoffmann et al. demonstrated that novice rowers can improve their performance more quickly and reduce race duration when competing against an avatar in VR [30]. At the same time, Plante et al. found that VR technology used for people walking on a treadmill can help relieve the perception of tiredness and tension, while also increasing energy [31]. After that, Lemmens also indicated that VR can provide and simulate some dangerous and relaxing environments; people's endurance in dangerous environments was better than in relaxing environments. They explain why dangerous environments put more pressure on people [32]. Moreover, VR exercise is also widely utilized to support older people's exercise. Zahedian-Nasab et al. conducted a study demonstrating that six weeks of VR exercises can significantly improve balance ability and reduce the fear of falling among elderly individuals [33]. Kim et al. found that a VR training program can effectively enhance hip muscle strength, which indicated that VR-based exercise may serve as an effective home training method to mitigate physical decline in older adults [34].

In addition to its application in sports training, VR is also used for sports rehabilitation and recovery of physical function, particularly in sports psychology. In exercise rehabilitation, Su et al. designed a VR system to help patients perform exercises for lower back pain, which would assist doctors in their evaluation. The system is also highly acceptable and can motivate patients to exercise. In terms of mental health, the immersive nature of VR can also effectively relieve sports anxiety and tension. Additionally, Lee et al. noted that VR contributes to women adhering to exercise over a prolonged period, and this not only improves their physical health but also provides

mental health benefits [35]. VR also offers special advantages in terms of fatigue management and perception. Chen et al. found that virtual exertions in VR can simulate muscle activity and fatigue patterns similar to real-world exercises, with muscle activity increasing in response to heavier loads. Although the muscle workload was higher in VR, participants' perceived exertion showed no significant difference compared to real exercise. This suggests that virtual exertions can be used for training and rehabilitation, providing a safe and effective exercise simulation [36].

In conclusion, VR has already demonstrated significant potential in exercise, rehabilitation therapy, and enhancing the exercise experience. These findings provide valuable theoretical and practical insights for the future design of VR gyms and personalised training programs. Despite the substantial evidence supporting the effectiveness of VR in exercise, there are still many areas worth further exploration. For instance, how to optimise VR exercise programs based on avatar design; the avatar is a crucial factor and it has more potential points to enhance the user's exercise experience.

2.1.1 Avatar design

The avatar(Fig. 2.2) was provided by game designers and researchers, representing the user's identity in games, VR, and all other virtual situations, which gives users and players a virtual representation of their body. The avatars not only affect users' self perception but also exert a profound influence on their cognition, emotions, and behaviors. The word "avatar" originates from the Hindi word "avatara", which refers to the descent of a deity to Earth in a terrestrial form [37]. It can also be translated as "birth" or "appearance." Banks elaborates on the avatar concept in the context of video games: "Hindu deities descend by taking physical forms; players descend into a game world by taking on digital bodies" [38]. Moreover, avatars and virtual bodies help individuals establish their identities and differentiate themselves from others in VR [39]. In addition, avatars can convey information to others, like gender, hairstyle, race, and physical features, that can influence other users through a social and interactive perspective. Notably, avatars are not limited to visual representations of the virtual body; they can also take other forms of user representation, such as text or sound [40]. Yee later developed a framework to categorize the various ways humans present themselves in virtual environments. This framework illustrates that avatars can range from text-based self-representations and social network profiles to highly detailed 3D characters in modern VR applications [41]. According to this framework, any representation of a human being can be considered an "avatar."
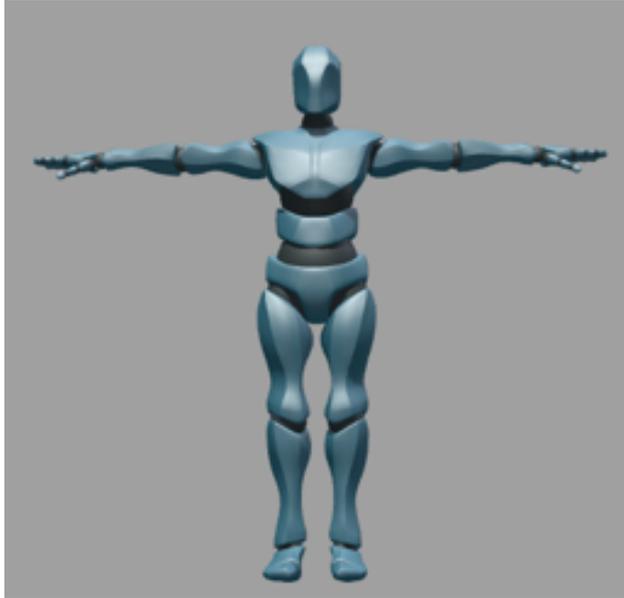
Figure 2.2: The avatar[2]

Avatars in virtual environments can be broadly categorized into two main types: "user-controlled avatars" and "computer-controlled avatars". The user-controlled avatar is intuitive and easily understandable, representing the embodiment of a user's self and manifesting their presence in VR. Bailenson and Blascovich defined a user-controlled avatar as a "real-time and perceptible digital representation that reflects the user's behavior" [42]. Banks further elaborated that a strong bond is formed between the user and their avatar, leading the user to perceive the avatar as an extension of themselves rather than as a separate entity [43]. The user-controlled avatar primarily influences users' performance through "the Proteus effect", a phenomenon where users unconsciously adjust their behavior and psychological state based on the avatar's external appearance. These effects even persist when the user takes off the device and leaves the virtual environments. For example, controlling a taller avatar in a negotiation setting can enhance a user's confidence, which can help users obtain more benefits in the process of negotiation [10]. Similarly, when users embody an avatar with dark skin, it can reduce implicit racial bias between interpersonal communication [44]. Banakou et al. also found that when users controlled an avatar with children appearance, they usually tend to overestimate the size of objects [45]. Havie et al. also demonstrated that the design of " super hero" appearance avatars

---

[2]The source of avatar: https://www.mixamo.com/#/

can help users improve body image and relieve their chronic back pain [46]. The avatar design can also have a positive effect on users' cognitive abilities. For example, Banakou et al.found that when participants were embodied with an avatar with the design of "Albert Einstein" appearance, this resulted in improved users' cognitive performance and also decreased the implicit bias from old people [47].

Computer-controlled avatars are also referred to as digital characters, or objects that represent any entity other than the user. Compared to a user-controlled avatar, a computer-controlled avatar is controlled by a computer program; for example, non-player characters (NPCs) and monsters in games are considered computer-controlled avatars. However, in this thesis, "the surrounding avatars" are avatars that exist around the user; their behavior or performance maybe will affect the user's exercise experience. In comparison, the surrounding avatars do not directly integrate into the user's perception of their identity and life stereotypes, but instead create interactions or social psychological effects that influence the user's behavior. For instance, during the COVID-19 pandemic, when users observe surrounding avatars wearing masks in virtual spaces, they tend to exhibit decreased social distancing behaviors [48]. Moreover, Kocur et al. indicated that when users perform cognitive tasks in VR, the surrounding avatar, which resembles the appearance of Albert Einstein, typically contributes to improved user performance and higher scores on mental tasks. This is because the external visual stimulus of the "Einstein" avatar inspires the user's competitive target, prompting them to strive to their utmost ability on the task [49].

In a VR, avatars are not only a medium for users to present their physical bodies, but can also influence users' behavior and psychological state through a social perspective. The surrounding avatars, by simulating the social situation, enable users to experience social influence in VR, thereby subtly changing their behavior. Compared with the users' controlled avatars, the surrounding avatars involve more complex interaction and social mechanisms, and there are still many directions worth further research. Therefore, optimizing the design of surrounding virtual characters from a social and interactive perspective is expected to enhance the user's exercise experience further, increase exercise motivation, and create a more immersive and personalized VR gym.

2.1.2 The design of the user's avatar on the user's exercise experience

Most previous studies about avatar design on users' exercise were focused on the static features of avatars. The appearance design of avatars plays a crucial role in the user's exercise motivation, performance, and experience. First, most of the research on the design of avatars' appearance on users' exercise experience was focused on users' exercise motivation. For example, Li et al. found that when overweight children controlled a "normal" weight body composition avatar, they were more motivated in exercise compared with controlling an "overweight" weight body composition avatar, when they engaged in exercise [50]. Similarly, Peña and Kim found that female players tend to increase their physical activity when controlling a normal weight body composition avatar in a virtual tennis game compared to the avatar with "obese" body composition [51]. In addition to body composition, similarities in external appearance between avatars and users can also affect users' physical activity. Fox et al. found that when users control an avatar with a similar appearance to themselves, it can increase their physical activity during exercise [52]. Furthermore, Navarro et al. demonstrated that an avatar with a similar appearance to users could significantly increase users' heart rate during exercise, and when a user observed an avatar with sports clothes, they had higher physical activity in running than an avatar with a suit [53]. This study's results suggest that the avatar's external appearance can be a key factor in enhancing users' physical performance, especially in terms of personalized exercise incentives. Secondly, the physical resemblance between the avatar and the user also affects their physical activity. Such as the avatar's design on body composition not only affects their exercise motivation but also impacts their physical performance during exercise. Kocur et al. found a different result regarding the avatar's body composition; specifically, a muscular body avatar can improve the user's physical performance, increasing their grip strength while simultaneously decreasing self-perceived exertion during weightlifting [54]. At the same time, when users embody an avatar with the athlete's body (Fig. 2.3) it can reduce heart rate while the user is cycling in VR [17]. Additionally, Czub and Janeta found that users with athletic avatars in VR tend to perform more bicep curls than in the physical world [55]. However, some reverse results were also found, such as Lin et al. demonstrated that compared with the standard body composition avatar, the avatar with "six-pack abdominal muscles" led to users improving their confidence in their body, made them perceive they are good enough, and did not need more exercise, leading to a decrease in their physical activity [56]. In addition to the physical shape and appearance

Figure 2.3: User's avatar- Overweight, normal, and athletic avatar

Figure 2.4: User's avatar- Sweating and non-sweating avatar

of the avatar, the visual representation of some physiological characteristics of the human body will also affect the user's sports experience. The study found that when the virtual character presents a visual effect of sweating(Fig. 2.4), the user's subjective exercise load is reduced. At the same time, the perception of their endurance will be enhanced [16] .

In conclusion, the avatar design on "the user-controlled avatar" has been investigated, but studies focusing on surrounding avatar designs in the exercise domain remain limited. Therefore, investigating the design of surrounding avatars in VR gyms is both crucial and highly valuable for advancing our understanding of users' exercise motivation and performance.

2.1.3 The surrounding avatar design on the user's exercise experience

The research on surrounding avatars has not been enough explored. Until now, most of the research on surrounding avatars has focused on the special
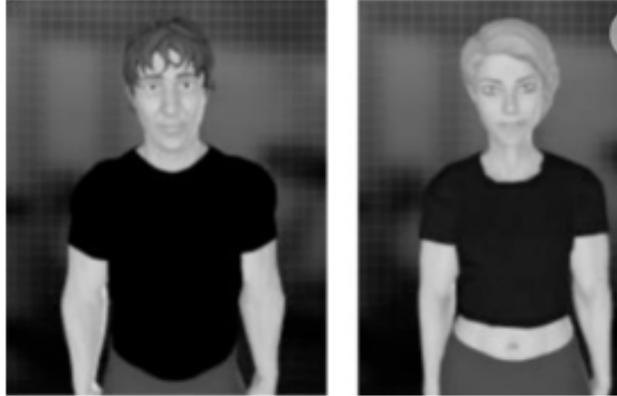
Figure 2.5: The surrounding avatar: virtual partner

relationship between users and surrounding avatars, such as opponents, audience or coaches. Although the surrounding avatar does not directly affect the psychological and physiological reactions of the user, this special relationship influences the user's behavior interactively.

For example, Peña and Kim found that the opponent avatar, which is typically with an overweight body composition design, usually decreases the user's physical activity while they are playing the tennis games [51]. Because when they play tennis games against overweight body composition avatars, it increases their confidence in tennis games. Thus, they may decrease their physical activity. After that, Samendinger et al. found that virtual exercise partners (Fig. 2.5) can enhance users' exercise persistence while they are doing exercise together, as the presence of others induces the Köhler effect, significantly increasing exercise duration. However, the avatars with introductory dialogue style showed no significant differences in the effects on users' exercise performance in exercise processes [57]. For the audience role, human audiences providing some feedback on physical progress have significantly enhanced an individual's exercise motivation; meanwhile, some research has also found similar results on VR exercise. Xu et al. found that the presence of the virtual audience (Fig. 2.6) and their feedback in VR exergames can enhance users' exercise performance, experience, and exertion, with larger groups and active feedback leading to greater improvements in performance, immersion, and exercise engagement [58]. At the same time, the virtual audience, through rhythmically clapping in VR sports games, can also improve users' performance by increasing cycling speed and heart rate, providing a high-intensity workout experience without the need for a human trainer. After that, Rhea et al. found that maximum weight lifting

20

in front of an audience or a competitive environment can improve weight lifting performance because of the self-presentation theory and self-awareness theory [59]. For the avatar role of coaches, Graf et al. found that during the VR sports game, virtual coaches with emotional behavior can affect players' emotional states and improve their motivation and performance. Specifically, happy coaches help enhance game motivation, while angry coaches can encourage players to improve their punching speed. This suggests that adding emotional elements to sports games can help promote the health of players [60]. This type of virtual coach could also provide users with more feedback, enhancing their enjoyment during exercise.
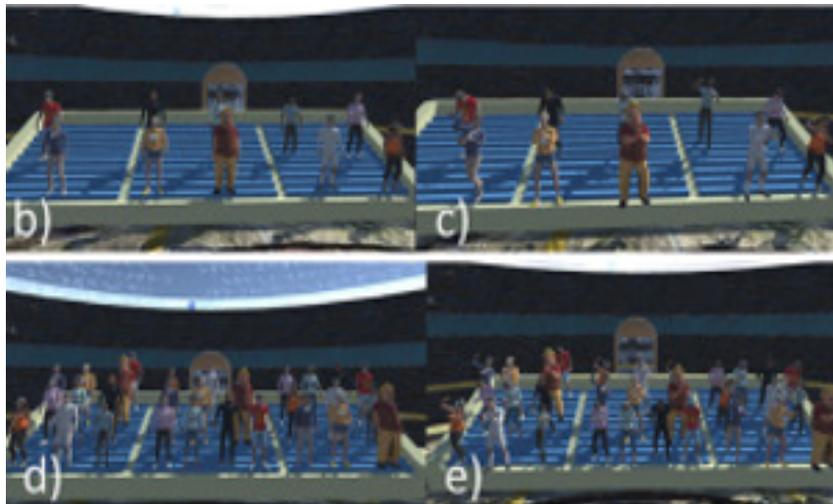
Figure 2.6: The surrounding avatar: virtual audiences

Regarding the research on the surrounding avatars, it is still insufficient. Existing studies mainly highlight the avatar's social role and relationship with the user. But still need to further investigate how the design of the surrounding avatar without that social role will affect users' experience in VR gyms.

2.2 Time perception

Time perception refers to how people experience and understand time. Human time perception is an important dimension in the decisions people make about their daily behavior. It is a subjective phenomenon and can be affected by various factors in the physical world, such as different environments, sensory, and cognitive factors. It is shaped by internal factors such as

individuals' physiological and psychological states, as well as external factors, including environmental conditions and biological rhythms.

External factors refer to various elements arising from the surrounding environment that influence time perception, such as the environment's high heat acclimation, which can impair time awareness and contribute to perceiving time longer [61]. Similarly, medicine that increases dopamine levels can prolong subjective time perception by affecting the brain; for instance, high-concentration attention leads the brain to deal with extra information [62]. Environmental stimuli such as music tempo and sound intensity also influence time perception. Specifically, slower tempos and louder sounds often lead to a distorted sense of time, making it feel longer [63,64]. Visual stimulation, such as flicker rates, can also alter time perception and increase time estimates [65]. In addition, Katsuura et al. found that the color of light also affects people's time perception in short-duration judgment. They asked users to make time judgments in monochromatic blue and red light environments and found that participants estimated time faster in red light conditions. Blue light, on the other hand, is slower to judge time [66].

Internal factors, however, are linked to an individual's inherent physiological and cognitive state of time perception. These factors can affect subjective time perception. For instance, conditions such as depression can slow time perception due to changes in brain function and neuroscience. People with mental illnesses generally experience time delay [67]. Emotions, such as fear and anxiety, can also impact time perception. Increased anxiety tends to make time feel longer because the heightened arousal from negative stimuli intensifies the perception of time passing slowly [68]. In addition, age is another factor that also affects people's time perception; for example, Baum et al. indicated that the elderly who reported they were younger than those who reported they were older perceived time passage more slowly [69]. At the same time, Tuckman found that self-reported older people about which part of their life the time passes slowly during their whole life, most of them reported "childhood" [70]. According to Ogden et al., the anticipation or experience of pain increases arousal and attentional focus, thereby resulting in an overestimation of time duration [71].

2.2.1 Time perception model

In the field of time perception research in psychology, numerous models have been developed to explain the underlying mechanisms of how humans perceive time. Among these, one of the most influential and widely accepted models is the internal clock model [72]. This model proposes the existence of

22

an internal timing system in the human brain, consisting of a pacemaker that emits regular pulses. These pulses are captured and accumulated through a switch mechanism, and the individual's level of arousal influences the rate at which the pacemaker emits pulses. The pulses are counted by a cognitive counter, which only records them when the individual's attention is directed toward time. The accumulated number of pulses is then transferred to working memory, where it is compared with stored values in retrospective memory that represent known durations. This comparison allows individuals to estimate how much time has passed and how fast it seemed to pass [73]. The internal clock model has been instrumental in explaining how various psychological and physiological factors affect time perception. For instance, in states of boredom, where brain activity is reduced and attention is more likely to be focused on time, people often experience time as passing more slowly. This model provides a valuable framework for understanding such distortions in subjective time perception.
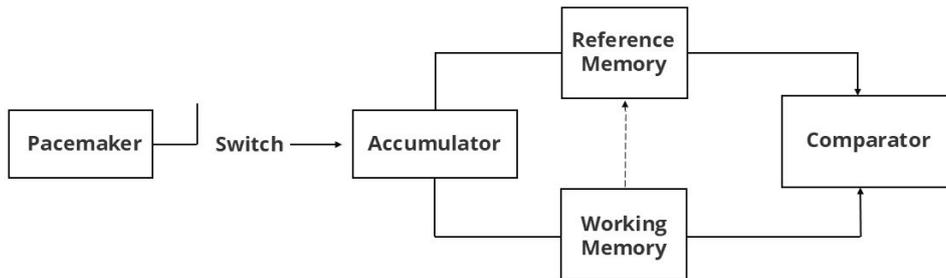
Figure 2.7: Time Perception Models

In psychology, people's subjective time perception is typically evaluated in two main ways: prospective and retrospective. In prospective measurements, participants are informed in advance that they will be required to judge the passage of time. For example, when participants are placed in a waiting situation, they tend to perceive the duration as longer because they focus more on the passage of time and have fewer distractions [74]. In retrospective measurements, participants are not informed ahead of time that they will need to make a time judgment; instead, they are asked to estimate the duration after the task has ended. According to time perception models, this means that the measurement method itself strongly influences time perception, as whether or not participants are aware of the time judgment

task significantly affects their estimates [75]. For instance, people often perceive time as passing quickly while playing video games, which reflects a temporary loss of time perception. After the game ends, they regain awareness of time and perceive that time passed quickly [76]. Researchers have referred to this phenomenon as the flow state, in which individuals become fully immersed in the task at hand and are not focused on the passage of time. Arousal levels are generally elevated during this state. The flow state typically occurs when the difficulty of a task aligns with an individual's skill level.

2.2.2 Time perception in the VR

VR has enormous potential to offer immersive experiences that significantly affect time perception. Previous research has shown that while engaged in VR activities such as games or immersive videos, users often lose track of time, experiencing what is commonly called "time flying." This effect is likely owing to the high level of engagement in VR, which distracts users from external time cues and body rhythms. Schneider et al. attempted to use VR to relieve breast cancer pain during chemotherapy. They found that the patients' duration judgment during VR-immersive chemotherapy underestimated the actual time by 28 percent, demonstrating how VR can distract attention from discomfort [77]. And then, Sabat et al. also found that the bad perception from VR sickness usually contributes to longer duration judgment [78]. And the more severe the symptoms, the more distorted the time estimates. Lugrin et al. highlighted that, by comparing waiting times in the real world and virtual environment (VE) in the same situations, participants perceived time as being shorter than in real waiting room conditions because people focus more on the VR content, and the higher arousal distracted their attention [79].

Recently, avatars have become the main target in VR time perception research. Unruh et al. highlighted that the presence of avatars and embodiments in VR can affect time perception. Participants reported the perceived time to be faster when they had self-controlled avatars(Fig. 2.8) [80]. Unruh et al. also investigated the effect of avatars with different levels of embodied representation, such as hands, arms, and the full body, which are controlled by the participants, on their time perception (Fig. 2.9). They found that when participants controlled the avatar only with hands without any other part of the body, it contributed to the perception of time passing more slowly than in other conditions [81]. In a study by Landau et al., participants who embodied avatars with a child's appearance perceived the duration of

time in the VE as longer than those with other avatar appearances [82]. Charbonneau et al. demonstrated that different designs on the appearance of avatars significantly influence users' time judgment, for example, with a Godzilla avatar leading to greater temporal underestimation compared to realistic human avatars [83].

Figure 2.8: With avatar or without avatar in waiting situation

In addition to avatars, various virtual objects and elements, such as audio-visual stimuli and object motion, influence time perception in VR. Picard et al. examined the effects of audio, visual, and combined stimuli when participants performed object-sorting tasks in a VE. Their results demonstrated that a combination of visual and audio stimuli significantly decreased the judgment of time duration. Furthermore, synchronized stimuli, such as virtual and audio elements, can lead to time compression or dilation, depending on the tempo [84]. Yamamoto and Miura explored the effect of the coherence of visual object motion on time perception. They found that participants who observed four line segments forming a coherent motion experienced altered time perception, which was influenced by perceived motion speed [85]. After that, Kitajima et al. found that in VR, the fear of altitude does not directly affect users' time perception [86].In summary, in the VR environment, avatars and virtual objects affect participants' time perception by attracting attention, enhancing the sense of embodiment, and

eliciting emotional responses, thereby altering users' psychological states and the internal timing clock.

Figure 2.9: Avatar at different levels

2.2.3 Time perception research on exercise intensity

The relationship between exercise and time perception has been the focus of numerous studies aimed at understanding the underlying mechanisms. For instance, Lambourne's study on cycling found that participants perceived time to be approximately 15% longer during exercise than during rest. This can be explained by the internal clock model: cycling alters the internal clock pulse rate, leading to an overestimation of time [3]. Petrizzo et al. demonstrated that running can cause individuals to overestimate the time spent on visual stimulation tasks, suggesting that exercise acts as a distraction that influences time evaluation [87].

Exercise intensity is a vital factor affecting time perception during exercise. Hanson and Lee found that increased exercise intensity leads to a slower perceived passage of time when people are running at higher exertion levels, like a Rating of Perceived Exertion (RPE) of 17, and the estimated time is significantly lower than at moderate levels, such as RPE 13 [88]. Edwards and McCormick also found that exercise intensity distorted the participants' time perception. The study found that performing Wingate cycles and rowing ergometer boats at slight and medium intensities did not affect time perception, while exercising at maximum intensity caused participants to perceive a shorter duration [13]. Additionally, Hanson and Buckworth found that women chose to run at a relatively higher intensity when they could select for themselves, compared to men. Simultaneously, a higher intensity leads to a relatively slow feeling of time passage [89]. Moore and Olson indicated that time perception differed before and after high-intensity exercise. They tested people before and after exhaustive cycling and found that high-intensity exercise usually induced time distortion owing

to fatigue. Under the fatigue state of people, duration judgment increases, and the relative error significantly increases [90].

In general, heightened sensory awareness and physical discomfort during intense exercise contribute to a longer perceived duration. This phenomenon is often linked to the release of catecholamines, which trigger hyperarousal—a state where the brain processes more information than usual, making time seem to pass more slowly than it does [91].

However, exercise intensity has been proven from the internal perspective to affect their time perception. But, the stimuli of exercise intensity from outside will also work on people's time perception, which is still not known, like the surrounding avatars. Thus, this is still important to investigate whether the intensity of the surrounding avatars affects people's time perception.

2.2.4 Time perception research on speed

The speed also significantly influenced time perception. For example, compared with the static mode, running led people to perceive that time was going longer [92]. By contrast, Rietzler et al. found that controlling an avatar with a slowed-down motion in a VE results in a shorter estimated duration [93].
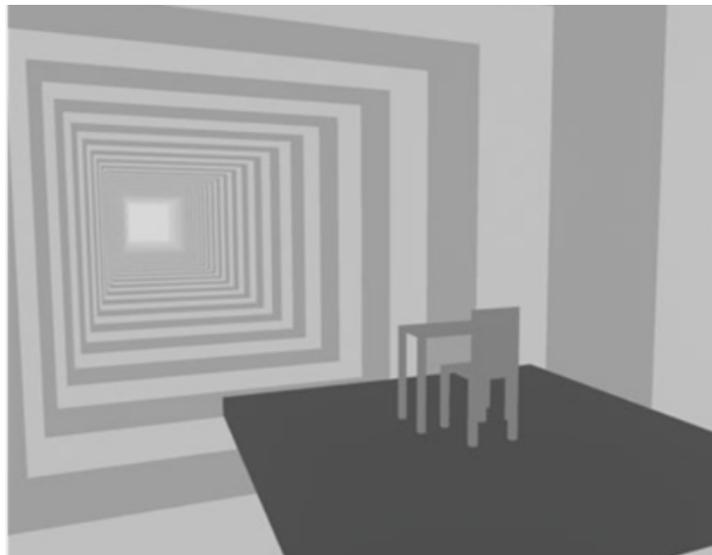
Figure 2.10: Self movement speed through virtual tunnel

In addition to self-motion, external motion stimuli also affect time perception. Kaneko et al. demonstrated that participants in a virtual car perceive a

longer time when experiencing a faster motion speed [94]. Similarly, Landeck et al. immersed participants in virtual tunnels with numerous different sections and found that a stronger sensation of self-motion and fast speed increased subjective time [95](Fig. 2.10). Additionally, Landeck's further research showed that external object motion within VE, such as pendulum movements, caused time to be perceived as passing more quickly than simpler motions like linear or rotary because the complexity of the pendulum motion captured more of the participants' attention [96] (Fig. 2.11). Dynamic images and speed cues can influence people's time perception, often causing them to overestimate the duration [97]. Another study compared a virtual object's motion speed to a human movement speed, such as point-light displays (PLDs), with only a few points of light representing the major joints or key parts of a moving body, after watching themselves and other people's dancing movements, which are recorded as PLDs at different speeds(Fig. 2.12). The results showed that the PLDs' moving speed also affects people's time perception, with a faster motion speed of human movement frames leading to longer duration judgments [98].

Figure 2.11: The external movement objects

In summary, both the internal and external motion speeds affect time perception. Images and PLDs with human motion information and speed properties are effective. In VR environments, such as VR gyms, the influence of motion speed is further compounded by social and interpersonal factors, where avatar behavior can introduce additional stimuli that affect users' time perception [99]. Furthermore, human information, such as dynamic facial expressions and high-arousal emotional displays, induces a longer perceived

duration. Thus, displaying only PLDs, despite being understood as a human performance action, loses considerable information compared to avatars [100].

