Mixed Reality Office System Based on Maslow's Hierarchy of Needs: Towards the Long-Term Immersion in Virtual Environments

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Abstract

In a mixed reality (MR) environment that combines the physical objects with the virtual environments, users' feelings are immersed in the virtual world, while their bodies remain in the physical world. Compared to the purely physical environments, such characteristic has led to some special needs for users' long-term immersion. However, the deficiency needs that we have to face for long-term immersion still need further research. In this paper, we apply the theory of Maslow's Hierarchy of Needs (MHN) to guide the design of MR systems for long-term immersion. Taking the normal biological rhythm of human beings as the basic unit (24 hours), we propose the fundamental needs for long-term immersion in VEs through combining the theory of MHN with the special needs of virtual reality (VR). In order to verify whether those needs can satisfy users' long-term immersion, we design an MR office system for basic operations based on the theory of MHN. A long-term exposure experiment (duration of 8 hours) is designed to evaluate those needs by comparing the results with a physical work environment after a short-term preliminary study. The physiological and psychological effects are tested in both two environments and the deficiency needs for short-term immersion and long-term immersion are also compared. The results showed that the design based on the theory of MHN can support users' long-term immersion, which means that it can be a guideline for long-term use of MR systems.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality; Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies

1 Introduction

With the rapid development of computer technology and optical design technology, head-mounted displays (HMDs) are becoming more portable and comfortable, which makes it possible to reimagine our daily lives. Mixed reality (MR) combines the virtual world and the physical world and can expand the boundaries of our physical world. Augmented virtuality (AV) that superimposes the real objects into the virtual environments (VEs) is a special case of MR, it keeps the advantages of VR and avoids the problem caused by users' complete isolation with the physical world, providing the possibility of long-term immersion.

The characteristic of immersion and the sense of presence are the core features and advantages of VR, which make users feel that the virtual world really exists [55]. The experience of "presence" may allow the mind access to memories that are out of conscious awareness for memory processing and emotional effects [94]. The presence of the VEs can induce emotional reactions of participants and reflect their cognitive changes to the real world [36], which is suitable for training and learning [88]. Such characteristics endow VR a great potential in training, education, psychology, military, and entertainment, et al. However, most of the current applications focus on short-term immersion and target specific contents. There are two main factors that constrain the applications of long-term immersion. One is the health and safety issue, i.e., uncertain physiological, psychological and cognitive effects on users of long-term immersion. The other one is that the unsystematic requirements and insufficient system are not enough to support the long-term immersion.

The health and safety issue is one of the most important problems for long-term immersion in VEs. VR creates a new environment which combines the physical world with the virtual world and extends the boundaries of the physical world. In such a mixed world, our bodies remain in the physical world while our feelings are influenced by the virtual world. Compared to the purely physical world, those differences may lead to certain side-effects. Visual discomfort and simulator sickness have been studied for many years and we have known the symptoms of the side-effects of short-term exposure to VEs. Existing researches have show that the side-effects of short-term immersion can be eliminated. However, there are few researches about the side-effects caused by long-term immersion, especially about their elimination. Apart from this, prolonged exposure to VEs may temporarily change the perceptual systems of the users' brain, but whether regular and daily doses can have permanent effects and whether they can be remedied are still uncertain. Such uncertain physiological, psychological and cognitive effects restrict the development of long-term exposure.

The unsystematic requirements and the insufficient system are also important for a long-term exposure to VEs. Requirements guide the system design, however, the current requirements about the VR system mainly focus on the visual, tactile and auditory issues. Although several existing researches concentrate on the human-centered requirements, they just study one or two specific points. Systematic requirements analysis is necessary for long-term immersion. The lack of such analysis leads to the insufficient system to support the long-term applications. However, with the integration of a common VR interface to television, smartphone, computer and even the radio, newspapers and books, VEs will take up more of

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our time and provide more possibilities for our daily lives in the future. Therefore, we have to face those two factors in the design of long-term immersion systems. Fortunately, the technology of MR offers us a possibility to solve the health and safety issue, and the human needs theory provides us a way to think about the systematic requirements for long-term immersion.

To the best of our knowledge, the proposed framework based on the theory of MHN is the first expedition to systematically study the requirements of a human-centered long-term immersion system. The discussion in the light of fundamental human needs provides a new perspective for future VEs design. In order to verify the requirements framework, we design an MR office environment for long-term immersion. The reasons why we choose office environments as a case study is as follows: Firstly, work occupies majority of the daily time of adults. In fact, adults (aged 15 to 64) spend more than 40 hours a week on their jobs [66], and the proportion of computer-based work is growing rapidly. We believe that the MR office which opens up a novel design space with exciting new opportunities for office work is on the go. Secondly, no matter what kind of computer-based work people are conducting, the basic elements of operation are similar. Thirdly, majority of office population is familiar with the basic computer operations based on the input devices (the keyboard and the mouse) and this can reduce the unrelated influence caused by participants' experience. In consideration of these reasons, we choose the office system as the first step to verify our framework.

In this paper, we aim to explore the two issues. We provide a possible way to guide the design of long-term immersion systems and explore the health and safety issue on long-term exposure to provide a reference for future researches. The research contents in this paper are divided into three steps: analysis of requirements, system design, and experimental verification. Firstly, we provide the requirements framework of long-term immersion based on the theory of Maslow's Hierarchy of Needs. Then we design a long-term immersion system based on the proposed framework. Finally, we conduct experiments to verify this framework and discuss the physiological, psychological and cognitive effects of long-term immersion on humans. We believe that this 8-hour long