Hence, it is crucial to extend prior research on self-perceived motion speed and visual stimuli such as PLDs by investigating the impact of the surrounding avatar's motion speed on individuals' perception of time.
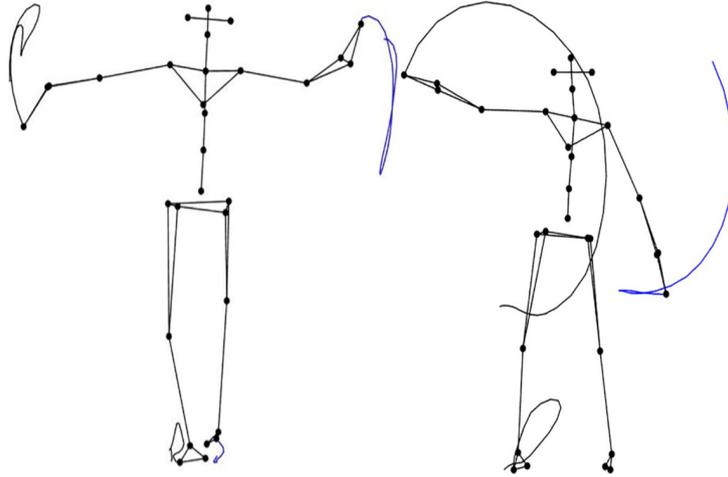
Figure 2.12: Point-light displays of dance movement

2.3 Social comparison theory

Social comparison is widely regarded as a central feature of human social life. It refers to the psychological process by which an individual evaluates their abilities, characteristics, or social status by comparing themselves to others in the absence of an objective standard [101]. Psychological research supports the idea that people's self-cognition develops through continuous comparison with others. For example, when people receive information about others, such as their characteristics, capabilities, achievements, or failures, they tend to relate this information to themselves [102]. Similarly, when they seek to understand their state or capabilities, they are likely to find answers by comparing themselves to others. According to Gilbert et al., not only humans but also other species engage in social comparison; this mechanism has played a highly adaptive role in evolution, enabling individuals to assess the strength of their competitors [103]. Since its early theorization in the 1950s, psychologists have expanded the theory by introducing the concepts of upward and downward comparisons and exploring alternative motivations

for social comparison.

Upward social comparison refers to the comparison with others who are better than the individual in some respect, such as intelligence, athletic ability, or performance on a specific activity or task—for example, higher test scores or faster marathon times. Research has demonstrated that upward comparisons tend to increase negative emotions [104]. It not only triggers negative emotions but may also weaken people's self-perception. For instance, Brown et al. found that when people make comparisons to physically attractive others, participants tend to decrease their self-reports of their attractiveness [105].

When people perceive a large gap between their abilities and those of the comparison targets, it can lead to a more negative impact on their performance. For example, people who are told they performed poorly on a task often show lower interest than those who are said to have performed well [106]. Similarly, another study found that children who were given false feedback indicating they were performing poorly showed less interest in peers who were performing well, and more interest in those also performing poorly, compared to children who were told they were performing well [107].

Although upward social comparison may produce negative emotional effects—for example, undermining self-esteem—it can also provide motivational targets that help people close the gap and boost their self-esteem [108]. Gerrard et al. found that smokers who compare themselves to successful quitters, or who want to connect with them, have a higher chance of quitting successfully [109].

Downward comparison, as the name suggests, refers to the psychological process by which individuals compare themselves to those who are inferior to them in some way [110]. Previous research indicated that downward comparison can improve individuals' emotions [111]. At the same time, individuals with relatively positive emotions may also tend to engage in downward comparisons to maintain or improve their positive emotions [112].

Except for emotion, the downward comparison also affects other factors. For example, Buunk et al. found that the unhappy couple is induced to compare their relationship with other couples who are less satisfactory than they are, which can improve their satisfaction [113]. In addition, when normal people stay with a physically handicapped individual, that can boost their self-rating of life satisfaction [114]. Especially from a health perspective, patients are more inclined to make social comparisons with their more severe counterparts [115].

Thus, downward social comparison can be seen as a way of inspiring, but it can also remind people that if they do not make changes for the current situation, they may face worse situations in the future. Lane and Gibbons also demonstrated that some students who were not dissatisfied with their score, who tend to compare themselves with worse students for downward social comparison, improved their test scores throughout the semester [116].

Meanwhile, in the gym and exercise environment, people not only exercise alone in the gym environment but also in a social environment, which means that people are often surrounded by many others who are exercising (Fig. 2.13). Such a context may trigger social comparison: when observing those who perform better, individuals may engage in upward comparison, which can lead to pressure or motivation; conversely, when encountering others who perform worse, they may engage in downward comparison, gaining comfort or confidence. Thus, the gym is not only a place for physical training but also a space where social interaction and psychological comparison intersect, with social comparison potentially playing an important role in shaping individuals' motivation, emotions, and exercise experience.

Figure 2.13: Exercise with others in a real gym[3]

---

[3]The source of exercise with others in a real gym: https://www.menshealth.com/fitness/a25427584/dirty-gym-germs-don-t-touch/

2.3.1 Köhler effect

Compared to social comparison, the Köhler effect is a distinct expression of social comparison effects; the Köhler effect is not induced solely by the presence of one or two others, but rather it is typically induced in a group. The Köhler effect refers to the phenomenon where less capable individuals are assigned to the same task as others, yet they are often seen as integral parts who usually perform better when working on the task alone. Hertel et al. found that in an exercise persistence task that required participants to hold the metal bar flat for as long as possible, in the group condition, two participants needed to keep the metal bar together; if any of the two participants put down the bar and touched the rope, the task would be finished. The results found that participants in the lower-capacity group condition performed better than those in the personal condition [117]. Due to the group effects, the ability of lower members in the group usually leads to upward social comparison, as they do not want to become the lowest member in the group.

Weber and Hertel found that whether the Köhler effect occurs depends on the type of task [118]. Following Sterner's proposed task classification, the group task is divided into three types: conjunctive, coactive, and additive [119]. In conjunctive tasks, team performance is often determined by the performance of the worst-performing member. In a joint action task, members work simultaneously yet independently of one another. Additionally, the total team performance is the sum of the individual members' performances. Although the Köhler effect was observed in all types of tasks, the weakest members showed the most improvement in the joint action task [118]. One of the explanations for the occurrence of the Köhler effect was the indispensability of their group. Group performance depends on each individual, so it motivates them to work harder. Especially in conjunctive tasks, team performance is directly affected by the weakest members, so their motivation increases the most. The second explanation involved social comparison: when cooperating with a higher-capacity group member, the weaker member may tend to adjust their target or view the higher-capacity member as a competitive object. In addition, group members who require feedback on group performance, which is also important for them, can induce the Köhler effect [120].

2.3.2 Social comparison on body composition

The external appearance, like body composition, is also considered from a comparative perspective for social comparisons. Social comparison theory

posits that individuals are most likely to compare themselves to those who are similar to them. Women usually like to compare themselves to unrealistic, thin media images of women just as frequently as they compare themselves to more relevant peers [121]. Tiggemann and Slater found that when women watch a video with a slim character, it can induce social comparison and perception of body dissatisfaction [122]. Tiggemann and McGill also found that advertisements that include a slender body, on the whole body, or only a part of the body will lead women to produce negative emotions and increase body dissatisfaction [123]. Nabi and Keblusek found that women, compared with media figures on the body, can improve their feeling of envy [124].

During exercise, people have numerous opportunities to compare their own bodies with those of others, including physical attributes such as body composition, appearance, and also body function, like physical performance and skills [125]. Body composition is defined as the distribution of fat mass and lean body mass [126]. It conveys cues about physical capabilities, such as strength or endurance [127]. For example, a fitness model on TV may be perceived as an ideal role model, inspiring and motivating users to set higher exercise goals [128]. Pila et al. found that compared with a fit body, it induces envy, which can affect people's exercise motivation [15].

The social comparison of body composition on exercise should depend on its applicability and representativeness [129]. For example, a tennis player was expected to have health, flexibility, and agility [130]. Therefore, in Peña et al.'s research, the opponent avatar with normal body composition can be integrated with proficiency in tennis; conversely, the overweight avatar performed poorly at tennis. After that, they found that when users controlled a normal body composition avatar against an overweight body composition opponent avatar, this attribute decreased physical activity [51](Fig. 2.14). A downward social comparison occurred because the overweight opponent avatar was perceived by users as less skilled and having lower physical ability.

For the social comparison aspect of exercise speed, the primary focus is on the physical performance of the surrounding avatar. First, for the physical performance, Max et al. demonstrated that when users cycled alongside a consistently fast-moving avatar, their exercise duration increased compared to scenarios involving avatars with fatigue characteristics or solo exercise [131]. Wang et al. found that with high-performing exercise partners, such as rapid squat speeds, users tend to compare their performance with it, affecting their perception of exertion [132]. Similarly, Barathy et al. reported that when users competed against a virtual opponent modeled on their previous cycling speed, their performance improved while maintaining

intrinsic motivation [133]. Lee et al. found that when users did exercise with a consistently superior performance avatar, it significantly decreased their performance and motivation in exercise compared with a non-always superior avatar [134]. Parton and Neumann's study found that when users rowed with competitors who performed at 120% of their baseline level, their performance declined rapidly; conversely, users rowed better when faced with competitors who were only 5% above their baseline [135]. This is consistent with social comparison theory; when the level of competence of the comparator is too high, it may undermine participants' confidence, thereby weakening their motivation. These studies are based on the social comparison between users and the surrounding avatar, resulting in upward social comparison, and the increase in exercise motivation further enhances their physical performance.

Figure 2.14: Virtual tennis game against with different body composition avatar

2.3.3 Social Comparison and Exercise Performance in VR

For the social comparison aspect of exercise speed, the primary focus is on the physical performance of the surrounding avatar. First, for the physical performance, Max et al. demonstrated that when users cycled alongside a

consistently fast-moving avatar, their exercise duration increased compared to scenarios involving avatars with fatigue characteristics or solo exercise [131]. Wang et al. found that with high-performing exercise partners, such as rapid squat speeds, users tend to compare their performance with 31 it, affecting their perception of exertion [132]. Similarly, Barathy et al. reported that when users competed against a virtual opponent modeled on their previous cycling speed, their performance improved while maintaining intrinsic motivation [133](Fig. 2.15). Lee et al. found that when users did exercise with a consistently superior performance avatar, it significantly decreased their performance and motivation in exercise compared with a non-always superior avatar [134]. Parton and Neumann's study found that when users rowed with competitors who performed at 120% of their baseline level, their performance declined rapidly; conversely, users rowed better when faced with competitors who were only 5% above their baseline [135]. This is consistent with social comparison theory; when the level of competence of the comparator is too high, it may undermine participants' confidence, thereby weakening their motivation. These studies are based on the social comparison between users and the surrounding avatar, resulting in upward social comparison, and the increase in exercise motivation further enhances their physical performance.

Figure 2.15: Cycling with an avatar

2.4 Summary

This chapter provided a comprehensive review of the existing literature related to VR exercise, avatars, time perception, and the social psychological effects of the presence of others. The integration of VR into exercise contexts has demonstrated significant potential in enhancing users' motivation, physical performance, and overall experience. VR technologies not only support physical rehabilitation and mental well-being for users but also could improve the efficiency and enjoyment of exercise routines across various populations, including children, the elderly, and patients.

The avatar, as the digital embodiment of the user or others in VR, plays a critical role in influencing users' psychological states and physical performance. Prior research has mostly focused on the effects of avatars' physical characteristics (e.g., body shape, appearance, fitness level) on motivation and behavior. The surrounding avatar was primarily focused on the special relationship between users and the surrounding avatar, such as a partner, an opponent, or a coach. These studies reveal that user-controlled and surrounding avatars can shape users' exercise performance and their experience in VR exercise.

Furthermore, time perception in exercise situations is an important psychological factor that influences user engagement. It is shaped by internal factors such as exercise intensity and arousal, as well as external elements including avatar embodiment and environmental features like motion and sound. These findings suggest that perceived duration can serve as an indicator of cognitive load and engagement during exercise.

Finally, this section examined how the presence of others, represented by surrounding avatars, evokes a range of social psychological effects, including social comparison, social facilitation, and the Köhler effect. These mechanisms illustrate how social cues and interactions in VR can alter users' motivation, emotional responses, and behavior. The review highlights that avatars serve not only as visual stimuli but also as social agents that can simulate real-world social contexts, thereby impacting users' exercise experiences.

In summary, the interplay between avatar characteristics, time perception, and the social presence of others provides valuable insights for designing more engaging and personalized VR exercise environments. However, further research is needed to investigate how specific visual and behavioral attributes of surrounding avatars impact users' performance, perception, and motiva-

tion, particularly in the context of VR gyms. In the following chapters (3 and 4), this thesis will present the experimental studies on the surrounding avatar on the dynamic and static aspects that address these questions from the literature review.

Chapter 3

The Effects of Surrounding Avatars' Exercise Speed and Intensity on Users' Time Perceptions in VR gym

3.1 Introduction

Recently, the development of VR has provided users with a highly immersive experience by simulating various scenarios and offering unique experiences. Moreover, VR provides some opportunities and possibilities that the physical world cannot easily realize; a case in point is that users can select where they are, such as walking on the beach or in a tropical rainforest. It is effortless to allow users, through the immersive experience, to relax their minds and fully engage with the entire VE. Hence, an increasing number of individuals are gravitating towards VR software to replace the conventional physical scenario in daily life, recognizing its manifold benefits. For instance, in VR Gym, individuals can easily slip into their ideal workout atmosphere to alleviate boredom and loneliness [136].

Designing an ideal VR Gym requires addressing the issue of users' willingness to continue exercising. Fatigue often reduces people's motivation to continue exercising, as noted by Brownsberger et al. [5]. Additionally, Lambourne and Tomporowski found that highly intense exercise can induce hyperarousal, causing people to perceive time as passing more slowly [3]. A review paper presents such a viewpoint that time distortions may play a role in exercise adherence, with individuals potentially being disinclined to continue with healthy exercise [4]. Therefore, it is essential to examine how individuals perceive time in a VR Gym and how time perception is impacted to help people maintain their exercise routine.

Time perception is generally defined as a person's awareness of natural time, and previous research on time perception has suggested that cognitive, emotional, and physiological factors such as attention, arousal, and bodily rhythms significantly influence people's perception of time from an internal perspective [137]. In recent years, researchers have paid attention to time perception in VR, trying to improve the user experience by controlling or adjusting subjective time. Apart from VR technology, many other factors that can change people's time perception in VE have been verified. For example, the exercise speed of the virtual sun, which rises and falls, and its acceleration contribute to users' overestimation of time [138]. Additionally, the representation of an avatar for the user also affects their perception of time. For example, users who perform cognitive tasks with a high-quality avatar, such as a full-body avatar, perceive time to pass more quickly than when they only control a virtual hand [81].

Until now, previous research on avatars and time perception in VEs has primarily focused on user-controlled avatars. However, it is important to consider the impact of the surrounding avatars and environments in VR Gym. These external factors may also influence people's time perception, including surrounding avatars that can be computer-controlled or those of other users. Despite this, there is currently limited research on the effect of surrounding avatars on time perception in the VR Gym. Thus, we raised a vital question: "What attributes of surrounding avatars in the VR Gym affect the user's perception of time?". We focused on two attributes: the exercise speed of the surrounding avatars and the intensity of the exercise workload undertaken by the surrounding avatars. An experiment was conducted to investigate the effects of these factors on people's time perception in a VR Gym. Through this research, we aimed to provide designers of VR Gym with valuable insights that enable them to craft more engaging and effective exercise experiences for users.

3.2 Method

To better understand the effect of surrounding avatars on time perception in VR gyms, we focused on two aspects: dynamic and static exercise speed and exercise intensity. Specifically, we examined how the exercise speed and exercise intensity of the surrounding avatars influenced the participants' time perception. Additionally, we focused on how the participants' states affect these effects. The entire experiment was conducted using a VR gym. The speed of the surrounding avatars' exercise and the weight of the barbell

changed within the scenario. The cycling task was chosen for our study because it is a common task in gyms, may have lower interference in duration judgment, and is safe when wearing an HMD. For the surrounding avatars' exercise, we selected the barbell squat for the reason that it was an exercise that affects squat time by the exercise intensity [139]. Meanwhile, it was a full-body exercise visually salient movement that can be easily perceived even from a seated position. Therefore, the squat is suitable for this experiment.

According to time psychology, some studies distinguish between two main types of time perception [140]. Therefore, we followed the time psychology method and focused on our hypothesis from two perspectives. Duration judgment refers to an individual's objective estimation of the duration of a specific period. The second part concerns the feeling of time passage, which is an individual's subjective perception of the rate at which time passes. We also focused on the participants' state; therefore, the hypotheses were set to test whether cycling on the bike provided a more immersive atmosphere in the VR gym, making participants more focused on the VR gym and the surrounding avatars exercising. Simultaneously, according to the internal clock mode theory, it can be explained that the sports state might increase the participants' heart rate. Further, their higher accumulation of pulses will increase their time perception [141]. Thus, we formed the following hypotheses:

- H1: The fast-exercise speed condition of the surrounding avatar leads to participants making longer duration judgments (H1-1) and feeling time passage faster(H1-2).

- H2: The high-intensity exercise condition of the surrounding avatar leads to participants making longer duration judgments(H2-1) and feeling time passage faster(H2-2).

- H3: The cycling state will increase the effect of the surrounding avatar on the participants' time perception compared to the sitting state.

3.2.1 Software and hardware

A fitness bike (ALINCO, AFB6119) with a magnetic load system was used by the participants for cycling. The maximum load capacity of this fitness bike was 120 kg, and various sports modes could be selected. The entire experimental system ran smoothly on a desktop PC(Intel(R)Core™ i7-12700, 16 GB RAM, NVIDIA GeForce RTX 3060). We selected the Meta Quest 2 as our head-mounted display device to provide participants with a truly

immersive virtual experience. This HMD has a 90° field of view, a resolution of 1832×1920 pixels per eye, and a 90 Hz refresh rate. To create the experimental environment, we have chosen Blender (v. 3.6.5.0) as the main tool to create 3D modeling and Unity 3D (v. 2021.3.9f1) as the main development tool. Using 3D modeling, we constructed a VR gymnasium environment consisting of many different training devices, such as treadmills, barbells, and chest push frames. Regarding the design of the entire virtual space, we opted for a low-poly aesthetic to craft 3D models constituting the VR gym. While this design choice lent a distinctive style to our environment, it could potentially trade off the degree of realism. However, based on our subjective experience, this stylistic decision did not markedly affect the overall virtual immersion. Unity3D was used to create an entire environment and arrange each position of the training device and VR application (Fig. 3.1). A specific experimental room was laid out to allow participants to slip into the VR gymnasium easily. A virtual bicycle station was placed within the experimental area, permitting participants to engage in experimental tasks while immersing themselves in the VR gymnasium scenario.

Figure 3.1: The VR gym design: 3D model of a training machine.

For the surrounding avatars and the avatar representing participants, both used low-poly style models from "Low Poly Animated People," which

can significantly enhance visual coherence and presence in VR gym environments. In addition, the outside appearance of the surrounding avatar assumed that of an athlete, which was more suitable for the VR gym (Figure 3.2 A). The default surrounding avatar was positioned centrally in the VR gym to ensure maximum visibility. Two barbells with different numbers of weight pieces will be used to perform a squat by the surrounding avatar: one with three large plates and a smaller plate on each side of the barbell pole, and another with only a barbell pole-like design (Figure 3.3 A-1, A-2). The surrounding avatar animation, a barbell squat, was obtained from the Mixamo website (Figure 3.4).
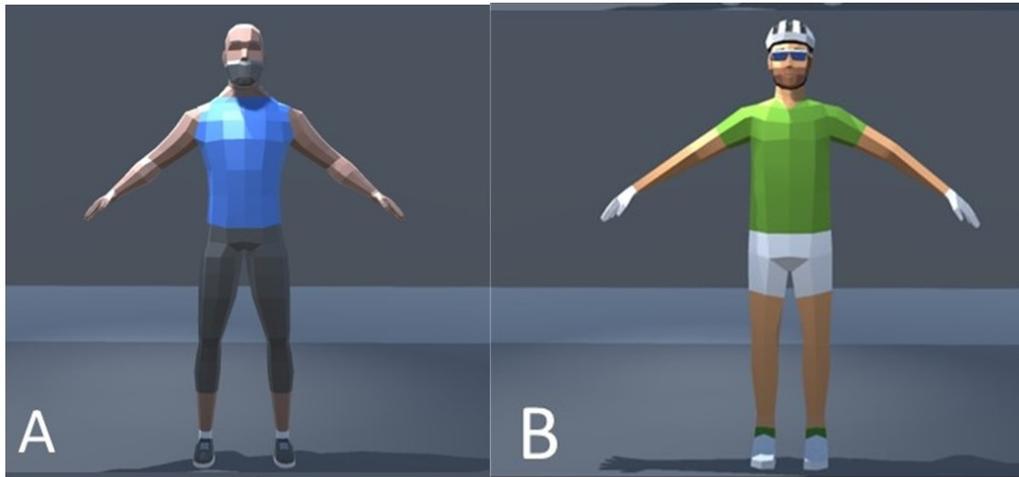
Figure 3.2: The avatar used in the experiment: A) Surrounding avatar B) Participant's avatar

To represent the participants within the virtual gym, we created an avatar positioned on a stationary bike (Figure 3.5 B-1). The participants perceived the VR gym through a first-person perspective to observe the environment, allowing them to change their sight view by simply moving their heads (Fig. 3.5 B-2). Considering the nature of the experiment, whether it was a sitting or cycling task, the participants remained seated on a stationary bike until each experimental section finished. Consequently, the participants' avatar was fixed to the virtual stationary bike in the VEs (Figure 3.5 B-1).
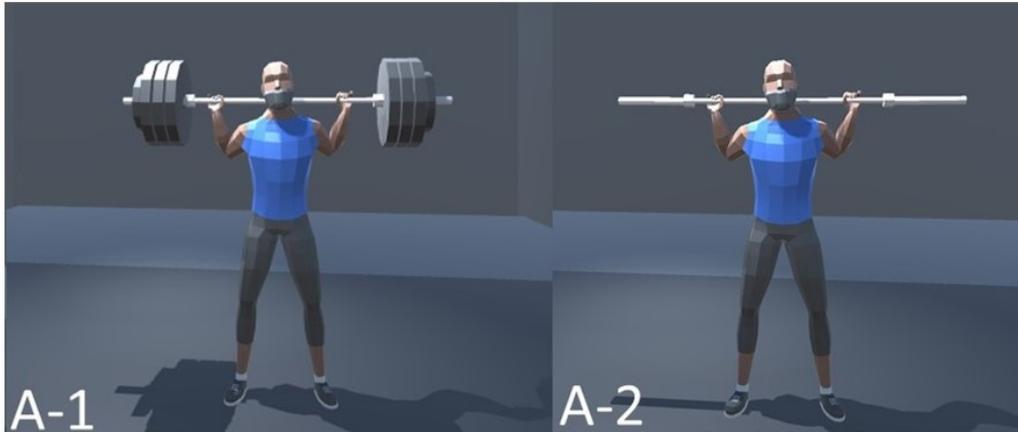
Figure 3.3: The surrounding avatar with different exercise intensity:(A-1) Surrounding avatar under heavy-intensity condition (A-2) Surrounding avatar under light-intensity condition

Figure 3.4: The surrounding avatar with the heavy intensity and animation of squat used in the experiment

3.2.2 Participants

We recruited 28 participants for the experiment through an online communication group. The recruitment period ran from September 14 to October

5, 2023, and the experiment was conducted from September 23 to October 10. The average patient age was 26 years, with a standard deviation of 2.4 years. Among the participants, there were 9 females and 19 males. All the participants were unaware of the purpose of the study. The participants had normal or corrected-to-normal vision. All participants provided written informed consent. Participants were free to withdraw at any time during the experiment. This experiment was approved by the Research Ethics Committee of the Japan Advanced Institute of Science and Technology and was conducted in strict compliance with its contents. The ethical approval number is Hito 04-053.
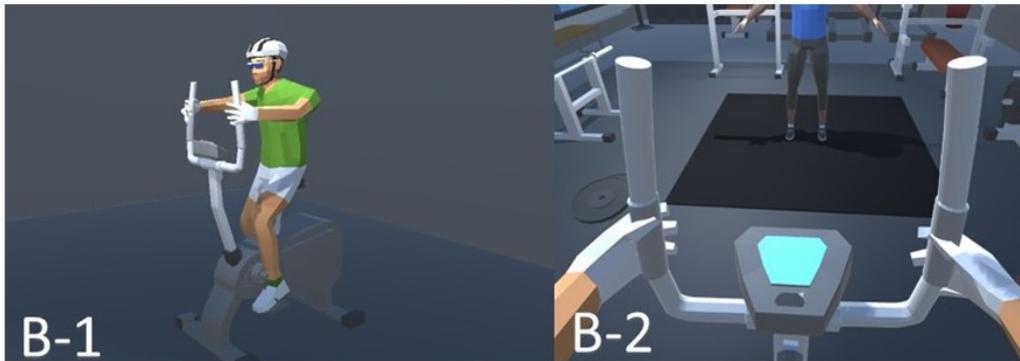
Figure 3.5: The avatar used in the experiment: (B-1) Participant's avatar with cycling gesture (B-2)User's viewpoint

3.2.3 Experimental conditions

In real-world gyms, people typically do squats or other resistance exercises following a mode like one training set with one rest set, which is called "Rest between sets (RBS)" [142]. For squats, people typically spend 20, 30, and 40 s to complete each training set.

We conducted a within-participants experiment using three independent variables. The first was exercise speed with three levels: I) slow speed, II) medium speed, and III) fast speed. The frequency was used to define three levels: for slow speed, the surrounding avatar performed 19 squats per minute; for medium speed, it was performed 28 times per minute; and for fast speed, it was performed 38 times per minute. The exercise speed of the surrounding avatar was based on "The Ruffier Squat Test", which is a quick fitness test that checks heart health by measuring heart rate before and after doing squats. It needs people to squat 30 times in 45 seconds. However,

since this is a high-intensity test, we reduced the frequency to 38 times per minute as the fast-exercise speed condition in our study. Furthermore, a 30% reduction was applied to create the other two conditions. The second independent variable was the exercise intensity of the surrounding avatar, with two different exercise intensities: I) low and II) high. For the low exercise intensity, the surrounding avatar lifted a barbell pole without any extra weight plates; for the heavy intensity, the surrounding avatar lifted a barbell pole with three big and two small weight plates on each side of the barbell. The last independent variable was the state condition of the participant. The participants observed and estimated the duration while either sitting on a stationary bike or cycling on a stationary bike.

In designing the duration of each trial, we took into account previous research by Landeck et al [95]. The duration of each trial was set to 20, 30, and 40 seconds. Each default time that we set for each trial was presented with equal frequency and in a random sequence. So for each experiment session, participants observed the surrounding avatar doing exercise with RBS, and the task was to estimate the time for each exercise set, with the rest time allocated for answering questions. This task design makes the duration judgment of each workout set more relevant to actual gymnasium training styles. Additionally, previous research found that long-term judgment is more affected by exercises [143]. Relatively, short-term duration judgment can reflect people's time perception more accurately. Meanwhile, Droit-volet et al. found that the feeling of time passage had a positive correlation between several seconds and several minutes of judgment [143, 144]. Also, when time exceeds a 1-second duration, the judgment and feeling of time passage correlate.

3.2.4 Procedure

The entire procedure of the experiment is shown in Fig. 3.7. Participants first signed a consent form after the experiment explanation, and they completed a demographic questionnaire to provide basic information. Next, they wore disposable socks and indoor sneakers, adjusted the bike seat height to match their height, and put on the HMD (Fig. 3.6).

First, they had a practice session to get used to the task, which included 6 trials and answering questions 6 times. Following the practice session, participants took a 5-minute rest in a separate room. The main experiment consisted of four sessions: two cycling sessions and two sitting sessions. To reduce the potential bias caused by cycling fatigue, there were no two consecutive cycling sessions. For the sitting session, which lasted 18 minutes,

45

Figure 3.6: Participants experimented

participants sat on the bike and were first shown a hint scene: "You are in the observation stage, please observe and familiarize yourself with the environment," to help them immerse themselves in the VR gym. After that, participants entered and observed the environment for 1 minute and familiarized themselves with the VR gym. Then, they began the first trial. After each trial, they answered two questions. After answering, they proceeded to the next trial. This process continued until all 19 trials were completed; one of the trials was without the avatar condition as the baseline in the experiment. The cycling sessions, lasting around 19 minutes, differed only in the hint scene: "You are in the warm-up stage, please start cycling. The remaining trials followed the same format as the sitting sessions. The stationary bike was set to a 30-watt mode to ensure all participants consumed the same amount of energy regardless of their pedaling frequency. The stationary bike was set to a 30-watt mode to ensure all participants consumed the same amount of energy regardless of their pedaling frequency.

After each session, the experimenter helped participants remove the HMD. There was a 10-minute rest period between each two sessions. During rest time, participants wore eye masks and headphones to listen to light music, promoting deep rest and reducing fatigue and outside interference. Throughout the experiment, participants completed an equal number of trials involving combinations of three exercise speeds, two exercise intensities, three observation times, and one blank scene without any surrounding avatar, counterbalanced in randomized sequences, totaling 76 trials. After the experiment, a brief interview was conducted, which focused on the effect of the surrounding avatars' exercise speed and intensity on their perception of time.

3.2.5 Measures

In this experiment, we designed the following two questions to measure how long the participants felt in each trial and their perception of time passage, as used by Lugrin et al., Unruh et al., and Landeck et al. [79,81,95,96]. Both of these questions were displayed in Chinese and were only explained during the experiment. All participants fully understood the meaning of the two questions by reading the experiment explanation document.

- Q1: Intuitively (no more thinking), how long do you think you existed in the VR gym? Please use seconds as the unit of estimated time and say it directly and orally.

- Q2: From your physical feeling, how fast is the time passage?
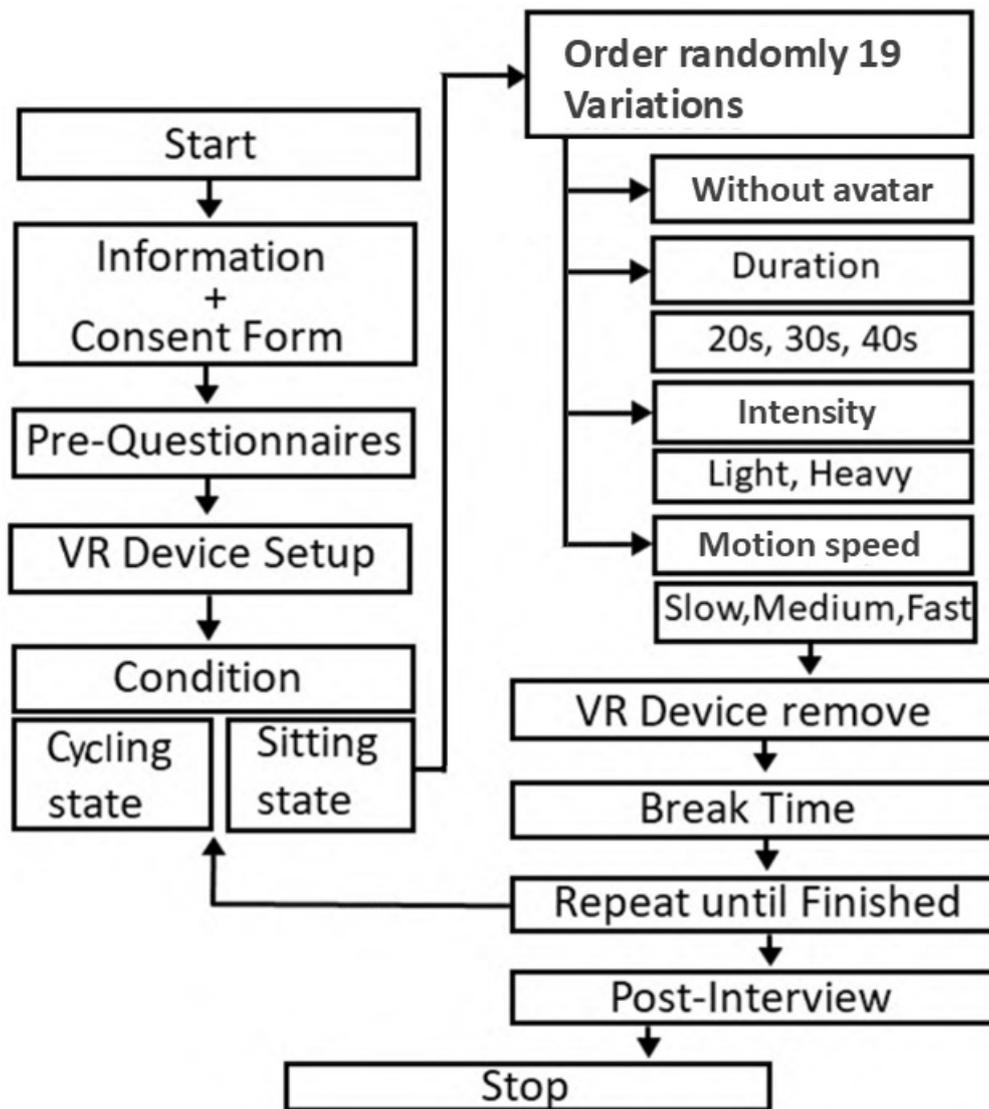
Figure 3.7: Experimental procedure

48

Q2 is a 7-point Likert scale adopted from the Inventory on Subjective Time Self and Space (STSS) [145]. Q1 was used to measure participants' subjective time perception, "an individual's objective estimation of the duration of a specific period." Q2 was used to measure "participants' subjective perception of the rate of time passage." Based on the specific situation in this experiment, we have revised the question slightly. For Q1, we added a description of how to answer the question orally and the details of duration judgment from existing in the VR gym. For Q2, "from your physical feelings" was added; participants needed answers from their physiological responses rather than relying on their brain's thinking to get more accurate and avoid errors in the feeling of time passage.

3.2.5.1 Statistical analysis

To evaluate the effects of the conditions on the percentage duration judgment, we applied three within-subject variables: exercise speed, intensity, duration, and participant state. We conducted a repeated-measures analysis of variance (ANOVA) to investigate the effects and interactions of these independent variables on the dependent variables, including time estimation and the feeling of time passage. Normality was then tested using the Shapiro-Wilk Test. Sphericity was assessed using Mauchly's test, and appropriate corrections were applied when violations were detected. All analyses were conducted using the R programming language in RStudio as the development environment.

3.3 Results

3.3.1 Duration judgment

The results of the duration judgment are presented in Table 3.1 and Figures 3.8 3.9 3.10. Although the assumption of normality was violated for the dependent variable (duration judgment), we converted the data logarithmically [146]. After conversion, most data were normal. However, several conditions were still violated; therefore, we also proceeded with ANOVA because it is quite robust in terms of normality [147, 148].

For the comparison between the surrounding avatars' different exercise speeds, there was a significant effect on the duration judgment ($F(1.33, 35.98)$ = 29.98, p <.001, η_p^2 = .051). After that, there was also an interaction with

Figure 3.8: Main results of the exercise speed on duration judgment: Scores on exercise speed, exercise intensity, and participants' state, with error bars.

	F-Value	P-Value	Effect size
Exercise speed	29.98	<.001*	.051
Exercise intensity	0.03	.865	<.001
Participant's state	0.52	.479	.029
Duration	1362.87	.001*	.407

Table 3.1: The result of the duration judgment

Table notes: The results of different surrounding avatar conditions on the comparison of duration judgments.

significant effects between speed and participants' state $(F(1.78, 48.13) = 8.61, p <.001, \eta_p^2 = .005)$. Furthermore, there was a significant difference in duration (F $(1.72, 46.35) = 1362.87, p <.001, \eta_p^2 = .407)$ on duration judgment.

For the comparison between the surrounding avatar's exercise intensities, the results revealed no significant difference in the duration judgment between exercise intensities $(F(1, 27) = 0.03, p = .865, \eta_p^2 <0.001)$. For the comparison of participants' states, the result presented that there was no significant difference $(F(1, 27) = 0.52, p = .479, \eta_p^2 = .001)$.

The Bonferroni test was used to perform post hoc tests following the significant main effect of exercise speed on duration judgment. Bonferroni-adjusted post hoc comparisons revealed that all pairwise differences between the surrounding avatar exercise speeds for the three durations were significant. The analysis revealed distinct differences among the various exercise speed conditions. The fast exercise speed condition (M = 3.02, SE = 0.04) compared with the medium exercise speed condition (M = 2.94, SE = 0.04) (fast exercise speed >medium exercise speed $(t(27) = 5.112, p <.001)$), the medium exercise speed condition (M = 2.94, SE = 0.04) compared with the slow exercise speed condition (M = 2.84, SE = 0.05) (medium speed >slow speed $(t(27) = 4.558, p <.001)$).

To further understand the interaction effects on the participants' states and the surrounding avatar's different exercise speeds, we also performed a post hoc comparison with Bonferroni adjustment. The results showed that at the slow exercise speed, the cycling state (M = 2.88, SD = 0.45) was not significantly different $(t(27) = -1.993, p = .0565)$ from the sitting state (M = 2.80, SD = 0.42). Similarly, under the medium exercise speed, the
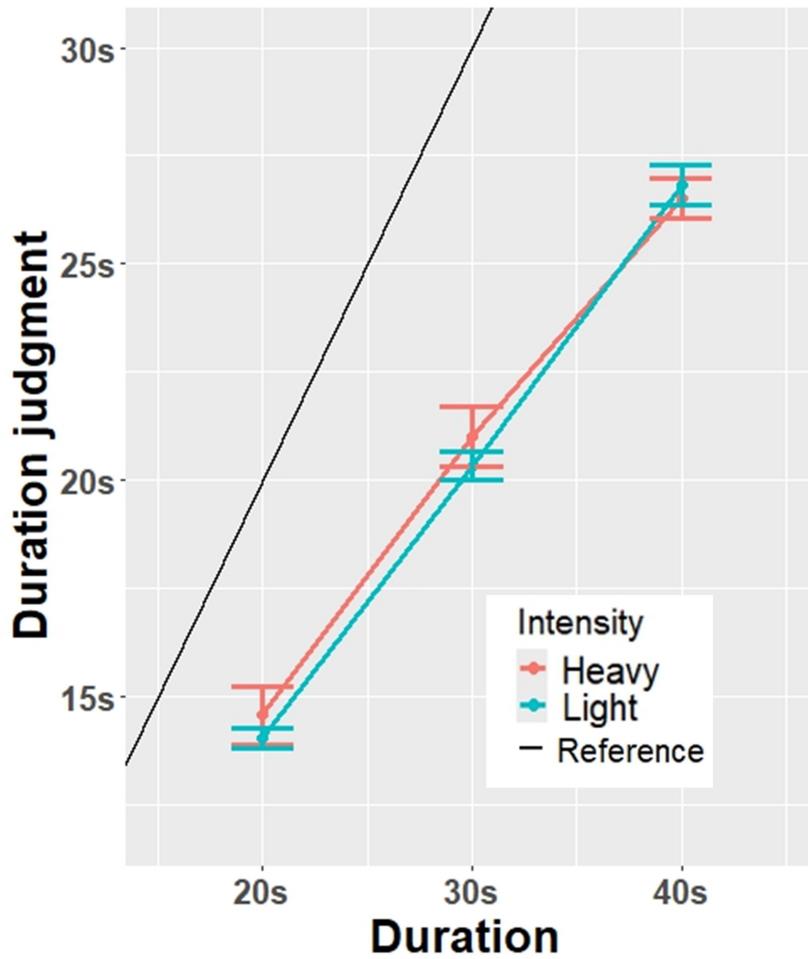
Figure 3.9: Main results of the dependent variable duration judgment: Scores on exercise speed, exercise intensity, and participants' state, with error bars.

sitting condition (M = 2.93, SD = 0.38) compared with the cycling condition (M = 2.95, SD = 0.43) was not significantly different (t(27) = -0.632, p = .532). Then, under fast speed, the sitting condition (M = 3.03, SD = 0.371) compared with the cycling state (M = 3.00, SD = 0.42) also did not show a significant difference(t(27) = 0.971, p = .340).
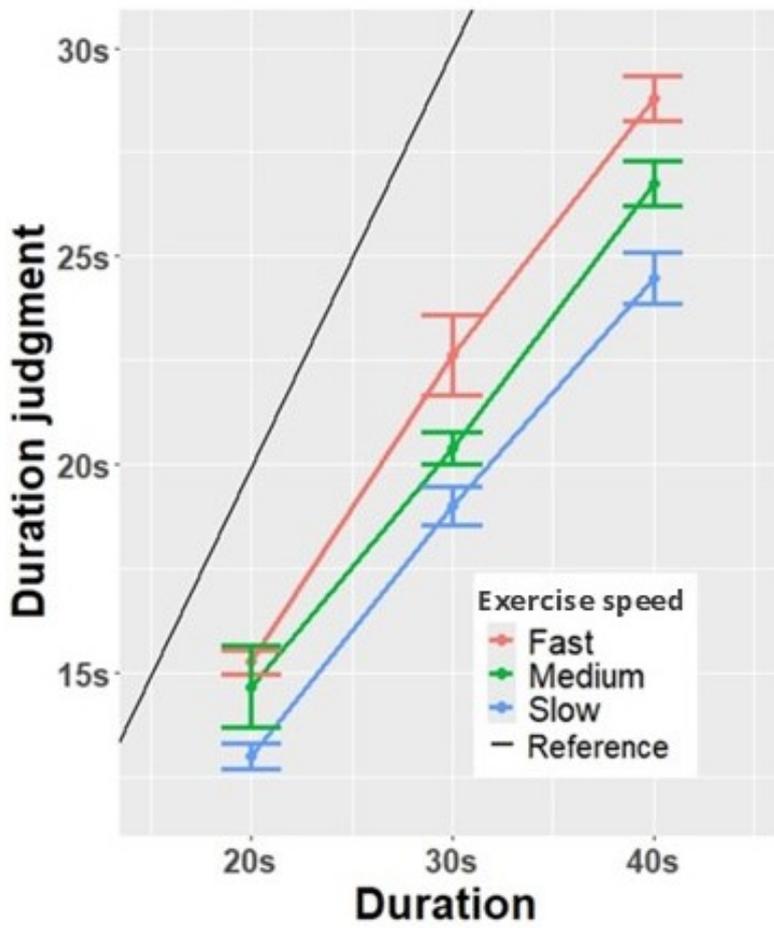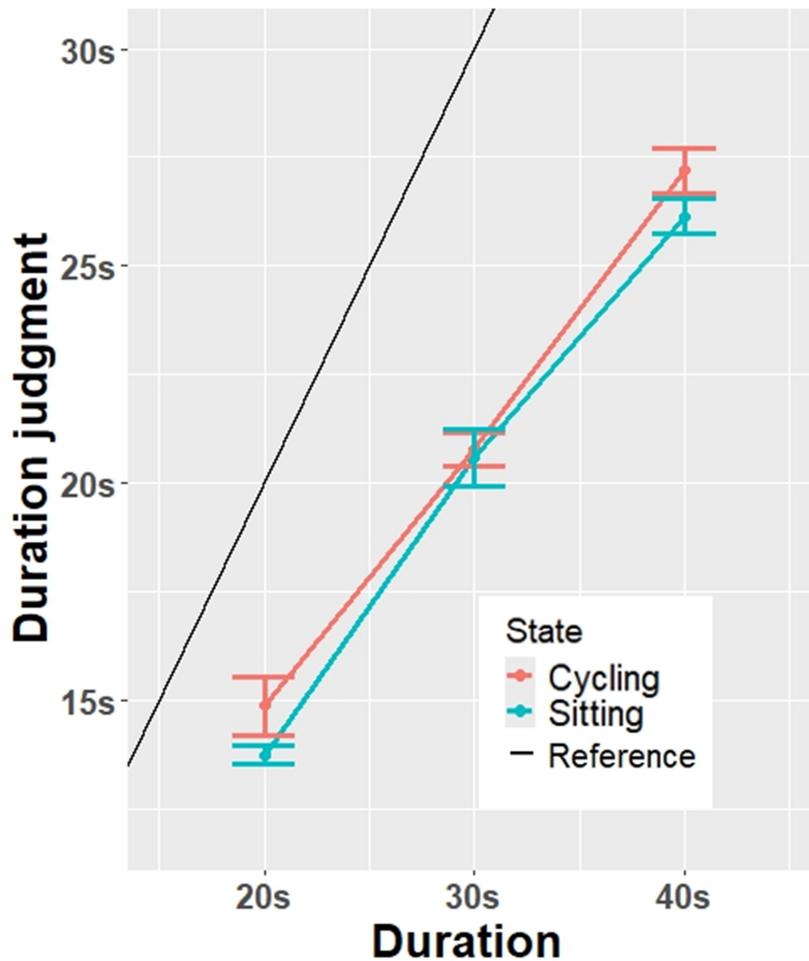

Figure 3.10: Main results of the users' state on duration judgment: Scores on exercise speed, exercise intensity, and participants' state, with error bars.

3.3.1.1 Compare with actual duration

From fig. 3.9, we found that almost all conditions of duration judgment were underestimated. Thus, we performed a one-sample t-test under all conditions

to determine whether the duration judgment and actual duration were statistically significant. The results showed a highly significant difference, with a mean difference of 9.44 (t(2016) = 43.521, p <.001). This indicates that duration judgment was significantly lower than the actual duration for all experimental conditions.

Except for the conditions of the surrounding avatar's exercise speed and intensity, we conducted another trial in each experimental session without any surrounding avatar, as the reference condition. We also conducted a one-sample t-test to evaluate whether the duration judgment and actual duration were significantly different in the reference condition. The results revealed a significant difference between duration judgment and actual duration, with a mean difference of 6.875 (t(111) = 12.808, p <.001), and the duration judgment was significantly lower than the actual duration.

3.3.1.2 Post hoc power analysis on duration judgment

To ensure that our sample size was adequate for detecting the expected effects, we conducted a post-hoc power analysis using statistical power and sample size calculation tools. Based on an effect size of 0.051, a significance level of 0.05, and a total sample size of 28 participants, the analysis yielded an actual power of 0.653 (65.3%).

3.3.2 Feeling of time passage

Table 3.2: The result of the feeling of time passage

	F-Value	P-Value	Effect size
exercise speed	116.99	<.001*	.437
Exercise intensity	6.25	.019*	.010
Participant's state	0.02	.891	<.001
Duration	1.82	.177	.001

Table notes: The results of different surrounding avatar conditions on the feeling of time passage.

The results of the feeling of time passage are presented in Table 3.2 and Figure 3.11 3.12 3.13. For the dependent variable of the feeling of time passage, the result of the assumption showed that normality was violated.

Although the normality assumption was violated, we continued with ANOVA because of its robustness [147, 148].

The results showed that the feeling of time passage was significantly affected by two independent variables related to the surrounding avatar, the exercise speed (F(1.11, 30.06) = 116.99, $p <.001$, $\eta_p^2 = 0.437$), and the exercise intensity (F(1, 27) = 6.25, $p = .019$, $\eta_p^2 = 0.01$).

Figure 3.11: Main results of the exercise speed on feeling of time passage: Scores on exercise speed, exercise intensity, and participants' state, with error bars.

To explore the effects of the surrounding avatar's different exercise intensities and speeds on the feeling of time passage, we conducted a post hoc pairwise comparison with Bonferroni adjustment, and the results showed that faster speed led to a higher feeling of time passage (fast speed (M = 5.38,

SE = 0.144) >medium speed (M = 4.34, SE = 0.083) (t(1, 27) = 8.432, p <.001); medium speed >slow speed (M = 3.18, SE = 0.105) (t(1, 27) = 12.817, p <.001)).

Figure 3.12: Main results of the exercise intensity on feeling of time passage: Scores on exercise speed, exercise intensity, and participants' state, with error bars.

For the participants' states, there was no significant difference in the feeling of the time passage (F(1, 27) =0.02, p = .891, η_p^2 <.001). There was also no significant difference in duration (F(1.79, 48.45) = 1.82, p = .177, η_p^2 = .001). There was a significant interaction between speed and participants' state (F(1.78, 47.93) = 10.26, p <.001, η_p^2 = .008). Other interactions did not show any significant differences. Subsequently, we performed a post hoc Bonferroni correction for the interaction effect of the participant's state and

speed. The results showed that under the slow speed condition, the sitting state (M = 3.06, SD = 0.99) was significantly lower (t(27) = -2.305,p = .029) than the cycling state (M = 3.30, SD = 1.11). However, under the medium speed condition, the sitting state (M = 4.38, SD = 0.80) compared with the cycling state (M = 4.30, SD = 1.02) showed no significant difference (t(27) = 0.656, p = .518). Under the fast speed condition, the sitting state (M = 5.48, SD = 1.05) and the cycling state (M = 5.28, SD = 1.20) also showed no significant difference (t(27) = 1.683, p = .104).
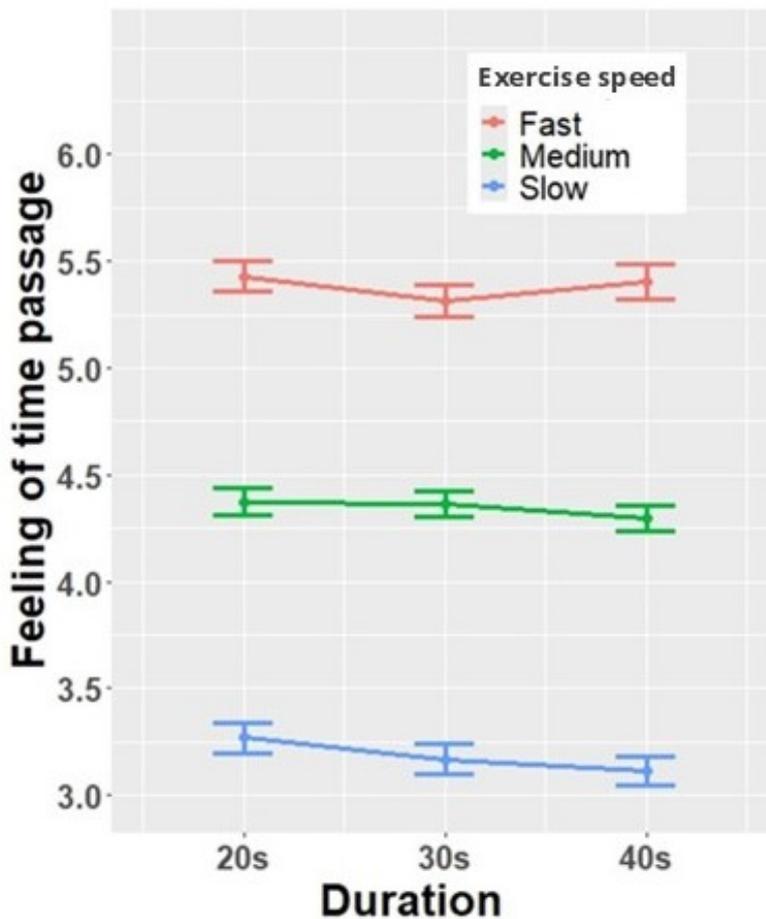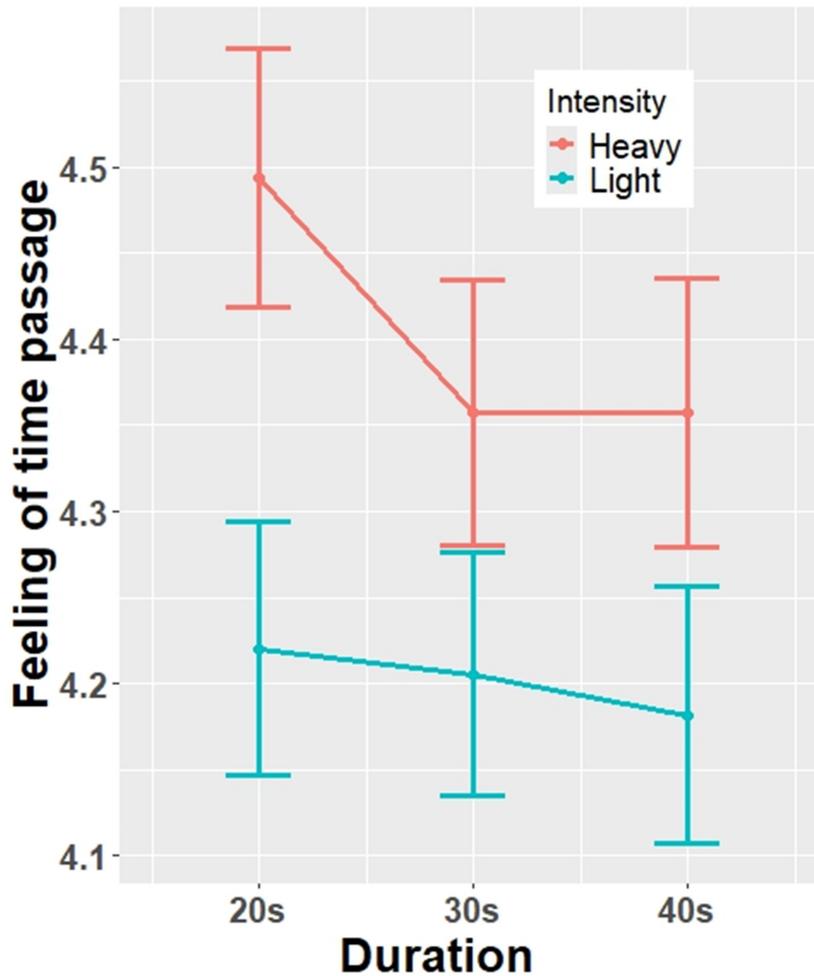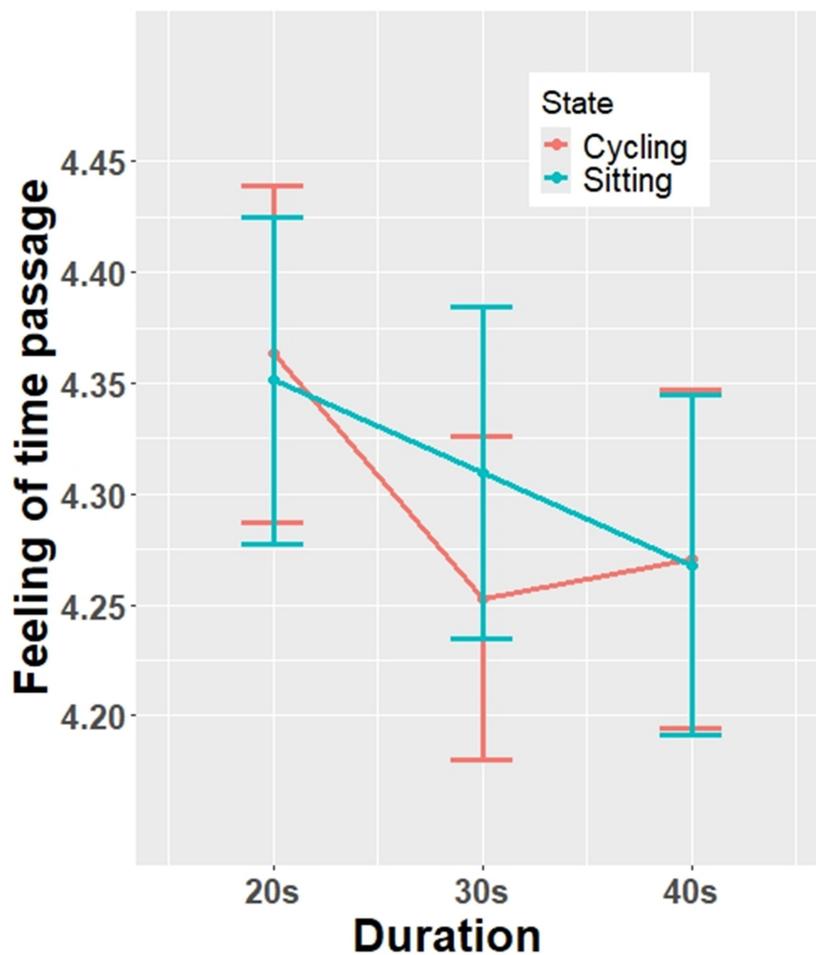

Figure 3.13: Main results of participants' state feeling of time passage: scores on exercise speed, exercise intensity, and participants' state, with error bars.

3.3.2.1 Post hoc power analysis on the feeling of time passage

To ensure that our sample size was adequate for detecting the expected effects, we conducted a post-hoc power analysis using statistical power and sample size calculation tools. Based on an effect size of 0.473, a significance level of 0.05, and a total sample size of 28 participants, the analysis yielded an actual power of 0.997 (99.7%). This power exceeded the typical 80% standard, indicating that our sample size provided a high level of statistical power for detecting significant effects.

3.4 Discussion

3.4.1 Summary of results

Our results strongly indicate that the attributes of the surrounding avatar significantly influenced the participants' time perception. For the hypothesis that the participants judge the duration longer in fast speed and high exercise intensity conditions compared to slow exercise speed and low exercise intensity conditions, responses to Q1 ("How long do you think you existed in the VR gym?") showed significant differences between conditions with varying exercise speeds, and the participants judged the duration to be longer in faster speed conditions. Thus, this result supports *H1-1*. However, the results did not show significant differences in the estimated duration between the two exercise intensity conditions; therefore, *H2-1* was rejected.

For the feeling of the passage of time, we hypothesized significant differences between the speed and exercise intensity conditions. Responses to "From your physical feeling, how fast is the time passage?" demonstrate significant differences between the different exercise speed conditions. Participants felt time passed faster in the fast speed condition than in the slow speed condition. Therefore, *H1-2* was supported. Meanwhile, for the exercise intensity conditions, high exercise intensity conditions led to a faster feeling of time passage. Therefore, *H2-2* is supported.

For *H3*, we hypothesized that participants' cycling states would lead to higher duration judgments and a faster feeling of time passage. However, our results did not align with our expectations, as the findings indicated no difference in time perception between the cycling and sitting states. One possible reason that in this study the surrounding avatar attracts almost all the attention of the participants is that participants cannot spare their

attention to cycling or not cycling, so the participants' state, cycling or sitting, cannot affect people's time perception.

3.4.2 Difference between duration judgment and feeling of time passage

In this section, we discuss the effects of surrounding avatars on time perception. Our results showed that exercise speed and exercise intensity played important roles in the participants' time perception. However, the two attributes had different effects: while the exercise speed affected both the duration judgment and the feeling of the passage of time, the exercise intensity only affected the latter. This difference may be due to the different mechanisms between duration judgment and the feeling of time passage. Droit–Volet et al. examined the relationship between duration judgment and the passage of time with concurrent measurements and duration judgment and found that the feeling of time passage should be considered distinct. Moreover, duration judgment and the feeling of the passage of time lack a direct connection [149]. Another study has also highlighted that duration judgment is affected by the internal clock, and when the pacemaker of the internal clock increases, the emitted pulses speed up, and the duration judgment will be longer. However, the passage of time is affected by experiential valence, arousal, attention to time, and time expectation [150]. As evidence, patients with depression experience a slowing down of time passage, although they do not exhibit any deficit in duration judgment compared to healthy individuals [151].

Based on these ideas, in the next two sections, we separately discuss the effects of the attributes of the surrounding avatars on the two dependent variables.

3.4.2.1 Duration judgment

Our experimental results demonstrated that the exercise speed of the surrounding avatars significantly affected duration judgment, whereas exercise intensity had no significant impact on duration judgment. One possible explanation is that duration judgments are often affected by the temporal attributes of stimuli and factors that are connected to temporal attributes, such as speed and frequency, but not by the magnitude of the stimuli. In Brown's research, participants observed various stimuli displayed on a monitor, and the speed and number of stimuli were manipulated. The results indicate that the former affected duration judgment, whereas the latter did

not affect the duration judgment [152].

Our results show a similar phenomenon. Regarding the speed of the surrounding avatars, faster-surrounding avatars made the visual stimuli move faster, which further resulted in a higher duration judgment. In addition to Brown's research, which was conducted using 2D monitors, the research conducted by Landeck et al. also supports our ideas. They demonstrated that altering the speed of a virtual tunnel shuttle influenced duration judgment [95].

For exercise intensity, while the high exercise intensity condition provided a high exercise intensity from visual stimuli because of the larger size of the barbell, it did not enhance the temporal attributes of stimuli, such as exercise speed or frequency, throughout each trial. Therefore, exercise intensity did not significantly affect the participants' duration judgment. Similar research can be found in a study conducted by Unruh et al., which provided varying levels of avatar embodiment and did not alter duration judgment [81].

3.4.2.2 Feeling of time passage

Our experimental results indicated that the surrounding avatar's exercise speed and exercise intensity affected participants' feelings of time passage. The comparison of temporal expectations is crucial in the feelings of the passage of time. This refers to the psychological phenomenon in which individuals anticipate or expect time consumption based on situational cues or prior experiences [153]. When people perceive that their subjective feelings of duration exceed their expected or anticipated duration, they often experience a sense of time dilation and perceive time as passing more slowly. Conversely, when the actual time falls short of the anticipated duration, individuals may feel that time passes more quickly, resulting in a sense of time compression. Discrepancies between anticipated and actual time duration represent pivotal determinants that influence individuals' feelings of time passage [154].

In this study, it is likely that participants used squats as a reference to judge time. Since squats were the only available stimulus, participants had a sense of how fast time passed.

For the exercise speed of the surrounding avatars, a fast-moving avatar shortens the duration of each squat. Therefore, for a fixed number of squats, the participants observed a shorter duration compared to the expected consumed time of those squats. This may explain why the participants

60

perceived the passage of time to be faster.

However, for the exercise intensity of the surrounding avatar, the expected time consumed for a one-time squat depended on the weight of the barbell. The expected consumption time for heavyweight materials may be considered greater than that for lightweight materials. At the same exercise speed, the participants observed the same duration for both exercise intensity conditions. However, the expected durations of the two exercise intensity conditions were different; therefore, the comparison between the observed and expected durations may be different. Consequently, the feeling of time passage was different, while the feeling of time passage in the high-intensity exercise group was higher than that in the low-intensity exercise group.

3.4.3 Relationship between participants' state and exercise speed

Our findings revealed a significant interaction effect between the participants' states (sitting or cycling) and the exercise speed of the surrounding avatar. This interaction affects duration judgment and the subjective feeling of the passage of time; thus, we suppose that it could be shared by the same underlying factor.

Specifically, the avatar's exercise speed and the participants' state jointly influenced the feeling of time passage and duration judgment. This could be due to the different exercise speeds of the surrounding avatars, which attracted the participant's attention to the VR gymnasium. For instance, as explained in the previous section, factors related to temporal clues affect people's judgments of duration and their feelings about the passage of time. Therefore, in the condition of fast exercise speed, the surrounding avatar's squatting speed attracts the participant's attention because there are many temporal clues released by the avatar's fast exercise speed. Thus, whether the participants stated cycling or sitting alone did not affect their time perception. The converse holds in the slower exercise condition; the slower exercise of the avatar provides less temporal stimulation, allowing participants to be affected by the surrounding avatar and cycling. During cycling, the brain processes more information, including temporal aspects, such as cycling frequency and body rhythm, which may contribute to a heightened perception of time. Previous studies have shown that physical activity can influence the judgment of duration. In contrast, when sitting, the lack of additional stimuli beyond the avatar may result in less pronounced effects on time perception [3, 87].

3.4.4 Compare with actual duration

Our results indicated that all experimental conditions on duration judgment were underestimated; even without the influence of surrounding avatars, participants consistently underestimated the duration in the reference conditions. This finding aligns with previous research on time perception in VR, which can distort an individual's perception of time, independent of other factors [155]. In VR, people often perceive that time passes more quickly because they lose access to natural time cues, such as bodily rhythms and environmental signals, like sunlight or other factors. This phenomenon has been observed in similar contexts; for example, Lugrin et al. found that people waiting in VR perceived time as shorter than waiting in the real world under identical conditions [79]. This also explains why nearly all the conditions for duration judgment were underestimated.

3.4.5 Contribution to VR design

Our findings suggest that the surrounding avatars in a VR gymnasium may strongly affect people's time perception. These findings may contribute to the design of VR in two ways.

3.4.5.1 VR gym

As mentioned above, painful sensations and time distortion resulting from vigorous exercise may indirectly affect one's willingness to continue exercising. Our study provides a possible solution to the issue of time distortion in VR gyms. For future VR gymnasium scenario designs, the designer may base the user's perspective on adjusting the parameters of the surrounding avatar's exercise speed and intensity in the VR gym. When users need to adjust their time perception, our study provides a scheme or possibility to change people's time perception. Adjust the surrounding avatar in the VR gymnasium to help them alleviate negative experiences from time distortion induced by exercise fatigue and to increase their willingness to complete their exercise goals. However, while this is a statistically valid method to adjust people's perceptions of time, it doesn't rule out individual differences.

3.4.5.2 A new zeitgeber

Another contribution is that our results indicated that surrounding avatars can be seen as a "zeitgeber." A zeitgeber is a thing that contains time cues

and can synchronize people's inner clocks and regulate their sense of time. Previous research has shown that virtual objects with explicit time cues, such as clocks and virtual objects performing pendulum exercise, can be seen as the "zeitgebers" [96]. In addition to non-living things, our findings showed that the participants used surrounding avatars, whose movements were not consistently static, to judge the duration. Thus, the surrounding avatar can be recognized as a zeitgeber in VR.

3.5 Conclusion

This study explored the effects of the surrounding avatar's exercise speed and intensity on time perception in a VR gym. We demonstrated that the exercise speed of the surrounding avatars significantly influenced both the judgment of duration and the feeling of the passage of time. Faster exercise speeds led to longer judgments and a faster perceived passage of time. However, exercise intensity only influenced the perception of time passage, with higher intensity leading to a faster perceived passage of time, but not affecting duration judgment.

Additionally, our findings suggest that the interaction between the participants' states (cycling or sitting) and the exercise speed of the surrounding avatars can influence time perception. In particular, the effect of exercise speed on time perception was more pronounced when participants were cycling, likely because of the additional temporal stimuli provided by the physical activity.

Our research provides valuable insights for designing future VR gyms, suggesting that adjusting the parameters of the surrounding avatars can help alleviate negative experiences of time distortion and increase users' willingness to continue exercising. Furthermore, this study introduces the concept of surrounding avatars as potential "zeitgebers" in VR environments, offering a new perspective on how time cues can be integrated into virtual settings to regulate the users' sense of time.

In the next chapter, I will do the experiment about the effects of the surrounding avatar design on user's physical activity and perceived exertion in VR gyms.

Chapter 4

The effect of the surrounding avatar design on participants' physical activity and exertion perception

4.1 Introduction

Recently, virtual reality (VR) technology has rapidly advanced in the field of exercise and fitness. Through head-mounted displays (HMDs) that provide immersive environments, VR has been shown to promote physical activity [7], optimize exercise performance [32], and contribute to physical rehabilitation [8]. VR has also been shown to affect users' behaviors and engagement across different contexts [156], which suggests that its application in exercise settings may similarly shape how users interact with virtual environments. Especially in VR gym environments, users receive continuous visual feedback through HMDs while interacting with virtual objects and avatars, making visual stimuli critical in shaping exercise experiences and performance outcomes [157, 158].

In a real gym, people's perceived exertion should align with the actual exercise intensity. However, previous research has shown that exercise outcomes are not determined by physical activity alone but are also shaped by additional contextual and environmental factors [159]. Therefore, it is difficult to focus solely on exercise while ignoring distracting visual and social stimuli, during exercise. Previous research indicated that the social relationships and interactions within a gym can influence whether people use the gym and how they use the gym [160]. For example, Schvey et al. found that overweight and obese people are usually affected by other gym members' weight stigma, such as being judged or feeling watched, which

64

contributes to producing negative effects on their attitude and psychological health [161]. The weight stigma also affects people's exercise motivation and behavior [162]. These studies indicated that beyond physical effort, the social presence of others in the gym can shape users' exercise experiences as well [161]. The presence of others often triggers social comparison effects in exercise, influencing individual behaviors from a psychological perspective [15]. Actually, weight stigma can be seen as a form of negative social comparison, where individuals perceive themselves as disadvantaged relative to others. According to social comparison theory, individuals tend to evaluate their abilities and performance by comparing themselves to others [101]. This comparison is typically categorized into upward and downward comparisons. When people compare with someone who has better performance, they will engage in upward comparison, which can improve their motivation. In contrast, when compared with someone who performs worse, it results in downward comparison, which will enhance their confidence but decrease their performance. For social comparison on exercise situations, others' dynamic attributes, such as exercise speed, may serve as key determinants affecting users' physical activity and perceived exertion. However, the visual representation of avatars can be controlled to affect users' behavior. For example, avatars wearing face masks in a VR supermarket led users to maintain longer interpersonal distance, indicating that avatars' visual features can convey social information that influences user behavior [48]. Therefore, the avatar may provide opportunities to alleviate such negative effects and improve the exercise experience in the VR gym, which is difficult to realize in the real world.

Regarding the visual representation of the avatar, body composition is an important factor for people to produce social comparison effects. Lewallen et al. demonstrated that avatars, characterized by athletic body composition and fluid motion, increase users' inclination to upward social comparison, thereby encouraging users to produce more motivation and then put more effort into exercise [163]. Body composition is defined as the distribution of fat mass and lean body mass [126]. It conveys cues about physical capabilities, such as strength or endurance [127]. For example, Peña and Kim examined that playing against an overweight avatar decreased the user's physical activities in tennis games [51]. A downward social comparison occurred because the overweight opponent avatar was perceived by users as less skilled and having lower physical ability.

In addition, the avatar's exercise speed may also play a crucial role in social comparisons. For example, Max et al. demonstrated that when users cycled alongside a consistently fast-moving avatar, their exercise duration

65

increased compared to scenarios involving avatars with fatigue characteristics or solo exercise [131]. Exercise speed is a critical parameter that typically reflects physical exertion and conveys the exercise performance information. This dynamic visual stimulus is more likely to elicit competitive behavior or self-assessment compared to static characteristics. For example, Wang et al. found that with high-performing exercise partners, such as rapid squat speeds, users tend to compare their own performance with it, affecting their perception of exertion [132]. Similarly, Barathy et al. reported that when users competed against a virtual opponent modeled on their previous cycling speed, their performance improved while maintaining intrinsic motivation [133]. These findings suggest that in VR exercise settings, exercise speed not only serves as a key driver of social comparison but also plays a significant role in enhancing exercise motivation. Overall, this effect mainly stems from upward comparison; avatars with fast exercise speed can serve as a benchmark that improves their own performance and motivation.

Although previous studies have examined the effects of surrounding avatars on users' exercise behavior, these avatars usually have an explicit social relationship with the user, such as training partners [57], coaches [164], or direct competitors [51, 131, 132]. These studies are based on the task consistency, such as users performing the same cycling or squatting task with a virtual opponent, which triggers competition, and then the user's performance and motivation improve. However, in the real gym, users often do not directly interact or share tasks with others, yet social comparisons may still occur due to the presence of others. Similarly, in a VR gym, surrounding avatars that co-exist in the space with the user but have no direct relationship with the user may also act as implicit social referents, influencing the user's physical activity and perceived exertion during exercise. Meanwhile, the surrounding avatar is different from real exercisers in the gym, which allows researchers to manipulate the avatar's static and dynamic features. In other words, the surrounding avatars provide controllable manipulation of social information for social comparison in the VR gym, compared with a real gym situation. Furthermore, although some studies have indicated that social comparison can lead to long-term behavioral effects, such as in academic achievement contexts [165], research on VR exercise environments has mostly focused on immediate, short-term influences. It remains unclear whether the effects of surrounding avatars persist after they leave the VR environment.

Therefore, this study investigates how the visual representation of surrounding avatars in the VR gym, specifically their exercise speed and body composition, affects users' physical activity and perceived exertion based on social comparison effects. During the social comparison effects, when users

66

perceive that surrounding avatars have better physical performance than themselves, they may exert themselves in exercise. If users perceive that the surrounding avatars have worse performance on exercise, they may also decrease their physical activities. By focusing on dynamic visual stimuli presented through HMDs. This research aims to advance our understanding of the effects of surrounding avatars' visual representation on users' physical activity and perceived exertion, and aims to provide information on how to optimize the surrounding avatar design in the VR gym. Furthermore, this study also examines whether the effects of social comparison persist after the surrounding avatars are left, and whether social comparison keeps affecting users' physical performance.

4.2 Method

To better understand the effect of surrounding avatars on the user's physical activity and exertion perception in the VR gym, we focused on two visual characteristics of exercise speed and the body composition of the surrounding avatars. For surrounding avatar design, we followed the previous research's method that manipulated fixed body parameters in virtual environments [166], and applied a similar operationalization approach in the VR gym context. Additionally, we focused on three stages during the exercise to further investigate if there would be an ongoing effect on the user's physical activity and exertion. The entire experiment was conducted in a VR gym. The cycling task was chosen for our study because it is a common exercise activity in the gym and is relatively safe when wearing a head-mounted display (HMD) while cycling. Based on the social comparison effects, the following hypotheses were formed:

- `H1`: The fast speed condition of the surrounding avatar leads to an increase in the participant's physical activity (H1-1) and higher perceived exertion (H1-2).

- `H2`: The overweight body composition condition of the surrounding avatar leads to the participants' physical activity decrease (H2-1) and lower perceived exertion (H2-2).

- `H3`: When the surrounding avatars leave, the effect of the surrounding avatars lasts on the participant in exercise.

This experiment aims to investigate the effects of the surrounding avatar's

67

Figure 4.1: VR gym used in the experiment.

condition on exercise speed, body composition, and the experimental stages on participants' physical activity and perceived exertion. We experimented with the design, using within-participant and three independent variables. The first condition was exercise speed with two levels: I) slow speed and II) fast speed. The treadmill running was chosen as the surrounding avatars' activity to enable participants to more clearly perceive the relationship between body composition and exercise speed. The animations for the surrounding avatar were sourced from Mixamo [1]. Two types of animation were used: "slow running" [2] and "running" [3] animation. Animations were controlled using the Unity3D animation controller, with playback speeds adjusted to 1.2 times and 0.8 times the original rate to create the fast and slow exercise speeds of the surrounding avatar. The original animation was set to 24 frames per second (FPS), and the adjusted playback speeds corresponded to 28.8 FPS (fast speed condition) and 19.2 FPS (slow speed condition), respectively. This adjustment ensured a perceptible distinction between the

---

[1]The Mixamo website, which provides animation. https://www.mixamo.com/#/?page=1

[2]The animation of "slow running" https://www.mixamo.com/#/?page=1&query=slow+running

[3]The animation of "running" https://www.mixamo.com/#/?page=1&query=run
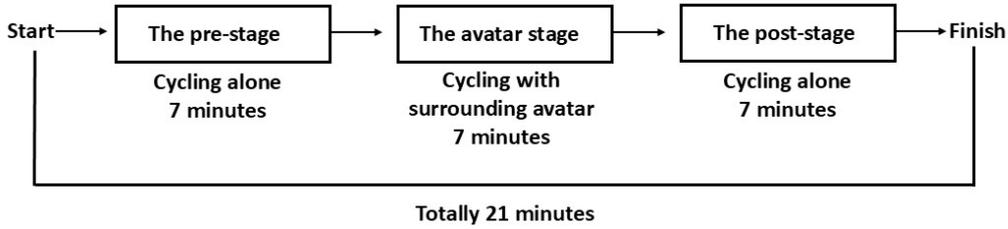
Figure 4.2: The experiment with three stages in one session

fast and slow speeds of the surrounding avatars.

To manipulate the surrounding avatar's body composition, the parameters were adjusted in Daz Studio. For the normal weight condition, the parameters were set: Bodybuilder (100%), Bodybuilder details (100%), Bodybuilder size (75%), Emaciated (100%), Portly (0%). For the overweight body condition, only the Emaciated (0%) and Portly (100%) dimensions were different from normal weight. This design corresponds to the World Health Organization's classification of body composition: normal weight ($18.5 \leq BMI < 25$) and overweight ($BMI \geq 25$) [167]. To ensure the surrounding avatar design has the visual representation we need for the experiment, a survey of people's perception of avatar body composition was conducted, in which participants rated avatar body composition on a 7-point Likert scale (1 = Very Thin, 7 = Very Overweight).

The questions used in the survey were the following:

- Q1: Please rate their body composition on a scale of 1-7 based on your perception.

We analyzed the scores that people reported on "The Survey of People's Perception of Avatar Body Composition." The result shows that the body composition of the surrounding avatar is a significant difference, $F(1,32) = 99.441$, p <.001, $\eta_p^2 = 0.76$. That indicates that the surrounding avatar is perceived by participants as two different body compositions. The mean value of the two different body compositions surrounding the avatar, overweight = 5.82 and normal = 3.82. Based on "The Survey of People's Perception of Avatar Body Composition," our self-created avatar can be seen as having "overweight" and "normal" body composition.

The last independent variable was the stage. We subjectively divided the entire experiment session into three stages, as shown in Fig. 4.2: (I)

69
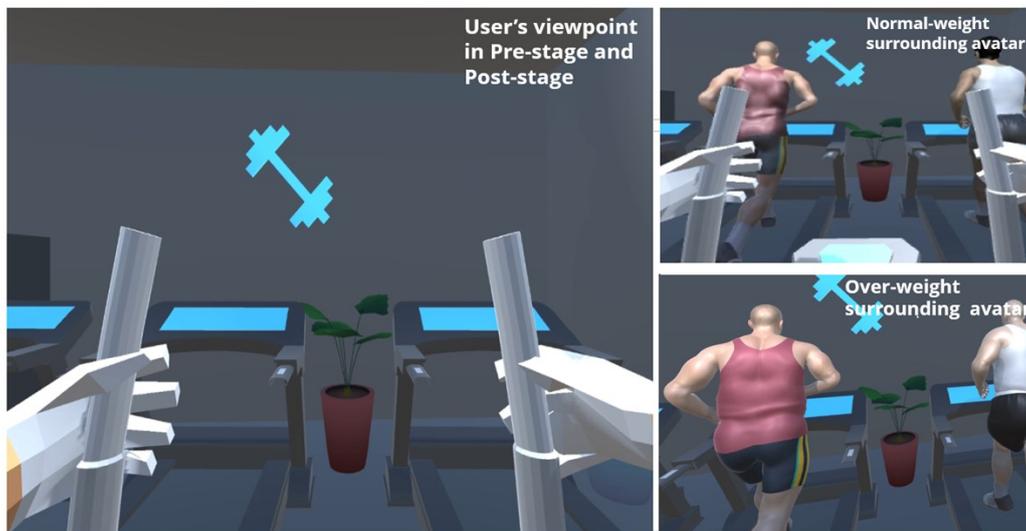
Figure 4.3: The participant's view in the experience and two differences of body composition surrounding the avatar.

pre-stage, (II) avatar-stage, and (III) post-stage. Each stage will last for 7 minutes, allowing participants' heart rates to reach a steady state and to maintain consistent exercise effects [168]. The pre-stage means that when one session starts, at the first stage, there is no surrounding avatar inside the VR gym and the participant will cycle alone. The avatar stage refers to the point after the pre-stage, where the surrounding avatar appears in the VR gym and walks to the treadmill. After that, while running on the treadmill, the participant will cycle alongside the surrounding avatar. The post-stage means that the surrounding avatar leaves the VR gym, and the participant cycles alone again.

4.2.1 Software and hardware

A fitness bike (ALINCO, AFB6119) with a magnetic load system was used for participants to cycle during the experiment. This fitness bike has a maximum load capacity of 120 kg and offers a range of sports modes. The experimental system ran smoothly on a desktop PC (Intel(R) Core™ i7-12700, 16 GB RAM, NVIDIA GeForce RTX 3060). We used the Meta Quest 3 as the HMD device to provide participants with a truly immersive virtual experience. This HMD features a 110° field of view, a resolution of 2064 × 2208 pixels per eye, and a refresh rate of 120 Hz.

To create the experimental environment, we selected Blender (v. 3.6.5.0) as the primary tool for 3D modeling and Unity 3D (v. 2021.3.9f1) as the primary development tool. Using 3D modeling, we constructed a VR gymnasium environment containing various training devices, such as treadmills, barbells, and chest press machines. Unity3D was used to create the entire environment, arrange the positions of each training device, and develop the VR application (Fig. 4.1). We created the VR gym with a first-person perspective for participants, and the surrounding avatar was created by DAZ Studio (v. 4.22), shown in Fig. 4.3.

An experimental room was set up to enable participants to conduct experimental tasks safely in the VR gym. A bicycle station was placed within the experimental area, allowing participants to participate in experimental tasks while immersing themselves in the VR gym.

4.2.2 Participants

We recruited 33 participants for the experiment through an online communication group. Two participants dropped out of the experiment due to physical condition problems. The recruitment period ran from September 18 to October 21, 2024, and was conducted from September 21 to October 30. The average age was 26 years, with a standard deviation of 2.4 years. Among the participants, there were 9 women and 24 men. According to their self-reported height and weight, the average BMI was 22.7. Based on the WHO classification, only 2 participants were obese, and the other participants were of normal weight. The participants reported normal or corrected-to-normal vision. All participants were unaware of the purpose of the study. All provided their informed consent in writing and were free to withdraw at any time during the experiment. This experiment was approved by the Research Ethics Committee of the Japan Advanced Institute of Science and Technology and was conducted in strict compliance with the content. The ethical approval number is Hito 04-053.

4.2.3 Procedure

First, participants signed a consent form after the experiment was explained. They then completed a demographic questionnaire to provide basic information. Second, participants wore disposable socks and indoor sneakers. The experiment conductor assisted participants in putting on the required devices, including a Garmin watch and a Bitalino physiological signal collector. The height of the bike seat was adjusted to fit each participant, and they wore the HMD with the help of the experiment conductor (Fig. 4.4).
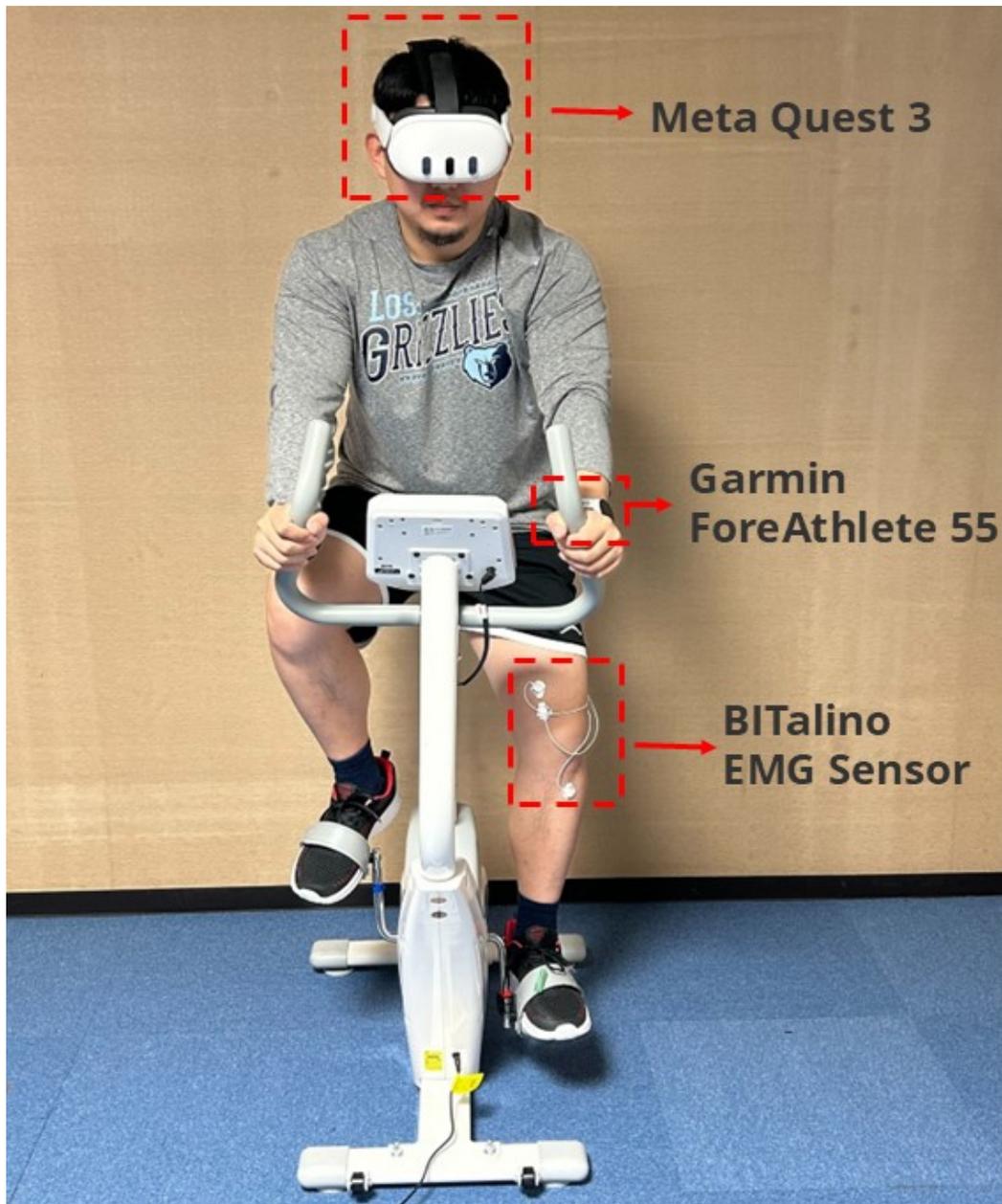
Figure 4.4: During the experiment, the participant is cycling a stationary bike while wearing the Meta Quest 3 VR headset and a Garmin ForeAthlete 55 sports watch. The BITalino EMG sensor is attached to the participant's thigh.

Participants began with a practice session to familiarize themselves with the task. This session replicated the structure of the main experiment, consisting of three stages, each lasting 2 minutes, for a total of 6 minutes. During the practice session, participants were asked to rate their perceived exertion (RPE) every 30 seconds. After the practice session, the participants had 5 minutes to rest and the main session started.

The main session lasted 21 minutes and followed a three-stage structure, with each stage lasting approximately 7 minutes. The participant sat on the bike and viewed a hint scene that read: "The experiment will start in 10 seconds. When you enter the VR gym, the experiment starts and please start cycling." They then entered the pre-stage, where they cycled alone for 7 minutes. At the end of this stage, the surrounding avatar appeared, walked past the participant on a treadmill, and began running in front of them. After 7 minutes in the avatar stage, the avatar exited the VR gym, leaving the participant to cycle alone during the post-stage.

Throughout the main session, participants were asked the RPE question orally every 3 minutes through three stages. Upon completion of all three stages, one session was concluded. Each participant completed a total of four sessions, with the order of the sessions counterbalanced across participants. At the end of each session, participants completed a self-fitness report questionnaire and rested for 15 minutes before the next session. To minimize fatigue associated with long-term exercise, the experiment was conducted over two consecutive days, with participants completing two daily sessions.

During the experiment, the participants' perceived exertion was evaluated using the RPE scale. Furthermore, physiological signals, heart rate(HR), and electromyography(EMG) were measured. Additionally, the pedaling frequency can be measured to determine the participant's cycling speed. Lastly, self-perceived fitness (SPF) was used to measure how the surrounding avatar affects the participant's self-feeling of fitness in each experiment session.

4.2.4 Measures

4.2.4.1 Heart rate

Heart rate (HR), measured in beats per minute (bpm), is a critical physiological indicator that reflects an individual's physical activity during exercise. To assess HR, we used a Garmin watch (ForeAthlete 55, Garmin, Japan), a wrist-worn optical heart rate monitor known for its safety, convenience, and accuracy, particularly during high-intensity physical activity. HR data

were continuously recorded throughout the four experimental sessions at a sampling rate of 1 Hz. The collected HR data (bpm) were analyzed to examine the impact of the surrounding avatars' conditions on participants' HR dynamics while cycling.

4.2.4.2 Pedaling frequency

To investigate how visual stimulation of exercise speed and the body composition of surrounding avatars affects participants' physical performance in cycling, pedaling frequency was recorded in revolutions per minute (RPM). A cadence sensor (Cadence Sensor 2, Garmin, Japan) was attached to the pedal of the stationary bicycle to measure pedaling frequency. The sensor continuously recorded cadence data at a sampling rate of 1 Hz. The average pedaling frequency per second (RPM/s) was calculated for analysis. This device was chosen for its accuracy and reliability in measuring pedaling frequency throughout the experiment.

4.2.4.3 Perceived exertion

Perceived exertion was measured using the updated 11-point version of the Rate of Perceived Exertion (RPE) scale [169]. This scale, derived from the original Borg RPE scale (6–20 scale) [170], was chosen for its simplicity and effectiveness in capturing perceived effort. Participants were asked to report their RPE score, ranging from 0 (without effort) to 10 (maximal effort), every three minutes during each cycling session. To ensure clarity and consistency, the RPE questions were displayed in Chinese, and the participants received a detailed explanation of the scale before the experiment.

The RPE question used in the experiment was the following:

- Q1: How hard do you feel you are cycling right now? Please answer orally.

After reading the experimental instructions, all participants confirmed their understanding of the RPE questions.

4.2.4.4 Self-perceived fitness

The Self-Perceived Fitness (SPF) questionnaire [171] was administered after each experimental session to assess participants' subjective feelings about

their fitness and perceived changes after cycling. The questionnaire, adapted from Delignieres et al. [172], evaluates five dimensions of fitness: endurance, strength, flexibility, body composition, and general fitness. Participants rated their fitness on a 13-point scale ranging from 1 (low) to 13 (high).

4.2.4.5 Electromyography

Electromyography (EMG) was used to measure muscle activation in participants during exercise. Thus, we measured the EMG to investigate the muscle activation of the participants during the experiment session, which was recorded using the BITalino (r)evolution Plugged kit (PLUX Wireless Biosignals, Portugal). The EMG electrodes were placed on the quadriceps of the dominant leg following standard electrode placement guidelines, as shown in Fig. 4.5. The EMG signals were sampled at a frequency of 1000 Hz and recorded in microvolts (μV), ensuring high-resolution data collection. To quantify muscle activation levels, root mean square (RMS) values (μV) were calculated for each minute.

4.2.4.6 Statistical analysis

To evaluate the effects of the exercise speed and body composition of the surrounding avatar and the stage as the independent variables, we set the data of the pre-stage as a covariate to control for individual differences at the start of the experiment. The dependent variables were perceived exertion, HR, pedaling frequency, and EMG. We used repeated measures mixed effects analysis of covariance (ANCOVA) to account for repeated measures and control for baseline differences in dependent variables. Only for the dependent variable of SPF, we used ANOVA to analyze the data. The normality was then tested using the Shapiro-Wilk test. Sphericity was assessed using Mauchly's test, and appropriate corrections were applied when violations were detected. All analyses were done using the R programming language in RStudio as the development environment.

When significant main or interaction effects were observed, simple effects tests with estimated marginal means (EMMs) and Tukey's HSD correction were conducted. To examine whether the avatar effects persisted after their disappearance, simple effects tests were also performed across the three stages (pre, avatar, and post). Normality was assessed with the Shapiro–Wilk test, and sphericity with Mauchly's test, with appropriate corrections applied when assumptions were violated. All analyses were conducted in R with

75
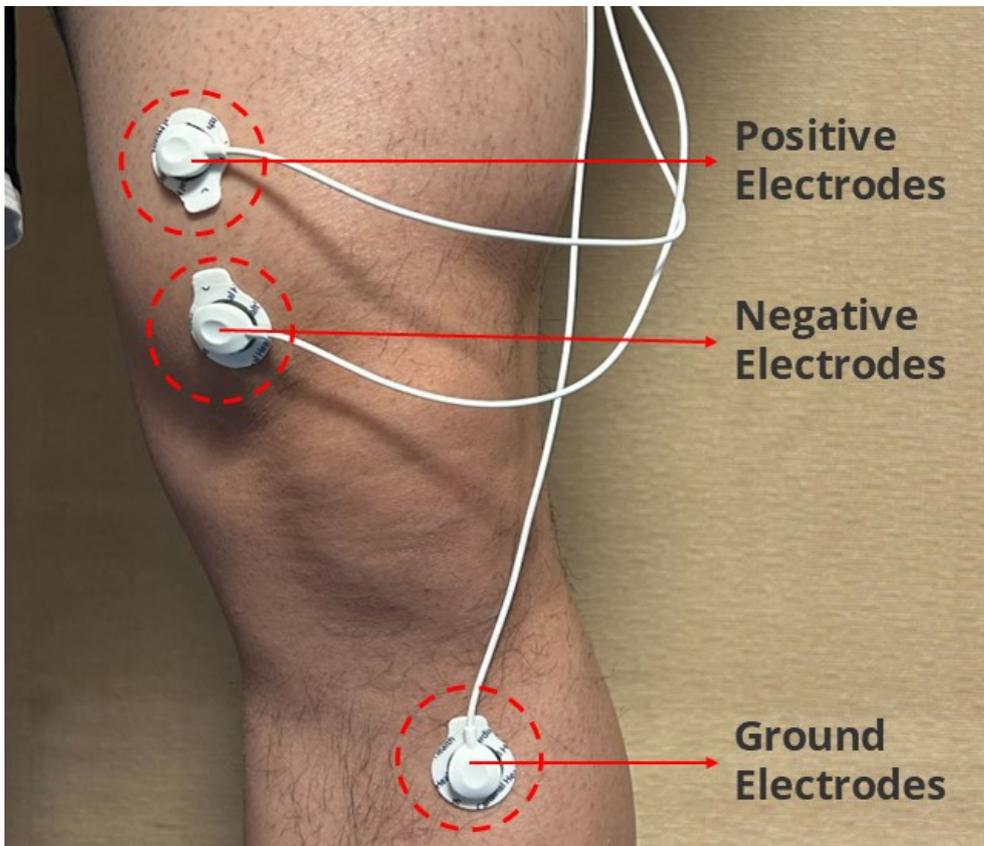
Figure 4.5: EMG Electrode stuck on the participants' medial side of the thigh's quadriceps muscle. The upper electrode is the positive electrode, the middle electrode is the negative electrode, and the lower electrode serves as the ground electrode.

RStudio as the development environment.

4.3 Result

For the Results part, due to the device disconnecting during the experiment, data from three participants were excluded from the heart rate and pedaling frequency analysis, and data from five participants were excluded from the EMG analysis. For the result of the assumption, although several conditions violated the normality test, we also proceeded with mixed ANCOVA because it is quite robust in terms of normality [147, 148].

4.3.1 The result of avatar stage

4.3.1.1 Heart rate

To examine how exercise speed and body composition of the surrounding avatar affect the participant's HR, we analyzed the average HR in each stage under each experimental condition. The average HR in each minute is shown in Fig. 4.6.

The result of mixed ANCOVA revealed that exercise speed, $F(1, 182.47)$ = 1.33, p = .25, η_p^2 = .007, and body composition, $F(1, 181.89)$ = 0.01, p = .927, η_p^2 <.001, did not show any significant difference on users' HR. However, the stage exhibited a significant difference, $F(1, 181.84)$ = 5.39, p = .21, η_p^2 = .03. And the interaction effect was found between the surrounding avatar's exercise speed and body composition, $F(1, 187.84)$ = 9.65, p = .002, η_p^2 = .12. However, no other interaction effects were found: exercise speed and stage, $F(1, 181.42)$ = 1.47, p = .228, η_p^2 = .008, body composition and stage, $F(1, 181.42)$ = 0.08, p = .783, η_p^2 <.001. Also, there was no three-way interaction effect among exercise speed, body composition and stage, $F(1, 181.42)$ = 0.05, p = .832, η_p^2 <.001.

To further investigate the effects of body composition and exercise speed on users' HR, the simple effect test using EMMs was conducted, with Tukey's HSD correction applied. The result is shown in Fig. 4.7. The result showed that within fast exercise speed conditions, users exhibited a significantly higher HR when cycling with an overweight avatar(M = 116, SE = 1.22) than a normal weight avatar (M = 114, SE = 1.22), $t(43.5)$ = 2.066, p = .045. Conversely, within the slow exercise speed conditions, HR was significantly lower with an overweight avatar (M = 113, SE = 1.22) compared to a normal weight avatar (M = 115, SE = 1.23), $t(44.9)$ = -2.180, p = .035.

4.3.1.2 Pedaling frequency

To examine the effects of exercise speed and body composition of the surrounding avatar on pedaling frequency, the average pedaling frequency for each minute was calculated and evaluated for each condition. After that, we analyzed the average value of pedaling frequency at each stage under each condition. The average data of pedaling frequency under each condition is shown in Fig. 4.8.
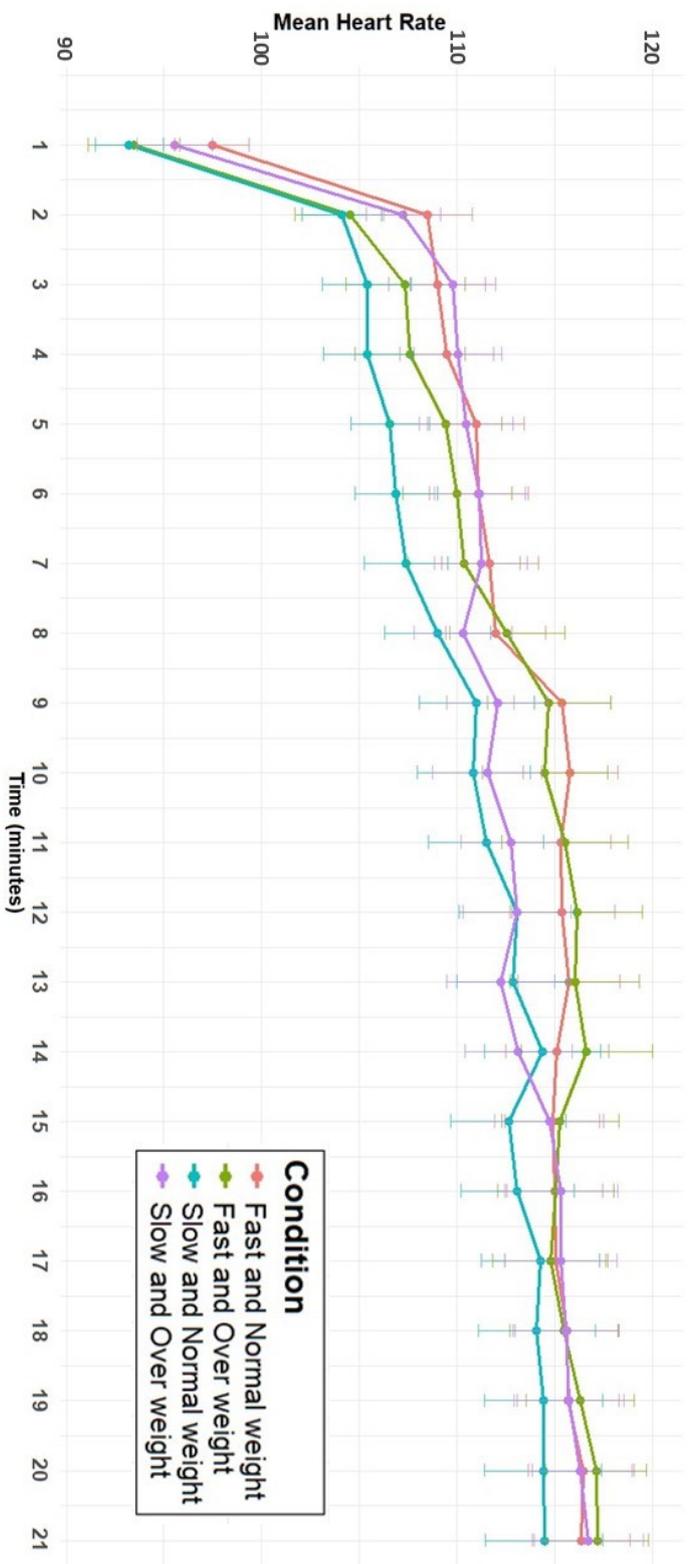
Figure 4.6: The average heart rate per minute under four different conditions with error bar: Fast and Normal weight, Fast and Overweight, Slow and Normal weight, and Slow and Overweight.
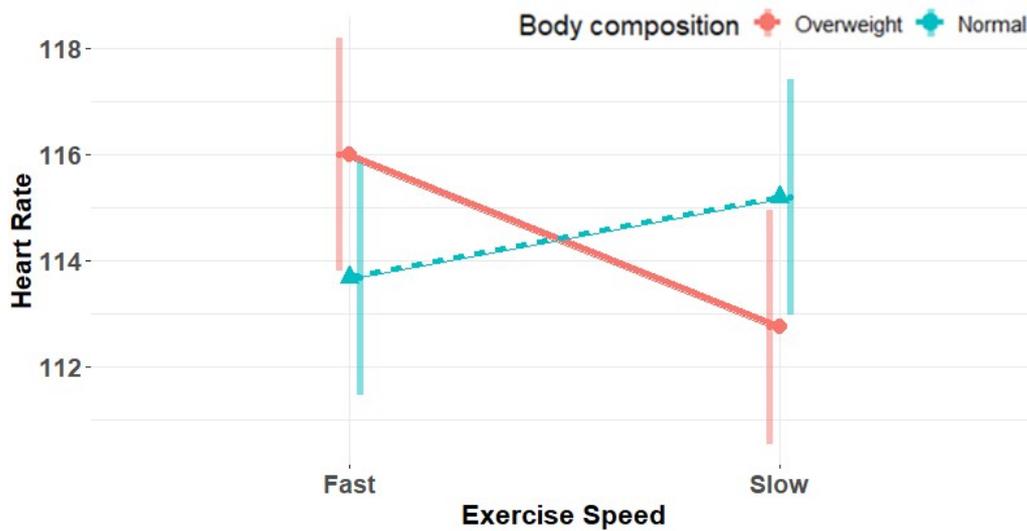
Figure 4.7: The interaction effect of exercise speed (Fast and Slow) and body composition (Normal and Overweight) on participants' heart rate while cycling in VR gym with error bars.

The mixed ANCOVA results revealed a significant main effect of the exercise speed, $F(1, 185.46) = 6.22$, $p = .013$, $\eta_p^2 = .03$, on the user's pedaling frequency. Both the body composition, $F(1, 185.46) = 2.73$, $p = .1$, $\eta_p^2 = .01$, and stage, $F(1, 185.46) = 0.19$, $p = .664$, $\eta_p^2 < .001$, did not have any significant difference and also no interaction effects were found: exercise speed and body composition, $F(1, 185.43) = 0.001$, $p = .990$, $\eta_p^2 < .001$, exercise speed and stage, $F(1, 185.43) = 1.3$, $p = .256$, $\eta_p^2 = .007$, body composition and stage, $F(1, 185.43) = 0.001$, $p = .971$, $\eta_p^2 < .001$. Moreover, there were also no three-way interaction effect among exercise speed, body composition and stage, $F(1, 185.43) = 0.01$, $p = .913$, $\eta_p^2 < .001$. These results indicated that the surrounding avatar's exercise speed significantly affected the participants' pedaling frequency during the avatar stage.

4.3.1.3 Perceived exertion

To investigate the effects of exercise speed and the body composition of the surrounding avatar on the participant's perceived exertion while cycling in a VR gym. We analyzed the data of the perceived exertion average value at each stage throughout the experiment. The average data of perceived exertion under each time is shown in Fig. 4.9 and Fig. 4.10.

79
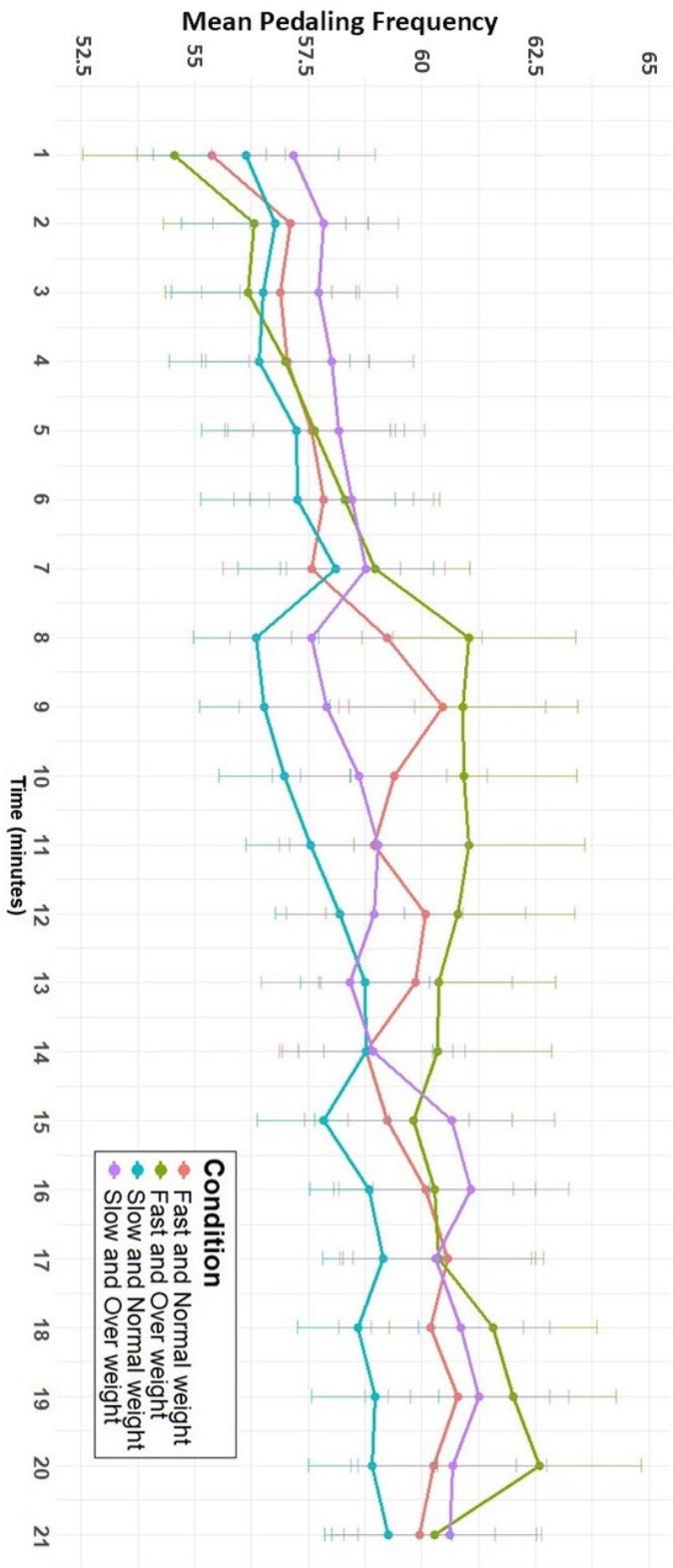
Figure 4.8: The average Pedaling Frequency under different conditions with error bars.

80
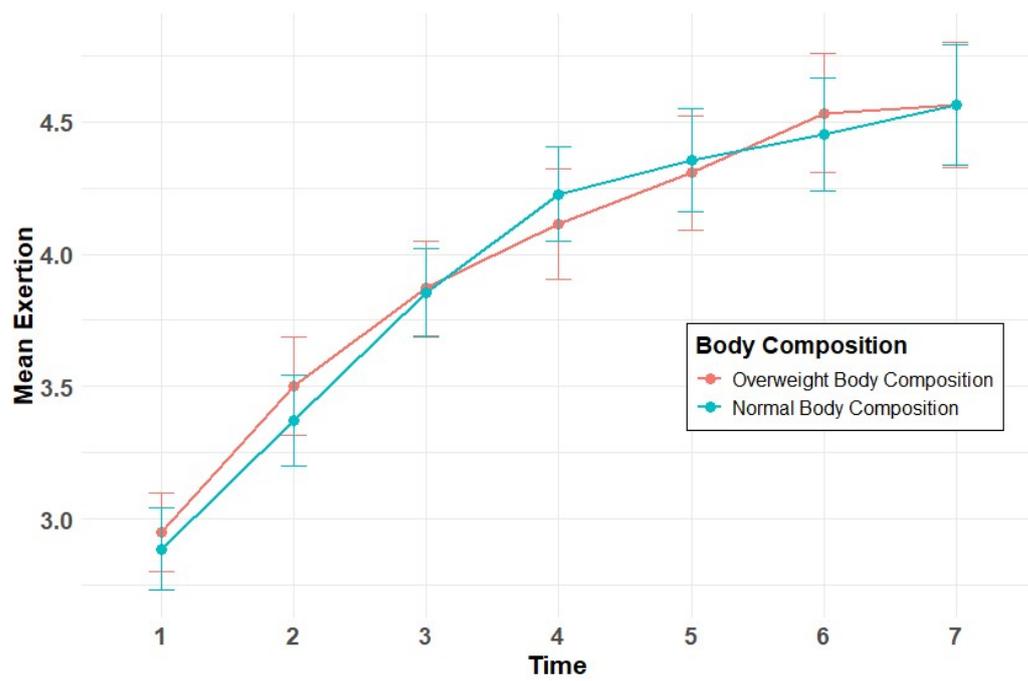
Figure 4.9: Mean exertion ratings over time under body composition with error bars.

The mixed ANCOVA results did not reveal any significant effects, the exercise speed of the surrounding avatar, $F(1, 209) = 1.67$, $p = .198$, $\eta_p^2 = .008$, body composition, $F(1, 209) = .63$, $p = .427$, $\eta_p^2 = .003$, the stage, $F(1, 209) = 2.05$, $p = .154$, $\eta_p^2 = .01$. Additionally, there were also no interaction effects observed on perceived exertion between exercise speed and body composition, $F(1, 209) = 0.42$, $p = .518$, $\eta_p^2 = .002$, exercise speed and stage, $F(1, 209) = 0.10$, $p = .749$, $\eta_p^2 < .001$, body composition and stage, $F(1, 209) = 0.38$, $p = .538$, $\eta_p^2 = .002$. Moreover, there was also no significant difference found in the three-way interaction effect among exercise speed, body composition and stage, $F(1, 209) = 0.001$, $p = .961$, $\eta_p^2 < .001$.
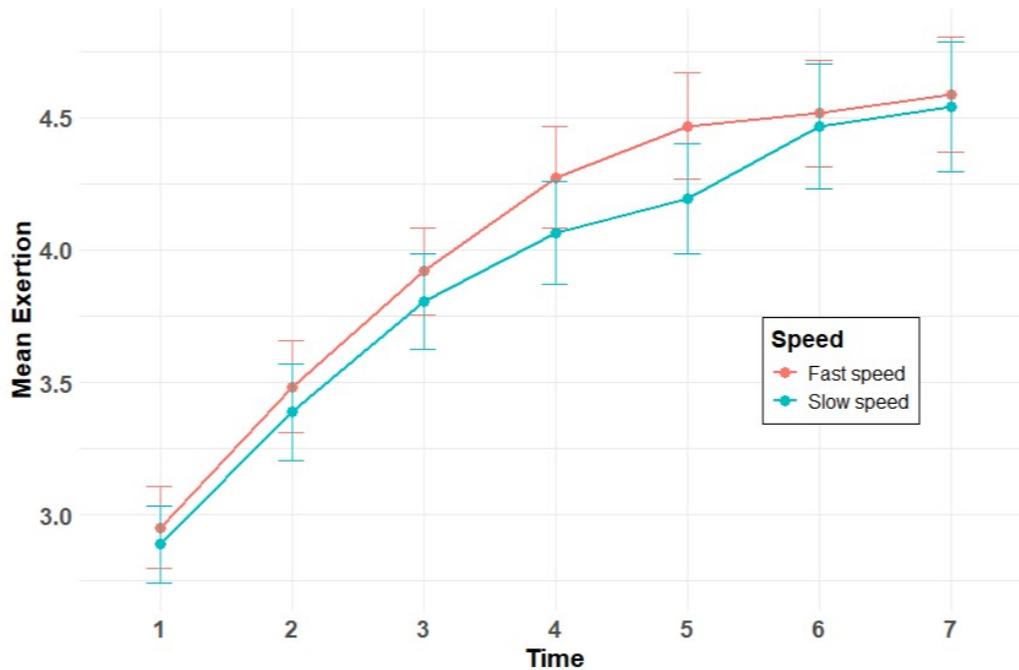
Figure 4.10: Mean exertion ratings over time under exercise speed with error bars.

4.3.1.4 Electromyography

We investigated the effects of the surrounding avatars' exercise speed and body composition on the EMG activity while participants cycled in the VR gym. First, we calculated the root mean square (RMS) value of the EMG signal and then calculated the average RMS value for each minute in each

session to quantify the participant's quadriceps activation. The average data of EMG under each condition is shown in Fig. 4.11.

The result of mixed ANCOVA revealed no significant main effects shows of exercise speed, $F(1, 204) = 0.004$, p = .843, $\eta_p^2 < .001$, body composition, $F(1, 204) = 0.003$, p = .955, $\eta_p^2 < .001$, and stage, $F(1, 204) = 0.61$, p = .436, $\eta_p^2 = .003$. However, the interaction effects between the exercise speed and body composition of the surrounding avatar were found, $F(1, 204) = 9.02$, p = .003, $\eta_p^2 = 0.04$. No other conditions show any significant interaction effects, exercise speed and stage, $F(1, 204) = 0.31$, p = .579, $\eta_p^2 = .002$, body composition and stage, $F(1, 204) = 0.04$, p = .852, $\eta_p^2 < .001$. Also, there were no three-way interactive effects, exercise speed, body composition, and stage, $F(1, 204) = 0.11$, p = .714, $\eta_p^2 < .001$.

To further examine the interaction between body composition and exercise speed, the simple effects test and EMMs were conducted for each exercise speed to compare differences in body composition. The result is shown in Fig.4.12. Under the fast exercise speed condition, the overweight body composition (M = 27.5, SE = 0.979) exhibited significantly higher values than the normal weight body composition (M = 24.5, SE = 0.979), $t(180) = 2.160$, $p = .032$. However, under the slow exercise speed condition, the normal body composition condition (M = 27.0, SE = 0.979) exhibited significantly higher values than the overweight body composition (M = 24.8, SE = 0.989), $t(180) = -2.090$, $p = .038$.

4.3.2 The result of post stage

4.3.2.1 Heart rate

To examine whether the effect of the surrounding avatar remains consistent after the avatar leaves the VR gym, we conducted a paired-sample t-test to compare the three different stages.

A significant difference was observed between the pre-stage (M = 107, SE = 0.696) and the avatar stage (M = 114, SE = 0.696), $t(296) = -10.379$, $p = .001$. However, there was also a significant difference between the avatar stage and the post-stage (M = 115, SE = 0.696), $t(296) = -2.613$, $p = .0255$. This indicates that the presence of the surrounding avatar significantly affects the participant's HR, and this effect does not persist after the surrounding avatar leaves the VR gym.
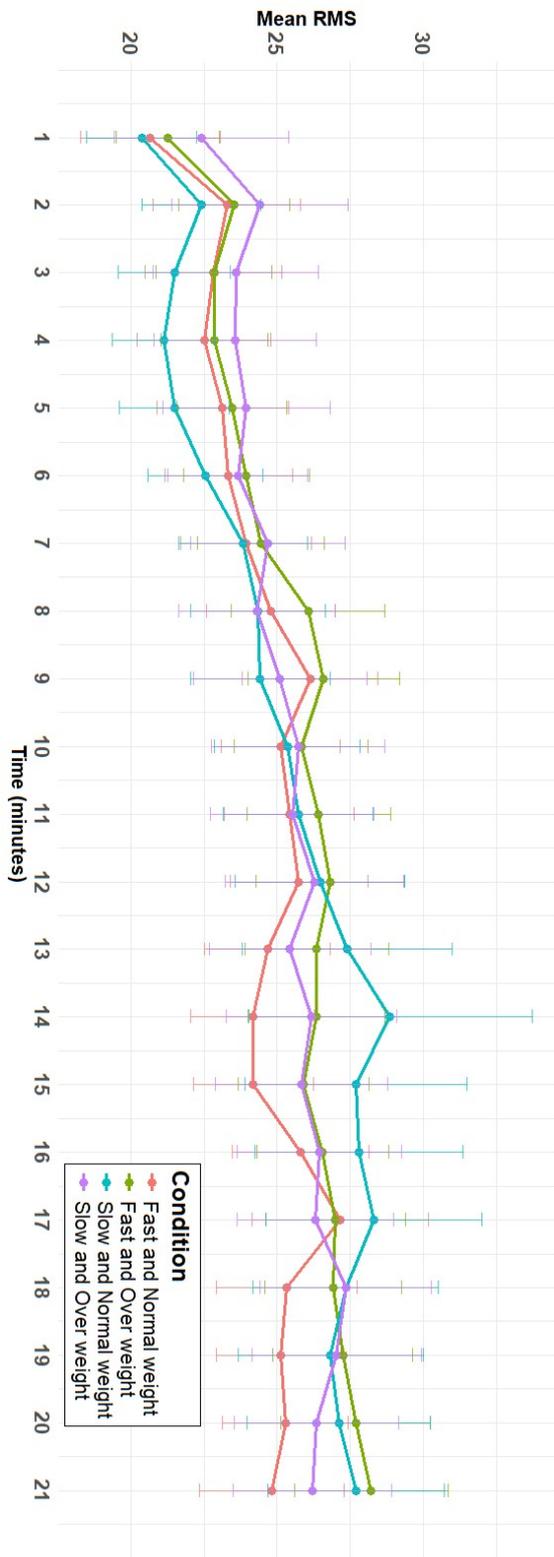
Figure 4.11: The average RMS per minute under four conditions with error bar.
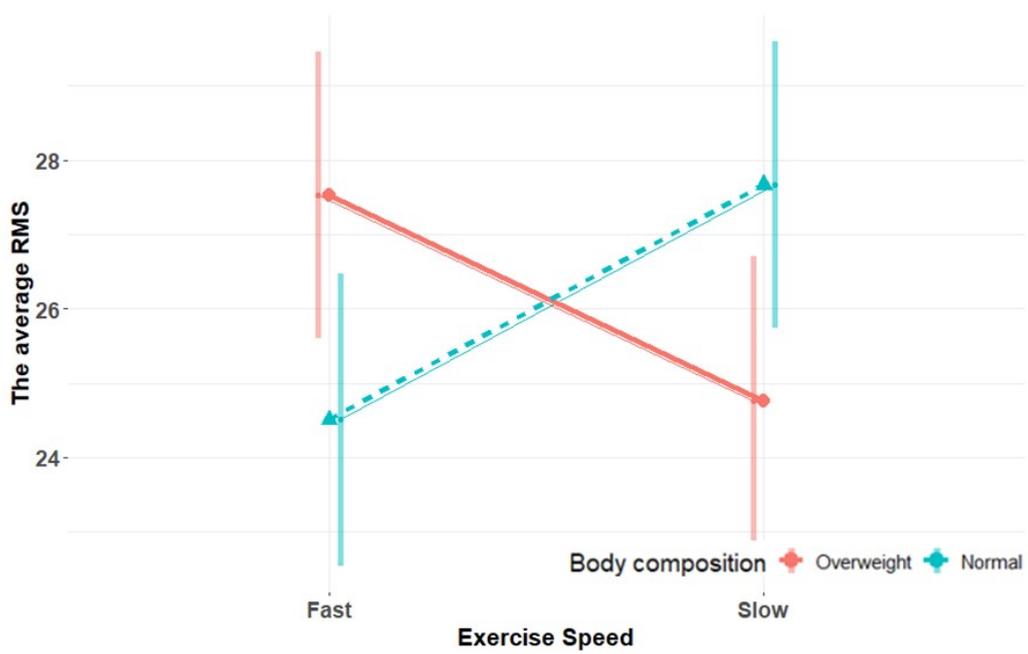
Figure 4.12: The interaction effect of exercise speed (Fast and Slow) and body composition (Normal and Overweight) on participants' EMG while cycling in the VR gym with error bars.

4.3.2.2 Pedaling frequency

For the purpose of examining whether the effect of the surrounding avatar remains consistent after the avatar leaves the VR gym, we conducted the simple effect test for pairwise comparisons on the three different stages. Compare the three different stages.

A significant difference was observed between the pre-stage (M = 57.3, SE = 0.905) and the avatar-stage (M = 59.5, SE = 0.905), t(296) = -3.486, p = .0016. There was no significant difference between the avatar-stage and the post-stage (M = 59.8, SE = 0.905), t(296) = -0.426, p = .9046. This indicates that the presence of the surrounding avatar significantly affects the participant's pedaling frequency, and this effect persists even after the surrounding avatar leaves the VR gym.

4.3.2.3 Perceived exertion

To examine whether the effect of the surrounding avatar remains consistent on participants' perceived exertion when the avatar leaves the VR gym, we conducted the simple effect test for pairwise comparisons on the three different stages.

The result revealed that perceived exertion was significantly higher in the avatar stage (M = 6.12, SE = 0.26) than in the pre-stage (M = 5.13, SE = 0.26), t(329) = 9.47, p <.001. No significant difference was found between the avatar stage and the post-stage (M = 6.72, SE = 0.26), t(229) = -1.49, p = .138.

4.3.2.4 Electromyography

To examine whether the effect of the surrounding avatar remains consistent after the avatar leaves the VR gym, we conducted the simple effect test for pairwise comparisons on the three different stages.

A significant difference was observed between the pre-stage (M = 22.7, SE = 0.575) and the avatar stage (M = 25.7, SE = 0.575), t(280) = -

3.625, $p = .001$. However, there was no significant difference between the avatar stage and the post-stage (M = 22.7, SE = 0.575), t(280) = -0.959, $p = .603$. This result indicates that the presence of the surrounding avatar significantly influences the participant's EMG, and this effect persists even after the surrounding avatar leaves the VR gym.

4.4 The result of self-perceived fitness

To explore the effects of exercise speed and the body composition of the surrounding avatar on SPF after users cycled in the VR gym, ANOVA was conducted for each subscale of the SPF.

A significant main effect of the surrounding avatar's body composition was found on the fitness dimension, F(1, 90) = 5.452, $p = .004$, $\eta_p^2 = 0.341$. The result is shown in the table 4.1. We did not find any significance for other dimensions. But for the effect of the surrounding avatar's exercise speed, for all five dimensions, we did not find any significant difference. The result is shown in the table 4.2. Moreover, for the interaction effect on exercise speed and body composition, there were no significant differences found in the five dimensions of SPF. The result is shown in the table 4.3

Table 4.1: The result of the avatar's body composition on the user's self-perceived fitness

Dimension	F-Value	P-Value	Effect size
Endurance	2.32	.13	0.03
Strength	1.475	.827	0.001
Flexible	3.055	.083	0.003
Fitness	5.452	.004*	0.341
Body composition	2.4	.125	0.03

The results indicated that the users perceived their fitness as higher when cycling while being visually stimulated by the overweight body composition of the surrounding avatar in the VR gym.

Table 4.2: The result of the avatar's exercise speed on the user's self-perceived fitness

Dimension	F-Value	P-Value	Effect size
Endurance	2.32	.13	0.001
Strength	3.0553	.833	0.001
Flexible	0.943	.334	0.001
Fitness	0.475	.492	0.005
Body composition	0.124	.492	0.03

Table 4.3: The result of the avatar's interactive effects on the user's self-perceived fitness

Dimension	F-Value	P-Value	Effect size
Endurance	0.4277	.51	0.005
Strength	0.447	.833	0.001
Flexible	3.0553	.833	0.03
Fitness	0.4754	.492	0.005
Body composition	0.6	.44	0.007

4.5 Discussion

4.5.1 Summary of result

This study investigated the effects of visual representation of the surrounding avatars' exercise speed and body composition on participants' physiological and psychological responses while cycling in a VR gym. The results demonstrated distinct influences of exercise speed, body composition, and stage on participant performance.

First, regarding exercise speed, the experiment results showed a significant main effect on pedaling frequency, which indicates that the visual attribute of the surrounding avatars' exercise speed affected participants' cycling performance at behavior level.

However, the visual attribute of the surrounding avatars' exercise speed did not show a significant main effect on HR and EMG, which indicates the surrounding avatars' exercise speed does not affect participants' performance on a physical level. So, the *H1-1* was partly supported. After that, the visual attribute of the surrounding avatars did not affect participants' perceived

exertion. That indicated that variation in the avatars' exercise speed alone does not directly affect participants' subjective effort levels. Then the *H1-2* was rejected.

Second, the visual attribute of the surrounding avatars' body composition only affected participants' self-perceived fitness. Then *H2-2* was rejected. This suggests that the physical attribute of the surrounding avatars, body composition, can shape participants' self-perceptions and potentially affect their motivation and engagement in virtual exercise environments. At the same time, body composition alone did not directly affect HR, pedaling frequency, perceived exertion, and EMG. Therefore, *H2-1* was also rejected.

Except for the main effects of exercise speed and body composition, an interaction effect can also be observed in HR and EMG. Specifically, under the fast exercise condition, an overweight body composition resulted in a significant increase in HR and muscle activation. In contrast, the surrounding avatar with body composition conditions resulted in a significant decrease in HR and muscle activation. On the other hand, the slower exercise condition, the surrounding avatar with an overweight body composition, resulted in a significant decrease in HR and muscle activation, and the surrounding avatar with a normal weight body composition resulted in a significant increase in HR and muscle activation.

Finally, the condition of the stage was found to have an effect on HR, but did not affect PF, EMGand perceived exertion, which indicates that when the surrounding avatar leaves the VR gym, the surrounding avatars' effect on the participant's HR was gradually diminished. However, the surrounding avatars' effects on participants' pedaling frequency, perceived exertion and EMG are consistent even when the surrounding avatars leave the VR gym. Thus *H3* was only partly supported.

Overall, these results suggest that while the surrounding avatars' exercise speed and body composition do not uniformly affect all physiological responses, they affect participants' pedaling frequency and SPF. Meanwhile, both exercise speed and body composition have an interaction effect on participants' HR and EMG in the VR gym. These findings provide valuable insights into the design of virtual exercise environments, highlighting the importance of surrounding avatar attributes in shaping participant experiences during exercise. The implications of these results will be further explained in the following section.

4.5.2 The effect of the surrounding avatar's exercise speed

Our results indicated that the surrounding avatar's fast exercise speed increased the participants' pedaling frequency during cycling in the VR gym.

According to the social comparison theory, people tend to evaluate their own capacity by comparing themselves to others, particularly when objective criteria are absent, social information is available, the dimension of comparison is self-relevant, and the target is comparable [101]. The previous paper also defines better performance in running games. In his experiment, the shorter the running time over the same distance, which means faster speed, the better the running performance [50]. Therefore, in our experiment, when participants observed surrounding avatars running at a fast speed, which can be interpreted as indicating better exercise performance in running, they had a higher exercise intensity compared to a slow speed. The fast-running surrounding avatars' better performance was the only dynamic visual information reference on exercise in the VR gym. participants may evaluate their own exercise performance based on surrounding avatars. Therefore, this may subconsciously induce upward social comparison, leading participants to want to adjust their own exercise performance to match the surrounding avatars, and consequently increase their own pedaling frequency. Conversely, observing avatars running slowly may have triggered downward comparisons, resulting in reduced pedaling frequency.

Previous studies have discovered similar results. Murray et al. found that when participants row a virtual boat with a virtual partner that is always faster at 40% speed than participants, this contributes to longer rowing distance [173]. Additionally, Wang et al. demonstrated that when the virtual partner performs more and faster squats, it also leads participants to improve their performance in squats [132]. That's two research studies that have demonstrated that better exercise performance surrounding avatars can improve participants' exercise performance. However, both of these studies employed the same type of exercise, such as an exercise competition, which can amplify the social comparison effects by directly comparing participants' performance with that of the avatar. However, competition is not an indispensable requirement for social comparison effects. Social comparison processes can also occur subconsciously [174]. In our study, although participants cycled while surrounding avatars ran, both activities fall under aerobic exercise and share a common dimension — rhythmic. participants could visually perceive the avatars' rhythmic movements, such as leg and arm swings. The rhythm was one of the features of exercise performance.

It can be considered that the participant unconsciously compares their own rhythm with that of the surrounding avatars. That is to say, if the avatar's running speed increases, the participant may unconsciously raise the pedaling frequency of their cycling to match or approach the avatar's rhythm. Therefore, the surrounding avatar's exercise speed affected the participant's pedaling frequency.

Despite the exercise type differing between participants and surrounding avatars, the exercise speed still affects the participants' pedaling frequency, and the results align with the trend of social comparison effects, which may indicate that the visual representation of surrounding avatars with social information can still influence participants' physical activity. Therefore, we suppose that even if the sports types are different, as long as there are relatively comparable dimensions (such as frequency), the surrounding avatar's exercise speed could be used as an important social benchmark standard to affect participants' physical activity during exercise. However, more experiments are needed to confirm this hypothesis in the future.

4.5.3 The effect of the surrounding avatar's body composition

The body composition of surrounding avatars primarily affects participants' SPF in the fitness dimension. Regarding the result, it means that after the participant exercised with an overweight body composition, surrounding avatars contributed to the participant's higher rating of fitness. According to the Proteus Effect, participants' behaviors and perceptions can be shaped by their avatar's appearance. In our study, controlling a normal-weight avatar may have strengthened participants' cognitive association with fitness. When subsequently exercising with overweight surrounding avatars, this obvious visual contrast provides additional social information. Although the surrounding avatars are not direct competitors, the "body composition differences" at the visual level may amplify participants' perception of fitness. According to the self-perception theory, the change in self-perception attributed to self-avatar and the surrounding avatar amplifies this self-perception. Therefore, exercising with the overweight body surrounding avatars may increase their perception of fitness in self-perception, which leads to a reported higher value on the fitness dimension. Previous research also found a similar phenomenon that when a participant runs alongside an avatar with a fit body composition, it results in higher negative emotions, pressure, and tension, as well as lower perceived competence [99].

However, our results on body composition may not be consistent with

those of Peña and Kim, who demonstrated that in the tennis game, participants controlling a normal-weight avatar significantly decreased physical activity when competing against an overweight avatar [51, 175]. Based on social comparison theory, when participants are confronted with an opponent avatar that has a more advantageous body composition, it triggers competitive motivation through upward social comparison. At the same time, participants adjust their physical performance, resulting in increased physical activity during tennis games. Conversely, overweight opponents can undermine this motivation and physical activity.

These contradictory findings may be explained by "the social role differences in task context". Although overweight avatars were used in the context of exercise in both studies, their effects on participant psychology produced different impacts. For example, Peña and Kim adopted a tennis game as the main experimental task, where participants directly competed against opponent avatars in tennis matches. Thus, participants perceived the overweight body composition as a disadvantage, which enhanced their self-confidence and reduced their sense of challenge and threat. As a result, participants perceived that they could defeat their opponent without exerting full effort, thereby reducing their motivation to exercise. In contrast, our study presented surrounding avatars as non-competitive co-exercisers. While this may create unconscious comparisons in terms of physical performance, participants do not need to see them as opponents or to defeat them. Meanwhile, exercise speed plays a role in representing physical performance in running, and body composition may not fully account for physical performance at different speeds. Thus, the surrounding avatars' body composition did not directly induce social comparison. In contrast, it creates a more supportive and encouraging atmosphere for their cognitive understanding of their body.

4.5.4 The interaction effects of exercise speed and body composition

In addition to the main effects, our findings revealed a significant interaction between the surrounding avatar's exercise speed and body composition in affecting participants' physiological responses in the VR gym. However, this interaction effect did not affect participants' pedaling frequency. This suggests that the influence of surrounding avatars on participants' physical activity and psychological responses may be dissociated.

Further investigation revealed that the surrounding avatars had normal body composition and higher speed, as well as overweight body composition

and slower speed. Under these two conditions, participants usually have lower HR and EMG values, which means participants' participation in exercise and physiological responses have decreased. The reason may be due to two different psychological responses that participants experience when exercising with surrounding avatars.

First, in a condition of normal body composition and fast speed, participants are facing surrounding avatars with a normal body and an extremely fast running speed; this combination may make participants feel that there is a "huge gap between exercise performance" or "never be able to compete." Excessive upward comparison, especially when the performance gap is perceived as unreachable, may trigger negative emotional responses and reduce participants' willingness to continue competing. Second, in the condition of overweight body composition and slow speed, participants are confronted with a surrounding avatar that is overweight and has a slow pace of running. participants may perceive the surrounding avatars' lack of exercise performance, and then produce a sense of ease and superiority. This may be attributed to participants engaging in downward comparison, which further leads to participants producing positive emotions. This psychological factor, which may contribute to the absence of meaningful challenge, may have resulted in decreased motivation and reduced physiological engagement.

Although EMG and HR values cannot directly reflect social comparison motivation, they can serve as an indicator of behavioral performance, reflecting whether the participant is in an active comparison or participation state. In our results, the normal body and fast speed, as well as the overweight body and slow speed, exhibit lower HR and EMG values, indicating participants are in a relatively lower motivational state under these conditions. That's state is highly consistent with Pena and Kim's proposed hypothesis, like "Give up" and "Take it easy," which is based on social comparison effects [51]. They proposed that when a participant goes against a higher advantage or disadvantage in tennis, the participant's physical activity will decrease in both situations. Although we haven't found a similar trend in participants ' physical performance, we found that the body composition and exercise speed have interactive effects on participants' effort and participation in exercise. Especially, "normal body composition and fast speed" can be seen as a superior advantage, and "overweight body and slow speed" can be seen as a disadvantage in exercise. Then achieve "Give up" and "Take it easy" motivational states.

Thus, even in a VR gym without direct competition, the surrounding avatars can still induce participants to experience psychological states, such

as social comparison. However, unlike in exergames with clear opponents, body composition alone is insufficient to serve as a meaningful reference for social comparison. Our findings suggest that the combination of body composition and exercise speed has a more substantial impact on participants' motivational and physiological responses than either attribute alone.

4.5.4.1 The persistence of the surrounding avatar's effects

Our findings reveal that the persistence of the surrounding avatar's effects on physiological and behavioral measures may not be related in the post stage. Normally, HR would be expected to correspond with exercise behavior. However, the results indicated that the stage condition significantly affected HR, which may mean that the effects of surrounding avatars on HR may be temporary and diminish in the post stage. In contrast, the behavior measure (the pedaling frequency and EMG) and perceived exertion did not show significant differences between the avatar and post stages, which indicates that the surrounding avatars' effects remain on users in the post stage.

That may be explained by the essential difference between physiological and behavioral measures. HR, as a physiological indicator, may be sensitive to psychological effects. The previous study also reported that embodying with athletic avatars can reduce HR without affecting pedaling frequency during cycling, which was interpreted as avatars enhancing users' psychological intentions and confidence, thereby decreasing HR in exercise [17]. From social psychological research, the presence of others will lead to psychological changes, such as social comparison [176], social facilitation [177], and the Köhler effect [178]. However, the absence of others cannot induce these psychological mechanisms. Meanwhile, the result of SPF also indirectly proves that the surrounding avatar has an impact on users' psychology.

Consequently, when the surrounding avatars leave the VR gym, the surrounding avatars' effects on users' psychological states may gradually decrease. Then, users' HR may no longer consistently reflect the surrounding avatars' effects. The behavioral measures may be different from HR. Although behavioral also affected by the surrounding avatars' effects, during several minutes of exercise, it is possible that users may develop a rhythm under the effects of the surrounding avatar. Since the experiment was not finished when the surrounding avatars left, users were required to continue cycling, and this established rhythm may have been maintained for a period of time. As a result, the effects of surrounding avatars on behavior may have

persisted, even after the avatars had left. Since the actual exercise behavior did not change, perceived exertion remained consistent with the behavioral measures and therefore did not change. Moreover, we only examined the persistence of these effects in the post stage and did not test their long-term duration. Future work should further investigate the persistence effects of the surrounding avatar for a longer time.

4.6 Conclusion

This study examines the impact of visual representations of exercise speed and body composition of surrounding avatars on participants' physical activity and perceived exertion in a VR gym. The results indicate that avatar exercise speed is a key factor influencing participant performance, with participants increasing their pedaling frequency in response to fast-moving avatars.

Regarding body composition, overweight avatars do not reduce participants' exercise motivation; instead, they enhance self-perceived fitness on the fitness dimension. Additionally, we found that although the surrounding body did not affect the participant's experience, the interaction effects between exercise speed and body composition will affect people's motivation and participation in exercise. Especially, overly high and overly low comparison references weaken participants' engagement.

Although the surrounding avatars can temporarily enhance participant performance, their effects do not persist after the surrounding avatars are left, except for pedaling frequency and EMG value. All others do not show a difference when the surrounding avatars leave the VR gym.

This study provides insights into optimizing future VR gym design, demonstrating that strategic design of avatar exercise speed and body composition can enhance participant motivation. Future research should extend to different types of exercise, such as running or strength training, and investigate whether prolonged exposure to specific avatars can sustain exercise motivation.

In the next chapter, I will be writing about a overall discussion and conclusion for the whole of this thesis about the surrounding avatar design on the user's exercise experience in the VR gym.

Chapter 5

Discussion and conclusion

5.1 Summary

This thesis, through two experiments, explored the effect of surrounding avatar design on dynamic and static visual attributes in a VR gym and how the surrounding avatar design influences users' time perception, physical activity, and perceived exertion during exercise in VR gyms. Although these two experiments focus on two separate aspects of users, they also manipulate and measure the variable of " dynamic and static visual attributes" of surrounding avatar design, which provides multi-dimensional evidence to support the understanding of the mechanism of avatar design in VR gyms.

The first experiment results indicated that the dynamic attribute of surrounding avatars significantly affects users' duration judgments. Compared to slow speed, the surrounding avatar with fast exercise speed on squat can compress the user's duration judgment, which contributes to the user perceiving time passage as faster. This demonstrates the ability of the surrounding avatars' visual rhythms to modulate time perception. However, the surrounding avatars' static attribute, which stands for the exercise intensity, only has a certain extent on the user's feeling of time passage, but it does not affect the user's duration judgment.

The second experiment further examined the effects of surrounding avatars' design on two aspects: the dynamic attributes were the avatar's exercise speed, and the static attribute was body composition, on users' actual exercise behavior and psychological responses. The result indicated that the fast running speed of the surrounding avatar significantly improves users' pedaling frequency, which was an apparent effect on users' behavior. However, the design of the surrounding avatars' body composition did not substantially affect users' physical activity; it only provided some positive guidance in users' subjective evaluation of their self-fitness. Especially an overweight body, which was seen as a positive reference, improves users' self-

96

reports on the fitness dimension. Despite the surrounding avatars' exercise speed and body composition having interaction effects on users' physiological responses, especially on HR and EMG values. It do not directly affect their physical performance, but it have effects on users' exercise efficiency.

In summary, a consistent finding across both experiments is that the dynamic visual attributes of surrounding avatars, particularly speed, consistently exert a significant influence on users' behavioral responses and psychological experiences. Whether in the distortion of time perception or the enhancement of physical performance, dynamic attributes demonstrate stable and robust effects. In contrast, static attributes, such as body composition or exercise intensity, show relatively limited influence; they usually depend on the user's pre-existing and self-experienced judgments about body image and exercise intensity.

5.2 Dynamic and static attributes of the surrounding avatar

Although the two research studies focused on different aspects of user experience in a VR gym, both experiments examined the same fundamental aspects of user experience. The first study concentrated on users' time perception, encompassing both duration judgment and the perception of time passage, whereas the second study focused on users' physical performance and perceived fatigue. Both experiments manipulated the dynamic and static visual attributes of surrounding avatars. The results suggest that these visual attributes not only affect users in a single and isolated dimension but also exert effects across both temporal cognition and physical behavior. For example, the dynamic attribute of the surrounding avatar's exercise speed significantly affected users' judgment of duration and their feeling of time passage in the first study. In the second study, the fast exercise speed also led to an increase in pedaling frequency, demonstrating a clear behavioral effect. This suggests that the exercise speed of surrounding avatars may not only affect users' time perception but also enhance their actual physical performance.

5.2.1 Dynamic attributes

For the surrounding avatar design on the dynamic attribute that both affect the user's time perception and physical activity. The reason may be that the user's time perception and physical activity can both be affected by

the frequency factor. Then, the surrounding avatar's exercise speed also provides this frequency factor from the visual attribute perspective. For example, in the first experiment about users' time perception, the result found that the surrounding avatar's speed of doing a squat affects the user's time perception. In other words, the density of the rhythm or the faster the speed in the external environment, the more likely users are to subjectively perceive that "duration becomes longer" or "time is compressed." Therefore, they will perceive time as longer and have the feeling that time passes faster. Meanwhile, when users exercise with the surrounding avatar, the fast exercise speed also creates a more rhythmic experience. And, the frequency of movements is also typically understood as a reflection of the fact that people express as good exercise performance or a better exercise state. And this improved exercise performance may lead users to engage in upward comparison with the surrounding avatar. Therefore, the user may adjust their own exercise performance on cycling. In other words, this means the user will adjust their pedaling frequency to match the external rhythmic pattern in dynamic visual stimuli. Therefore, it can be supposed that the surrounding avatar design on the dynamic attribute visual dynamic information feature of "frequency" acts simultaneously on the time perception and the physical activity, becoming the key clue connecting the two dimensions.

5.2.2 Static attributes

As for static features, the visual representation of exercise intensity, such as the size and weight of the barbell, affected users' perceptions of time passage. Meanwhile, body composition and overweight body composition served as visual reference points, positively influencing users' self-perception of fitness.

In conclusion, it can be supposed that the effects of static attributes of surrounding avatars on users' experience are primarily associated with users' understanding of the static attributes. For example, in the context of time perception, users tend to use the consumption of action as a reference to judge the feeling of time passage, such as the duration of an exercise, which is based on visual attributes like the size or weight of the barbell used by the surrounding avatars. For example, when the surrounding avatars perform squats with a heavy barbell, users may intuitively assume that such a high-intensity squat movement requires more time to complete. Based on this judgment, they will allocate more time to assess the feeling of time passage further. Conversely, a lighter barbell may be perceived as requiring less effort and time; based on this judgment, people will also change their feelings about

98

time passage.

For body composition, the effect is more closely connected to users' understanding of body composition's advantage or disadvantage in exercises. For example, normal or fitness body composition usually attributed that normal body composition is often associated with more advantage in exercise, and more fitness than an overweight body composition condition. Previous research has indicated that when users exercise with a fitness avatar, it typically produces negative emotions; however, an overweight body avatar can have positive effects [99]. Thus, in our experiment, the static attributes of an overweight body evoke positive emotions, such as confidence, and users perceive themselves as having a higher physical activity.

5.2.3 Interactive effects of dynamic and static attributes

In addition to the main effects of dynamic and static attributes, these attributes also exhibit interaction effects. Particularly at the physiological level during exercise, this affects HR and EMG values, suggesting that users may perceive comparability not only by considering static attributes, as in previous papers on opponents' avatars' body composition in tennis games, but also need to consider it by combining dynamic and static attributes.

In my thesis, I found that when users exercised together with the surrounding avatars, their psychological states were affected by the surrounding avatars. This effect is different from previous research, which only relies on the opponents' avatars' body composition [51, 175]. On the contrary, the users' response is jointly driven by the interaction of dynamic and static attributes. For instance, when the surrounding avatars possess both the attributes of "fast speed" and "normal body composition," the surrounding avatars exhibit double advantages during exercise, which may lead users to engage in excessive upward social comparison. Since this double advantage may be perceived as unattainable, users may reduce their willingness to participate in exercise, which further leads to a decrease in HR and EMG. In contrast, when the surrounding avatars are of "overweight" but "speed fast", although they have an advantage in the dynamic dimension, due to their static attributes not conforming to the stereotype of advantage. Therefore, users will not be affected by their engagement in this situation.

This thesis found that users' responses to surrounding avatars in VR exercise are not only influenced by a single visual attribute, but are jointly driven by the interaction between dynamic and static attributes. It emphasizes the need to comprehensively consider the matching relationship between dynamic and static attributes in avatar design.

5.3 Research contribution

This research made several contributions to academic fields, providing practical guidance on designing an ideal VR gym and advancing the field of knowledge science.

5.3.1 Academic contribution

This thesis expands the understanding of how surrounding avatars in VR gyms influence users' exercise experiences, particularly in terms of time perception and physical performance. First, it is the first to investigate the effects of surrounding avatars' dynamic visual attributes and static visual attributes on users' time perception. The results showed that dynamic attributes more significantly altered users' time perception both in duration judgment and feeling of time passage, while static attributes primarily influenced the subjective feeling of time passage. This fills a gap, which has largely focused on user-controlled avatars, and for the first time reveals the regulatory role of surrounding avatars in time perception within the VR gym. Furthermore, this study deepens the understanding of how surrounding avatars affect users' exercise experiences in VR gyms. It demonstrates that the exercise speed and body composition of surrounding avatars significantly influence users' physical activity and psychological responses. These avatars can serve as a social comparison reference, motivating users and enhancing their performance. Importantly, the effects of surrounding avatars persist even after they leave the scene, suggesting a profound and lasting sociopsychological impact on users' exercise behaviour.

5.3.2 Practical contribution

This research found that the surrounding avatar design provides a new perspective to help users promote their exercise experience in the VR gyms. From a traditional perspective, the surrounding avatars are often regarded as companions or exercise partners, with most of the previous paper focusing on the existence or non-existence, overlooking the effects of surrounding avatar design on user behaviour and psychology. However, this thesis demonstrated that the surrounding avatar design, particularly their dynamic and static attributes, can influence users' time perception, exercise performance, and subjective experiences. Therefore, in future VR gym design, it is advisable to adjust the dynamic and static attributes of surrounding avatars according with users' specific needs, so as to enhancing their exercise experience and further encouraging adherence to regular exercise in Therefore, in future VR

gym design, the dynamic and static attributes of surrounding avatars should be adjusted in accordance with users' specific needs, so as to optimize exercise experiences and further promote users' adherence to regular physical activity in VR gyms.

5.3.2.1 Dynamic attribute on VR gym design

Regarding the surrounding avatar design on dynamic attribute, the results indicated that the surrounding avatar's exercise speed can affect users' time perception both on duration judgment and feeling of time passage, and it also contributes to users improving their physical activity. Therefore, the VR gym designer can adjust the surrounding avatar's dynamic attribute, which follows the user's needs to adjust the avatar's speed to let users perceive "time compression". For example, during long-duration aerobic exercise, the fast-moving surrounding avatar can help users reduce the perceived "boredom" and "excessive duration", thereby maintaining a higher motivation and persistence for exercise. On another hand, when users hope to improve their physical activity, designers can also adjust the surrounding avatar's dynamic attribute to realise users' requirements. For example, when users require improving their exercise intensity, VR gym systems can improve the speed of the surrounding avatar to push the user into more higher intensity state.

However, the dynamic attribute may have effects on users' two different dimensions; it may have a "double effect." This "double effect" suggests that, in the future, VR gym developers should consciously use the surrounding avatars' exercise dynamic attribute should consider two-way effects on users in the design of the VR gym. For example, in exercise scenarios where the users want to improve exercise efficiency or enhance users' concentration, the designer can appropriately increase the exercise speed of the avatar to take advantage of the "time compression" experience brought about by the accelerated speed to motivate users to improve their performance; on the contrary, in recovery training or low-intensity aerobic exercise, designer should decrease the speed of the avatar to avoid the overlapping effects of physical fatigue and time distortion due to the fast exercise speed. Therefore, designers need to make differentiated adjustments under different training objectives.

It is worth mentioning that precisely because the dynamic attribute has a cross-dimensional effect, its design and adjustment must take into account the user's actual training objectives. If the system adjusts the speed based on one goal, such as to improve physical activity, while ignoring its potential impact

on another dimension, it may be counterproductive. For example, when the user only wishes to increase the movement frequency, the surrounding avatar can indeed achieve the purpose by adjusting the dynamic attribute. Still, at the same time, the user may also perceive the time lengthening as a result, which can lead to the side effect of early fatigue or decreased training motivation. On the contrary, in some special states, such as the user is in the stage of super-arousal or extreme fatigue, its time perception may have been distorted, at this time, if you want to slow down the pace of avatars to ease the time pressure, shorten the length of the subjective experience, but also need to be vigilant about this adjustment may bring the risk of sports performance decline.

5.3.2.2 Static attribute on VR gym design

Regarding the surrounding avatar designing on static attributes, such as the avatar's body composition or the intensity, although they do not directly affect the user's exercise performance, they also play a crucial role as social cognitive information in the user experience. From the result that the surrounding avatar's exercise intensity can affect the user's feeling of time passage. So when users only want to perceive time passage faster while they do exercise, the designer can adjust the surrounding avatar's exercise intensity to realise this purpose. Then, for the surrounding avatar's body composition, it is closely related to the user's perception of self-fitness. The study showed that users tended to rate their own fitness perception more highly when surrounded by avatars with an overweight body composition. This suggests that avatar images and external appearance with diverse body types can be strategically introduced into the training of users in the beginner, body-anxious, or fitness-recovery phase to reduce users' pressure and anxiety, which can enhance users' self-confidence in their body and emotional experience during exercise.

The role of body composition of the surrounding avatar in virtual gyms is not only reflected in individual effects, but more importantly, in their interaction with exercise speed. It also can decrease the social pressure from surrounding avatar's dynamic attribute (fast exercise speed). In practice, the interaction between body composition and exercise speed provides useful implications for avatar desing in VR gym. For beginners or users in rehabilitation, avatars with overweight bodies at a moderate speed can reduce social comparison pressure and enhance confidence. For advanced or competitive users, fit body avatars with high speed can increase motivation, and flexible combinations allow for personalized training difficulty.

102

5.3.3 Contribute to knowledge science

Knowledge science is an interdisciplinary area that focuses on exploring "Knowledge Creation and Transformation, Knowledge Representation, Systematization, Acquisition, Knowledge Management, Systems Science, Education and Knowledge Science, Technology innovation, etc" This study contributes to the interdisciplinary field of knowledge science in terms of "knowledge creation and theory construction" and "cognitive process understanding".

First, in terms of knowledge creation and theory construction, this study proposes a theoretical framework that distinguishes the different paths through which the dynamic attributes and static attributes of the surrounding avatars influence users' time perception, physical performance, and subjective experience during exercise. It is found that dynamic attributes are more inclined to influence users' behavioral execution and temporal perception through frequency. In contrast, static attributes are based on users' knowledge and understanding of static attributes.

Second, in terms of knowledge acquisition and cognitive regulation, the study revealed how users make social comparisons, self-judgments, and behavioral adjustments based on information about the surrounding avatars. This suggests that in VR environments, knowledge acquisition not only comes from the content itself, but is also moderated by social cues and environmental consistency. This provides empirical support for the mechanism of ecological influence on cognition and learning in knowledge science.

Finally, in terms of knowledge application and system design, this study provides a clear optimization strategy for avatar design in the VR gym. By adjusting the dynamic and static attributes of the surrounding avatars, the motivation and persistence of exercise can be enhanced, thereby improving the efficiency of knowledge transfer and cognitive performance within the system. This kind of data-driven, psychologically mechanism-based design is a key focus of knowledge science in the field of system design.

5.4 Limitations and Future Work

In this study, we gained detailed insights into the surrounding avatar design on users' exercise experience, like time perception, physical activity and exertion perception in VR gyms. I believe that our research results represent a first step toward helping realize the effectiveness of the surrounding avatar

design while users exercise in VR gyms. However, this requires a considerable amount of time. This section highlights some of the study's limitations and future directions.

First, the surrounding avatar in this experiment only adopted one male avatar, and it was always in a fixed position throughout all trials. This simplified treatment to some extent weakens the authenticity of the experimental situation and has a gap with the diverse interactive environment existing in the actual VR gym. In real-life contexts, a gym may include individuals of different genders and age groups, and the surroundings may consist not only of one individual but also of multiple people. These factors could potentially influence users' exercise experience and psychological responses. However, this experiment focused solely on manipulating the dynamic attribute of exercise speed and the static attribute of exercise intensity as independent variables. Future research should further focus on these independent variables for surrounding avatars, such as gender, age, and group size, with the purpose of providing a comprehensive understanding of surrounding avatar design in VR gyms.

Another limitation of this study lies in the characteristics of the subjects. This experiment only recruited postgraduate students (master's and doctoral students) from JAIST, who were generally younger and had a higher level of education. This limited scope of the population may restrict the generalizability of the research results to a wider range of people, such as the elderly, teenagers, or individuals with different educational and cultural backgrounds. Furthermore, this study did not take gender or other individual differences into account as experimental variables, and these factors might affect motor behaviour, social cognition, and responses to avatars. Therefore, the conclusions of this study need to be interpreted with caution. Future research should incorporate more heterogeneous samples and further investigate the moderating role of demographic factors.

5.4.1 On time perception

Firstly, the surrounding avatar plays the role of zeitgeber in the VR Gym, affecting the participants' time perception. In this study, the squat was selected as the exercise for the surrounding avatar. Compared to squat, which has a regular cycle, another exercise, such as running on a treadmill, does not have a regular cycle. Thus, it is necessary to investigate whether the attributes of surrounding avatars in such situations have a similar effect in the future.

Secondly, the effect of speed and intensity on time perception might not

104

be linear. Our research used a common range of speeds and workloads as our conditions. However, it is necessary to investigate further whether the effects remain in more extreme settings. It is possible that when the surrounding avatars' speed and workload are much higher than usual, the effects might diminish or disappear because the participant may not consider the surrounding avatars as zeitgebers in such an unusual situation. Therefore, in future work, we should reconduct the experiment with a wider setting to explore the effects.

5.4.2 On physical activity and perceived exertion

First, many of the data results found in our study are consistent with the hypothesis of psychological effects. However, we do not have direct measurements of these psychological changes. Although these are relatively plausible explanatory frameworks, future research may need to introduce direct measurement data. To confirm that these behavioral changes around avatars explain the psychological mechanisms behind users' behavioral and physiological responses.

Second, the present study focused exclusively on cycling as the user's exercise type in VR. Although both the user and the surrounding avatar engaged in aerobic exercises, such as cycling and running, the activities differed. Future research should investigate whether the effects of surrounding avatars' exercise speed and body composition extend to other types of activities, including running, planking, and barbell exercises. Moreover, it remains unexplored whether mismatches between the user's and avatar's exercise modalities, for example, user cycling and surrounding avatar squat, would influence users' physical responses and perceptions. Understanding these dynamics across different exercise modalities would provide a broader perspective on the role of surrounding avatars in VR-based physical activity.

5.5 Conclusion

This thesis aims to explore the surrounding avatars' design on both dynamic and static attributes, and their effects on users' exercise experiences in a VR gym. This thesis is based on two experiments investigating the role of avatars' dynamic and static attributes in affecting user behavior and psychological responses. The results show that the surrounding avatar not only served as a visual element in the VR gym but also influenced users' perceptions,

behaviors, and motivations during exercise.

The first research focused on users' time perception in the VR gym during exercise; the result shows that the dynamic attribute of the surrounding avatars' exercise speed significantly affects users' time perception. In particular, duration judgments and the feeling of time passing. In contrast, static attributes such as exercise intensity have a relatively limited effect on time judgments and only a limited impact on the subjective perception of time passing. This finding can help users adjust their subjective perception of time, which in turn can aid them in avoiding time distortion and maintaining high-intensity exercise for a longer duration. To help them have a better exercise experience and maintain exercise adherence.

The second study focused on users' physical activity and perceived exertion during exercise in the VR gym. It found that the surrounding avatars' exercise speed could improve the user's motivation during exercise. Meanwhile, when users exercise with an "overweight" body composition surrounding avatar, they had a more positive report on their own fitness value. It is more interesting that when the "normal" body composition is used, the surrounding avatars run at a very fast speed, while the overweight body composition runs at a very slow speed. This suggests that users' physiological responses decrease under these conditions, which in turn indicates that exercise participation is lower. It is possible that the overly high or overly low exercise comparison target could potentially decrease engagement. These findings have the potential to broaden the application of social comparison effects in immersive activity environments.

At the theoretical level, this thesis takes us to new heights by deepening our understanding of user perception and behavioral response in the VR gym. It achieves this by distinguishing between the dynamic and static visual attributes of the surrounding avatar, thereby enriching research on time perception and social comparison effects. This study is a changer, changing research and design from users' own controlled avatar to the surrounding avatars. This thesis includes actionable advice for designing VR gyms that are not only realistic and immersive but also help people change their psychological state. That included the image of the future VR gym, which provides the option for future users to adjust dynamic attributes and the exercise speed of their surroundings, as well as others' avatars, to create a unique and thrilling experience tailored to their own needs. Alternatively, get creative with surrounding the avatar's body composition to help users feel confident in their own body. It's more like having your own personal VR gym that can adapt to your style and push you to reach your goals!

From a theoretical perspective, this thesis deepens the influence of "social presence" and characteristics in VR exercise environments on users' perception of exercise in virtual gyms, and expands the application of social comparison theory, expectancy violation theory, and time perception in VR gyms. In particular, the distinction between dynamic and static attributes reveals the differences in visual information processing and how users integrate external stimuli and internal cognition to form perceptions and responses in socialized virtual scenarios, which provides a theoretical basis for future VR-HCI research.

From a practical perspective, this thesis provides actionable guidance on designing avatars for VR fitness systems. For example, designing avatars with high-speed movement can be used to regulate the user's temporal experience and enhance exercise engagement. By manipulating the combination of avatar body size and speed, it is possible to stimulate the user's physiological engagement and increase their motivation to exercise. Based on these findings, developers can consciously design the visual characteristics of the surrounding avatars to align with different training goals, thereby achieving more personalized, dynamic, and strategic fitness guidance.

In summary, this thesis constructs a framework on the surrounding avatar design that examines the effects of the surrounding avatars' visual attributes on user behavior and psychological experience, spanning multiple disciplines, including cognitive psychology, human-computer interaction, VR technology, and social psychology. This study not only offers new insights for theoretical research but also provides empirical evidence for the design and optimization of VR fitness systems in practice. It is hoped that this thesis can lay a solid foundation for building more immersive, motivating, and personalized virtual exercise environments in the future.

References

[1] A. Byrne and D. Byrne, "The effect of exercise on depression, anxiety and other mood states: a review," *Journal of psychosomatic research*, vol. 37, no. 6, pp. 565–574, 1993.

[2] S. N. Blair, "Physical inactivity: the biggest public health problem of the 21st century," *British journal of sports medicine*, vol. 43, no. 1, pp. 1–2, 2009.

[3] K. Lambourne, "The effects of acute exercise on temporal generalization," *Quarterly Journal of Experimental Psychology*, vol. 65, no. 3, pp. 526–540, 2012.

[4] D. G. Behm and T. B. Carter, "Effect of exercise-related factors on the perception of time," *Frontiers in Physiology*, vol. 11, p. 770, 2020.

[5] J. Brownsberger, A. Edwards, R. Crowther, and D. Cottrell, "Impact of mental fatigue on self-paced exercise," *International journal of sports medicine*, pp. 1029–1036, 2013.

[6] B. Zhang, M. Wu, H. Kang, E. Go, and S. S. Sundar, "Effects of security warnings and instant gratification cues on attitudes toward mobile websites," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2014, pp. 111–114.

[7] N. Farič, E. Yorke, L. Varnes, K. Newby, H. W. Potts, L. Smith, A. Hon, A. Steptoe, A. Fisher *et al.*, "Younger adolescents' perceptions of physical activity, exergaming, and virtual reality: Qualitative intervention development study," *JMIR Serious Games*, vol. 7, no. 2, p. e11960, 2019.

[8] M. Eckert, J. Zarco, J. Meneses, and J.-F. Martínez, "Usage of vr headsets for rehabilitation exergames," in *Bioinformatics and Biomedical Engineering: 5th International Work-Conference, IWBBIO 2017, Granada, Spain, April 26–28, 2017, Proceedings, Part II 5*. Springer, 2017, pp. 434–442.

[9] R. Klevjer, *What is the Avatar?* transcript Verlag, 2022.

[10] N. Yee and J. Bailenson, "The proteus effect: The effect of transformed self-representation on behavior," *Human communication research*, vol. 33, no. 3, pp. 271–290, 2007.

[11] R. S. Weinberg and D. Gould, *Foundations of sport and exercise psychology*. Human kinetics, 2023.

[12] M. Nunes, L. Nedel, and V. Roesler, "Motivating people to perform better in exergames: Competition in virtual environments," in *proceedings of the 29th annual ACM symposium on applied computing*, 2014, pp. 970–975.

[13] A. M. Edwards and A. McCormick, "Time perception, pacing and exercise intensity: maximal exercise distorts the perception of time," *Physiology & behavior*, vol. 180, pp. 98–102, 2017.

[14] S. M. Marcora, "Do we really need a central governor to explain brain regulation of exercise performance?" *European journal of applied physiology*, vol. 104, no. 5, pp. 929–931, 2008.

[15] E. Pila, A. Stamiris, A. Castonguay, and C. M. Sabiston, "Body-related envy: A social comparison perspective in sport and exercise," *Journal of sport and exercise psychology*, vol. 36, no. 1, pp. 93–106, 2014.

[16] M. Kocur, J. Bogon, M. Mayer, M. Witte, A. Karber, N. Henze, and V. Schwind, "Sweating avatars decrease perceived exertion and increase perceived endurance while cycling in virtual reality," in *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*, 2022, pp. 1–12.

[17] M. Kocur, F. Habler, V. Schwind, P. W. Woźniak, C. Wolff, and N. Henze, "Physiological and perceptual responses to athletic avatars while cycling in virtual reality," in *Proceedings of the 2021 CHI conference on human factors in computing systems*, 2021, pp. 1–18.

[18] B. Tan, A. R. Aziz, K. Chua, and K. C. Teh, "Aerobic demands of the dance simulation game," *International journal of sports medicine*, vol. 23, no. 02, pp. 125–129, 2002.

[19] H.-C. Huang, M.-K. Wong, J. Lu, W.-F. Huang, and C.-I. Teng, "Can using exergames improve physical fitness? a 12-week randomized controlled trial," *Computers in Human Behavior*, vol. 70, pp. 310–316, 2017.

[20] H. Song, J. Kim, K. E. Tenzek, and K. M. Lee, "The effects of competition and competitiveness upon intrinsic motivation in exergames," *Computers in Human Behavior*, vol. 29, no. 4, pp. 1702–1708, 2013.

[21] Y. Boas, "Overview of virtual reality technologies," in *Interactive Multimedia Conference*, vol. 2013. Bogota, Colombia, 2013, p. 4.

[22] G. Burdea, P. Richard, and P. Coiffet, "Multimodal virtual reality: Input-output devices, system integration, and human factors," *International Journal of Human-Computer Interaction*, vol. 8, no. 1, pp. 5–24, 1996.

[23] M. Slater and S. Wilbur, "A framework for immersive virtual environments (five): Speculations on the role of presence in virtual environments," *Presence: Teleoperators & Virtual Environments*, vol. 6, no. 6, pp. 603–616, 1997.

[24] R. Sigrist, G. Rauter, R. Riener, and P. Wolf, "Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review," *Psychonomic bulletin & review*, vol. 20, pp. 21–53, 2013.

[25] R. M. Banos, P. Escobar, A. Cebolla, J. Guixeres, J. Alvarez Pitti, J. F. Lisón, and C. Botella, "Using virtual reality to distract overweight children from bodily sensations during exercise," *Cyberpsychology, Behavior, and Social Networking*, vol. 19, no. 2, pp. 115–119, 2016.

[26] U. Dolu and A. F. Camliguney, "The effect of virtual reality on isometric muscle strength," *Progress in Nutrition*, vol. 24, no. 1, p. e2022004, 2022.

[27] M. Matsangidou, C. S. Ang, A. R. Mauger, J. Intarasirisawat, B. Otkhmezuri, and M. N. Avraamides, "Is your virtual self as sensational as your real? virtual reality: The effect of body consciousness on the experience of exercise sensations," *Psychology of sport and exercise*, vol. 41, pp. 218–224, 2019.

[28] L. A. Shaw, B. C. Wuensche, C. Lutteroth, J. Buckley, and P. Corballis, "Evaluating sensory feedback for immersion in exergames," in *Proceedings of the Australasian Computer Science Week Multiconference*, 2017, pp. 1–6.

[29] M. Farrow *et al.*, "Virtual-reality exergaming improves performance du..." *European Journal of Sport Science*, 2019.

[30] C. P. Hoffmann, A. Filippeschi, E. Ruffaldi, and B. G. Bardy, "Energy management using virtual reality improves 2000-m rowing performance," *Journal of sports sciences*, vol. 32, no. 6, pp. 501–509, 2014.

[31] T. G. Plante, A. Aldridge, D. Su, R. Bogdan, M. Belo, and K. Kahn, "Does virtual reality enhance the management of stress when paired with exercise? an exploratory study." *International Journal of Stress Management*, vol. 10, no. 3, p. 203, 2003.

[32] J. S. Lemmens, "Persistence and pleasure in vr: Enhancing exercise endurance and enjoyment through virtual environments," *Psychology of Sport and Exercise*, vol. 69, p. 102494, 2023.

[33] N. Zahedian-Nasab, A. Jaberi, F. Shirazi, and S. Kavousipor, "Effect of virtual reality exercises on balance and fall in elderly people with fall risk: a randomized controlled trial," *BMC geriatrics*, vol. 21, pp. 1–9, 2021.

[34] J. Kim, J. Son, N. Ko, and B. Yoon, "Unsupervised virtual reality-based exercise program improves hip muscle strength and balance control in older adults: a pilot study," *Archives of physical medicine and rehabilitation*, vol. 94, no. 5, pp. 937–943, 2013.

[35] M. Lee, J. Son, J. Kim, and B. Yoon, "Individualized feedback-based virtual reality exercise improves older women's self-perceived health: A randomized controlled trial," *Archives of gerontology and geriatrics*, vol. 61, no. 2, pp. 154–160, 2015.

[36] K. B. Chen, K. Ponto, R. D. Tredinnick, and R. G. Radwin, "Virtual exertions: Evoking the sense of exerting forces in virtual reality using gestures and muscle activity," *Human factors*, vol. 57, no. 4, pp. 658–673, 2015.

[37] J. Peña, J. T. Hancock, and N. A. Merola, "The priming effects of avatars in virtual settings," *Communication research*, vol. 36, no. 6, pp. 838–856, 2009.

[38] M. Alberto, "Avatar, assembled: The social and technical anatomy of digital bodies, jaime banks (ed.)(2018)." *Journal of Gaming & Virtual Worlds*, vol. 12, no. 3, 2020.

[39] E. Ash, "Priming or proteus effect? examining the effects of avatar race on in-game behavior and post-play aggressive cognition and affect in video games," *Games and Culture*, vol. 11, no. 4, pp. 422–440, 2016.

[40] J. N. Bailenson, N. Yee, D. Merget, and R. Schroeder, "The effect of behavioral realism and form realism of real-time avatar faces on verbal disclosure, nonverbal disclosure, emotion recognition, and copresence in dyadic interaction," *Presence: Teleoperators and Virtual Environments*, vol. 15, no. 4, pp. 359–372, 2006.

[41] K. L. Nowak and J. Fox, "Avatars and computer-mediated communication: a review of the definitions, uses, and effects of digital representations," *Review of Communication Research*, vol. 6, pp. 30–53, 2018.

[42] S. J. Ahn, J. Fox, and J. N. Bailenson, "Avatars," in *Leadership in Science and Technology: A ReferenceHandbook*. SAGE Publications, Inc., 2012, pp. 695–702.

[43] J. Banks, "Object, me, symbiote, other: A social typology of player-avatar relationships," *First Monday*, 2015.

[44] D. Banakou, P. D. Hanumanthu, and M. Slater, "Virtual embodiment of white people in a black virtual body leads to a sustained reduction in their implicit racial bias," *Frontiers in human neuroscience*, vol. 10, p. 601, 2016.

[45] D. Banakou, R. Groten, and M. Slater, "Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes," *Proceedings of the National Academy of Sciences*, vol. 110, no. 31, pp. 12 846–12 851, 2013.

[46] D. S. Harvie, J. Kelly, J. Kluver, M. Deen, E. Spitzer, and M. W. Coppieters, "A randomized controlled pilot study examining immediate effects of embodying a virtual reality superhero in people with chronic low back pain," *Disability and Rehabilitation: Assistive Technology*, vol. 19, no. 3, pp. 851–858, 2024.

[47] D. Banakou, S. Kishore, and M. Slater, "Virtually being einstein results in an improvement in cognitive task performance and a decrease in age bias," *Frontiers in psychology*, vol. 9, p. 368309, 2018.

[48] L. O. Kroczek, S. Böhme, and A. Mühlberger, "Face masks reduce interpersonal distance in virtual reality," *Scientific reports*, vol. 12, no. 1, p. 2213, 2022.

[49] M. Kocur, P. Schauhuber, V. Schwind, C. Wolff, and N. Henze, "The effects of self-and external perception of avatars on cognitive

task performance in virtual reality," in *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology*, 2020, pp. 1–11.

[50] B. J. Li, M. O. Lwin, and Y. Jung, "Wii, myself, and size: The influence of proteus effect and stereotype threat on overweight children's exercise motivation and behavior in exergames," *GAMES FOR HEALTH: Research, Development, and Clinical Applications*, vol. 3, no. 1, pp. 40–48, 2014.

[51] J. Peña and E. Kim, "Increasing exergame physical activity through self and opponent avatar appearance," *Computers in Human Behavior*, vol. 41, pp. 262–267, 2014.

[52] J. Fox and J. N. Bailenson, "Virtual self-modeling: The effects of vicarious reinforcement and identification on exercise behaviors," *Media psychology*, vol. 12, no. 1, pp. 1–25, 2009.

[53] J. Navarro, J. Peña, A. Cebolla, and R. Baños, "Can avatar appearance influence physical activity? user-avatar similarity and proteus effects on cardiac frequency and step counts," *Health Communication*, vol. 37, no. 2, pp. 222–229, 2022.

[54] M. Kocur, M. Kloss, V. Schwind, C. Wolff, and N. Henze, "Flexing muscles in virtual reality: effects of avatars' muscular appearance on physical performance," in *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, 2020, pp. 193–205.

[55] M. Czub and P. Janeta, "Exercise in virtual reality with a muscular avatar influences performance on a weightlifting exercise," *Cyberpsychology: Journal of Psychosocial Research on Cyberspace*, vol. 15, no. 3, 2021.

[56] J.-H. T. Lin, D.-Y. Wu, and J.-W. Yang, "Exercising with a six pack in virtual reality: Examining the proteus effect of avatar body shape and sex on self-efficacy for core-muscle exercise, self-concept of body shape, and actual physical activity," *Frontiers in psychology*, vol. 12, p. 693543, 2021.

[57] S. Samendinger, C. R. Hill, N. L. Kerr, B. Winn, A. Ede, J. M. Pivarnik, L. Ploutz-Snyder, and D. L. Feltz, "Group dynamics motivation to increase exercise intensity with a virtual partner," *Journal of Sport and Health Science*, vol. 8, no. 3, pp. 289–297, 2019.

[58] W. Xu, K. Yu, X. Meng, D. Monteiro, D. Kao, and H.-N. Liang, "Exploring the effect of the group size and feedback of non-player character spectators in virtual reality exergames," *Frontiers in Psychology*, vol. 14, p. 1079132, 2023.

[59] M. R. Rhea, D. M. Landers, B. A. Alvar, and S. M. Arent, "The effects of competition and the presence of an audience on weight lifting performance," *The Journal of Strength & Conditioning Research*, vol. 17, no. 2, pp. 303–306, 2003.

[60] L. Graf, S. Abramowski, F. Born, and M. Masuch, "Emotional virtual characters for improving motivation and performance in vr exergames," *Proceedings of the ACM on Human-Computer Interaction*, vol. 7, no. CHI PLAY, pp. 1115–1135, 2023.

[61] M. Tamm, A. Jakobson, M. Havik, S. Timpmann, A. Burk, V. Ööpik, J. Allik, and K. Kreegipuu, "Effects of heat acclimation on time perception," *International Journal of Psychophysiology*, vol. 95, no. 3, pp. 261–269, 2015.

[62] D. L. Harrington, J. L. Zimbelman, S. C. Hinton, and S. M. Rao, "Neural modulation of temporal encoding, maintenance, and decision processes," *Cerebral Cortex*, vol. 20, no. 6, pp. 1274–1285, 2010.

[63] A. C. North, D. J. Hargreaves, and S. J. Heath, "Musical tempo and time perception in a gymnasium," *Psychology of Music*, vol. 26, no. 1, pp. 78–88, 1998.

[64] H. Eisler and A. D. Eisler, "Time perception: Effects of sex and sound intensity on scales of subjective duration," *Scandinavian Journal of Psychology*, vol. 33, no. 4, pp. 339–358, 1992.

[65] M. Treisman and D. Brogan, "Time perception and the internal clock: Effects of visual flicker on the temporal oscillator," *European journal of cognitive psychology*, vol. 4, no. 1, pp. 41–70, 1992.

[66] T. Katsuura, T. Yasuda, Y. Shimomura, and K. Iwanaga, "Effects of monochromatic light on time sense for short intervals," *Journal of physiological anthropology*, vol. 26, no. 2, pp. 95–100, 2007.

[67] L. Kent, G. Van Doorn, and B. Klein, "Time dilation and acceleration in depression," *Acta psychologica*, vol. 194, pp. 77–86, 2019.

[68] J.-Y. Yoo and J.-H. Lee, "The effects of valence and arousal on time perception in individuals with social anxiety," *Frontiers in psychology*, vol. 6, p. 1208, 2015.

[69] S. K. Baum, R. L. Boxley, and M. Sokolowski, "Time perception and psychological well-being in the elderly," *Psychiatric Quarterly*, vol. 56, pp. 54–61, 1984.

[70] J. Tuckman, "Older persons' judgment of the passage of time over the life-span." *Geriatrics*, 1965.

[71] R. S. Ogden, D. Moore, L. Redfern, and F. McGlone, "The effect of pain and the anticipation of pain on temporal perception: A role for attention and arousal," *Cognition and Emotion*, vol. 29, no. 5, pp. 910–922, 2015.

[72] D. Zakay, R. A. Block *et al.*, "An attentional-gate model of prospective time estimation," *Time and the dynamic control of behavior*, vol. 5, pp. 167–178, 1995.

[73] D. Zakay and R. A. Block, "Temporal cognition," *Current directions in psychological science*, vol. 6, no. 1, pp. 12–16, 1997.

[74] D. Zakay, "The temporal-relevance temporal-uncertainty model of prospective duration judgment," *Consciousness and cognition*, vol. 38, pp. 182–190, 2015.

[75] ——, "Relative and absolute duration judgments under prospective and retrospective paradigms," *Perception & psychophysics*, vol. 54, pp. 656–664, 1993.

[76] J. Chen, "Flow in games (and everything else)," *Communications of the ACM*, vol. 50, no. 4, pp. 31–34, 2007.

[77] S. M. Schneider, C. K. Kisby, and E. P. Flint, "Effect of virtual reality on time perception in patients receiving chemotherapy," *Supportive Care in Cancer*, vol. 19, pp. 555–564, 2011.

[78] M. Sabat, B. Haładus, M. Klincewicz, and G. J. Nalepa, "Cognitive load, fatigue and aversive simulator symptoms but not manipulated zeitgebers affect duration perception in virtual reality," *Scientific reports*, vol. 12, no. 1, p. 15689, 2022.

[79] J.-L. Lugrin, F. Unruh, M. Landeck, Y. Lamour, M. E. Latoschik, K. Vogeley, and M. Wittmann, "Experiencing waiting time in virtual reality," in *Proceedings of the 25th ACM Symposium on Virtual Reality Software and Technology*, 2019, pp. 1–2.

[80] F. Unruh, M. Landeck, S. Oberdörfer, J.-L. Lugrin, and M. E. Latoschik, "The influence of avatar embodiment on time perception-towards vr for time-based therapy," *Frontiers in Virtual Reality*, vol. 2, p. 658509, 2021.

[81] F. Unruh, D. Vogel, M. Landeck, J.-L. Lugrin, and M. E. Latoschik, "Body and time: Virtual embodiment and its effect on time perception," *IEEE Transactions on Visualization and Computer Graphics*, vol. 29, no. 5, pp. 2626–2636, 2023.

[82] D. H. Landau, B. S. Hasler, and D. Friedman, "Virtual embodiment using 180 stereoscopic video," *Frontiers in Psychology*, vol. 11, p. 1229, 2020.

[83] P. Charbonneau, M. Dallaire-Côté, S. S.-P. Côté, D. R. Labbe, N. Mezghani, S. Shahnewaz, I. Arafat, T. Irfan, G. Samaraweera, and J. Quarles, "Gaitzilla: Exploring the effect of embodying a giant monster on lower limb kinematics and time perception," in *2017 international conference on virtual rehabilitation (ICVR)*. IEEE, 2017, pp. 1–8.

[84] S. Picard and J. Botev, "Rhythmic stimuli effects on subjective time perception in immersive virtual environments," in *Proceedings of the 14th International Workshop on Immersive Mixed and Virtual Environment Systems*, 2022, pp. 5–11.

[85] K. Yamamoto and K. Miura, "Effect of motion coherence on time perception relates to perceived speed," *Vision Research*, vol. 123, pp. 56–62, 2016.

[86] M. Kitajima, K. Kanari, and M. Sato, "An examination of effects of fear using vr content on time estimation," in *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology*, 2020, pp. 1–2.

[87] I. Petrizzo, E. Chelli, T. Bartolini, R. Arrighi, and G. Anobile, "Similar effect of running on visual and auditory time perception in the ranges of milliseconds and seconds," *Frontiers in Psychology*, vol. 14, p. 1146675, 2023.

[88] N. J. Hanson and T. L. Lee, "Time flies when you're at rpe13: How exercise intensity influences perception of time," *The Journal of Strength & Conditioning Research*, vol. 34, no. 12, pp. 3546–3553, 2020.

[89] N. J. Hanson and J. Buckworth, "Sex differences in time perception during self-paced running," *International journal of exercise science*, vol. 9, no. 4, p. 514, 2016.

[90] A. R. Moore and M. Olson, "Sense of time is slower following exhaustive cycling exercise," *Psychological Research*, pp. 1–11, 2024.

[91] A. Edwards and R. Polman, "Pacing and awareness: brain regulation of physical activity," *Sports Medicine*, vol. 43, pp. 1057–1064, 2013.

[92] A. Kroger-Costa, A. Machado, and J. A. Santos, "Effects of motion on time perception," *Behavioural processes*, vol. 95, pp. 50–59, 2013.

[93] M. Rietzler, F. Geiselhart, and E. Rukzio, "The matrix has you: realizing slow motion in full-body virtual reality," in *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, 2017, pp. 1–10.

[94] S. Kaneko and I. Murakami, "Perceived duration of visual motion increases with speed," *Journal of vision*, vol. 9, no. 7, pp. 14–14, 2009.

[95] M. Landeck, F. Alvarez Igarzábal, F. Unruh, H. Habenicht, S. Khoshnoud, M. Wittmann, J.-L. Lugrin, and M. E. Latoschik, "Journey through a virtual tunnel: Simulated motion and its effects on the experience of time," *Frontiers in Virtual Reality*, vol. 3, p. 1059971, 2023.

[96] M. Landeck, F. Unruh, J.-L. Lugrin, and M. E. Latoschik, "From clocks to pendulums: A study on the influence of external moving objects on time perception in virtual environments," in *Proceedings of the 29th ACM Symposium on Virtual Reality Software and Technology*, 2023, pp. 1–11.

[97] L. Lo, H. Tam, and W. Li, "Running fast and standing slow: a study on the effect of gesture posing on time perception," *Timing & Time Perception*, vol. 10, no. 1, pp. 40–55, 2021.

[98] E. Allingham, D. Hammerschmidt, and C. Wöllner, "Time perception in human movement: Effects of speed and agency on duration estimation," *Quarterly Journal of Experimental Psychology*, vol. 74, no. 3, pp. 559–572, 2021.

[99] R. Kroon, D. L. Neumann, T. M. Piatkowski, and R. L. Moffitt, "How the physical appearance of companions affects females with high or low social physique anxiety: a virtual reality exercise study," *Virtual Reality*, vol. 27, no. 2, pp. 541–551, 2023.

[100] J. Kurz, F. Helm, N. F. Troje, and J. Munzert, "Prediction of action outcome: Effects of available information about body structure," *Attention, Perception, & Psychophysics*, vol. 82, pp. 2076–2084, 2020.

[101] L. Festinger, "Social comparison theory," *Selective Exposure Theory*, vol. 16, no. 401, p. 3, 1957.

[102] D. Dunning and A. F. Hayes, "Evidence for egocentric comparison in social judgment." *Journal of personality and social psychology*, vol. 71, no. 2, p. 213, 1996.

[103] P. Gilbert, J. Price, and S. Allan, "Social comparison, social attractiveness and evolution: How might they be related?" *New ideas in Psychology*, vol. 13, no. 2, pp. 149–165, 1995.

[104] L. Wheeler and K. Miyake, "Social comparison in everyday life." *Journal of personality and social psychology*, vol. 62, no. 5, p. 760, 1992.

[105] J. D. Brown, N. J. Novick, K. A. Lord, and J. M. Richards, "When gulliver travels: Social context, psychological closeness, and self-appraisals." *Journal of Personality and Social Psychology*, vol. 62, no. 5, p. 717, 1992.

[106] R. H. Smith and C. A. Insko, "Social comparison choice during ability evaluation: The effects of comparison publicity, performance feedback, and self-esteem," *Personality and Social Psychology Bulletin*, vol. 13, no. 1, pp. 111–122, 1987.

[107] J. M. Levine and S. M. Green, "Acquisition of relative performance information: The roles of intrapersonal and interpersonal comparison," *Personality and Social Psychology Bulletin*, vol. 10, no. 3, pp. 385–393, 1984.

[108] R. L. Collins, "For better or worse: The impact of upward social comparison on self-evaluations." *Psychological bulletin*, vol. 119, no. 1, p. 51, 1996.

[109] M. Gerrard, F. X. Gibbons, D. J. Lane, and M. L. Stock, "Smoking cessation: social comparison level predicts success for adult smokers." *Health psychology*, vol. 24, no. 6, p. 623, 2005.

[110] T. A. Wills, "Downward comparison principles in social psychology." *Psychological bulletin*, vol. 90, no. 2, p. 245, 1981.

[111] L. G. Aspinwall and S. E. Taylor, "Effects of social comparison direction, threat, and self-esteem on affect, self-evaluation, and expected success." *Journal of personality and social psychology*, vol. 64, no. 5, p. 708, 1993.

[112] J. V. Wood, J. L. Michela, and C. Giordano, "Downward comparison in everyday life: Reconciling self-enhancement models with the mood–cognition priming model." *Journal of Personality and Social Psychology*, vol. 79, no. 4, p. 563, 2000.

[113] B. P. Buunk, F. L. Oldersma, and C. K. De Dreu, "Enhancing satisfaction through downward comparison: The role of relational discontent and individual differences in social comparison orientation," *Journal of experimental social psychology*, vol. 37, no. 6, pp. 452–467, 2001.

[114] F. X. Gibbons, "Social comparison as a mediator of response shift," *Social science & medicine*, vol. 48, no. 11, pp. 1517–1530, 1999.

[115] H. Tennen, G. Affleck, B. Buunk, and F. Gibbons, "Social comparison as a coping process: a critical review and application to chronic pain disorders. health, coping and well-being: perspectives from social comparison theory," 1997.

[116] D. J. Lane and F. X. Gibbons, "Am i the typical student? perceived similarity to student prototypes predicts success," *Personality and Social Psychology Bulletin*, vol. 33, no. 10, pp. 1380–1391, 2007.

[117] G. Hertel, N. L. Kerr, and L. A. Messé, "Motivation gains in performance groups: Paradigmatic and theoretical developments on the köhler effect." *Journal of personality and social psychology*, vol. 79, no. 4, p. 580, 2000.

[118] B. Weber and G. Hertel, "Motivation gains of inferior group members: a meta-analytical review." *Journal of personality and social psychology*, vol. 93, no. 6, p. 973, 2007.

119

[119] I. D. Steiner, *Group process and productivity.* Academic press New York, 1972.

[120] N. L. Kerr, L. A. Messé, E. S. Park, and E. J. Sambolec, "Identifiability, performance feedback and the köhler effect," *Group Processes & Intergroup Relations*, vol. 8, no. 4, pp. 375–390, 2005.

[121] E. J. Strahan, A. E. Wilson, K. E. Cressman, and V. M. Buote, "Comparing to perfection: How cultural norms for appearance affect social comparisons and self-image," *Body image*, vol. 3, no. 3, pp. 211–227, 2006.

[122] M. Tiggemann and A. Slater, "Thin ideals in music television: A source of social comparison and body dissatisfaction," *International Journal of Eating Disorders*, vol. 35, no. 1, pp. 48–58, 2004.

[123] M. Tiggemann and B. McGill, "The role of social comparison in the effect of magazine advertisements on women's mood and body dissatisfaction," *Journal of social and clinical psychology*, vol. 23, no. 1, pp. 23–44, 2004.

[124] R. L. Nabi and L. Keblusek, "Inspired by hope, motivated by envy: Comparing the effects of discrete emotions in the process of social comparison to media figures," *Media Psychology*, vol. 17, no. 2, pp. 208–234, 2014.

[125] T. F. Cash and L. Smolak, *Body image: A handbook of science, practice, and prevention.* Guilford press, 2011.

[126] A. H. Shah and R. Bilal, "Body composition, its significance and models for assessment," *Pakistan Journal of Nutrition*, vol. 8, no. 2, pp. 198–202, 2009.

[127] A. Rickenlund, K. Carlstrom, B. Ekblom, T. B. Brismar, B. Von Schoultz, and A. L. Hirschberg, "Effects of oral contraceptives on body composition and physical performance in female athletes," *The Journal of Clinical Endocrinology & Metabolism*, vol. 89, no. 9, pp. 4364–4370, 2004.

[128] C. M. Sabiston, J. Brunet, K. C. Kowalski, P. M. Wilson, D. E. Mack, and P. R. Crocker, "The role of body-related self-conscious emotions in motivating women's physical activity," *Journal of Sport and Exercise Psychology*, vol. 32, no. 4, pp. 417–437, 2010.

[129] J. Suls and L. Wheeler, *Handbook of social comparison: Theory and research*. Springer Science & Business Media, 2013.

[130] M. Harris and S. Foltz, "Attitudes toward weight and eating in young women tennis players, their parents, and their coaches," *Eating Disorders*, vol. 7, no. 3, pp. 191–205, 1999.

[131] E. J. Max, S. Samendinger, B. Winn, N. L. Kerr, K. A. Pfeiffer, and D. L. Feltz, "Enhancing aerobic exercise with a novel virtual exercise buddy based on the köhler effect," *Games for health journal*, vol. 5, no. 4, pp. 252–257, 2016.

[132] Y. Wang, M. Zhang, J. Wu, H. Zhang, H. Yang, S. Guo, Z. Lin, and C. Lu, "Effects of the interactive features of virtual partner on individual exercise level and exercise perception," *Behavioral Sciences*, vol. 13, no. 5, p. 434, 2023.

[133] S. C. Barathi, D. J. Finnegan, M. Farrow, A. Whaley, P. Heath, J. Buckley, P. W. Dowrick, B. C. Wuensche, J. L. Bilzon, E. O'Neill *et al.*, "Interactive feedforward for improving performance and maintaining intrinsic motivation in vr exergaming," in *Proceedings of the 2018 CHI conference on human factors in computing systems*, 2018, pp. 1–14.

[134] S. Lee, N. D. Myers, T. Park, C. R. Hill, and D. L. Feltz, "An exploratory study on the köhler effect and flow in long-term exergaming," *Simulation & gaming*, vol. 49, no. 5, pp. 538–552, 2018.

[135] B. J. Parton and D. L. Neumann, "The effects of competitiveness and challenge level on virtual reality rowing performance," *Psychology of Sport and Exercise*, vol. 41, pp. 191–199, 2019.

[136] D. Zakay, "Psychological time as information: The case of boredom," *Frontiers in psychology*, p. 917, 2014.

[137] A. Angrilli, P. Cherubini, A. Pavese, and S. Manfredini, "The influence of affective factors on time perception," *Perception & psychophysics*, vol. 59, pp. 972–982, 1997.

[138] C. Schatzschneider, G. Bruder, and F. Steinicke, "Who turned the clock? effects of manipulated zeitgebers, cognitive load and immersion on time estimation," *IEEE transactions on visualization and computer graphics*, vol. 22, no. 4, pp. 1387–1395, 2016.

[139] C. Valenzuela-Barrero, F. J. Núñez-Sánchez, I. Loturco, and F. Pareja-Blanco, "Effects of light-vs. heavy-load squat training on velocity, strength, power, and total mechanical work in recreationally trained men and women," *Biology of Sport*, vol. 41, no. 2, pp. 3–11, 2023.

[140] A. Jones, "Title of the article," *Journal Name*, vol. X, no. Y, pp. Z–ZZ, 2019.

[141] M. A. Schwarz, I. Winkler, and P. Sedlmeier, "The heart beat does not make us tick: The impacts of heart rate and arousal on time perception," *Attention, perception, & psychophysics*, vol. 75, pp. 182–193, 2013.

[142] J. M. Willardson, "A brief review: how much rest between sets?" *Strength & Conditioning Journal*, vol. 30, no. 3, pp. 44–50, 2008.

[143] N. Martinelli and S. Droit-Volet, "Judgment of duration and passage of time in prospective and retrospective conditions and its predictors for short and long durations," *Scientific Reports*, vol. 12, no. 1, p. 22241, 2022.

[144] S. Droit-Volet and Q. Hallez, "Difference between the judgment of short and long durations: estimates of durations and judgment of the passage of time," *Timing & Time Perception*, vol. 12, no. 1, pp. 15–30, 2022.

[145] T. Jokic, D. Zakay, and M. Wittmann, "Individual differences in self-rated impulsivity modulate the estimation of time in a real waiting situation," *Timing & Time Perception*, vol. 6, no. 1, pp. 71–89, 2018.

[146] W. G. Manning, "The logged dependent variable, heteroscedasticity, and the retransformation problem," *Journal of health economics*, vol. 17, no. 3, pp. 283–295, 1998.

[147] L. M. Lix, J. C. Keselman, and H. J. Keselman, "Consequences of assumption violations revisited: A quantitative review of alternatives to the one-way analysis of variance f test," *Review of educational research*, vol. 66, no. 4, pp. 579–619, 1996.

[148] U. Knief and W. Forstmeier, "Violating the normality assumption may be the lesser of two evils," *Behavior research methods*, vol. 53, no. 6, pp. 2576–2590, 2021.

[149] S. Droit-Volet and J. Wearden, "Passage of time judgments are not duration judgments: Evidence from a study using experience sampling methodology," *Frontiers in psychology*, vol. 7, p. 176, 2016.

[150] Y. Liu, S. Ma, J. Li, X. Song, F. Du, and M. Zheng, "Factors influencing passage of time judgment in individuals' daily lives: evidence from the experience sampling and diary methods," *Psychological Research*, pp. 1–10, 2023.

[151] S. Thönes and D. Oberfeld, "Time perception in depression: A meta-analysis," *Journal of affective disorders*, vol. 175, pp. 359–372, 2015.

[152] S. W. Brown, "Time, change, and motion: The effects of stimulus movement on temporal perception," *Perception & psychophysics*, vol. 57, pp. 105–116, 1995.

[153] N. Tal-Perry and S. Yuval-Greenberg, "The spatiotemporal link of temporal expectations: contextual temporal expectation is independent of spatial attention," *Journal of Neuroscience*, vol. 42, no. 12, pp. 2516–2523, 2022.

[154] R. Tanaka and Y. Yotsumoto, "Passage of time judgments is relative to temporal expectation," *Frontiers in Psychology*, vol. 8, p. 187, 2017.

[155] G. Mullen and N. Davidenko, "Time compression in virtual reality," *Timing & Time Perception*, vol. 9, no. 4, pp. 377–392, 2021.

[156] W. L. Abdullah, S. Hashim, and A. Kaleel, "Bridging traditional and immersive technologies in design education: A comprehensive framework for institutional adoption," *MEDAAD*, vol. 2024, pp. 1–8, 2024.

[157] S. Zhou, "Using virtual reality to promote physical activity," *Journal of Software Engineering and Applications*, vol. 13, no. 11, pp. 312–326, 2020.

[158] T. H. Stewart, K. Villaneuva, A. Hahn, J. Ortiz-Delatorre, C. Wolf, R. Nguyen, N. D. Bolter, M. Kern, and J. R. Bagley, "Actual vs. perceived exertion during active virtual reality game exercise," *Frontiers in Rehabilitation Sciences*, vol. 3, p. 887740, 2022.

[159] B. S. Sindhuja, I. Sankar, and S. Tiwari, "Comparison of managing fibromyalgia syndrome by integrated siddha manual therapy and energy sessions with exercises to exercise alone in women: A randomized controlled trial," *Health Sciences (IJMRHS)*, vol. 13, no. 12, pp. 01–10, 2024.

[160] F. Rapport, H. Hutchings, M. A. Doel, B. Wells, C. Clement, S. Mellalieu, S. Shubin, D. Brown, R. Seah, S. Wright *et al.*, "How are university gyms used by staff and students? a mixed-method study exploring gym use, motivation, and communication in three uk gyms," *Societies*, vol. 8, no. 1, p. 15, 2018.

[161] N. A. Schvey, T. Sbrocco, J. L. Bakalar, R. Ress, M. Barmine, J. Gorlick, A. Pine, M. Stephens, and M. Tanofsky-Kraff, "The experience of weight stigma among gym members with overweight and obesity." *Stigma and Health*, vol. 2, no. 4, p. 292, 2017.

[162] L. R. Vartanian and J. G. Shaprow, "Effects of weight stigma on exercise motivation and behavior: A preliminary investigation among college-aged females," *Journal of health psychology*, vol. 13, no. 1, pp. 131–138, 2008.

[163] J. Lewallen and E. Behm-Morawitz, "Pinterest or thinterest?: Social comparison and body image on social media," *Social media+ society*, vol. 2, no. 1, p. 2056305116640559, 2016.

[164] A. Eyck, K. Geerlings, D. Karimova, B. Meerbeek, L. Wang, W. IJsselsteijn, Y. De Kort, M. Roersma, and J. Westerink, "Effect of a virtual coach on athletes' motivation," in *Persuasive Technology: First International Conference on Persuasive Technology for Human Well-Being, PERSUASIVE 2006, Eindhoven, The Netherlands, May 18-19, 2006. Proceedings 1.* Springer, 2006, pp. 158–161.

[165] M. J. Wehrens, H. Kuyper, P. Dijkstra, A. P. Buunk, and M. P. Van Der Werf, "The long-term effect of social comparison on academic performance," *European Journal of Social Psychology*, vol. 40, no. 7, pp. 1158–1171, 2010.

[166] K. M. Awad, L. F. Tulaib, and H. M. Saleh, "Gait recognition by computing fixed body parameters," *Babylonian Journal of Networking*, vol. 2024, pp. 191–197, 2024.

[167] D. Sellen, "Physical status: The use and interpretation of anthropometry. report of a who expert committee. who technical report series no. 854. pp. 452.(who, geneva, 1995.) swiss fr 71.00." *Journal of Biosocial Science*, vol. 30, no. 1, pp. 135–144, 1998.

[168] V. A. Bittner, L. A. Coke, J. L. Fleg, D. E. Forman, T. C. Gerber, M. Gulati, K. Madan, and J. Rhodes, "Exercise standards for testing and training," *Circulation*, vol. 128, pp. 873–934, 2013.

[169] B. E. Arney, R. Glover, A. Fusco, C. Cortis, J. J. de Koning, T. van Erp, S. Jaime, R. P. Mikat, J. P. Porcari, and C. Foster, "Comparison of rpe (rating of perceived exertion) scales for session rpe," *International journal of sports physiology and performance*, vol. 14, no. 7, pp. 994–996, 2019.

[170] G. Borg, J. Skinner, O. Bar-Or, and S. universitet. Institute of Applied Psychology, *Self-appraisal of Physical Performance Capacity*, ser. Reports from the Institute of Applied Psychology, the University of Stockholm. University of Stockholm, Institute of Applied Psychology, 1972. [Online]. Available: https://books.google.de/books?id=Vba3xQEACAAJ

[171] G. Borg, "Psychophysical scaling with applications in physical work and the perception of exertion," *Med. Sci. Sports Exerc*, vol. 5, no. 2, pp. 90–93, 1973.

[172] J. Decety, M. Jeannerod, M. Germain, and J. Pastene, "Vegetative response during imagined movement is proportional to mental effort," *Behavioural brain research*, vol. 42, no. 1, pp. 1–5, 1991.

[173] E. G. Murray, D. L. Neumann, R. L. Moffitt, and P. R. Thomas, "The effects of the presence of others during a rowing exercise in a virtual reality environment," *Psychology of Sport and Exercise*, vol. 22, pp. 328–336, 2016.

[174] D. T. Gilbert, R. B. Giesler, and K. A. Morris, "When comparisons arise." *Journal of personality and social psychology*, vol. 69, no. 2, p. 227, 1995.

[175] J. Peña, S. Khan, and C. Alexopoulos, "I am what i see: How avatar and opponent agent body size affects physical activity among men playing exergames," *Journal of Computer-Mediated Communication*, vol. 21, no. 3, pp. 195–209, 2016.

[176] A. P. Buunk and F. X. Gibbons, "Social comparison: The end of a theory and the emergence of a field," *Organizational behavior and human decision processes*, vol. 102, no. 1, pp. 3–21, 2007.

[177] N. Hertz and E. Wiese, "Social facilitation with non-human agents: Possible or not?" in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 61, no. 1. SAGE Publications Sage CA: Los Angeles, CA, 2017, pp. 222–225.

[178] B. C. Irwin, J. Scorniaenchi, N. L. Kerr, J. C. Eisenmann, and D. L. Feltz, "Aerobic exercise is promoted when individual performance affects the group: a test of the kohler motivation gain effect," *Annals of Behavioral Medicine*, vol. 44, no. 2, pp. 151–159, 2012.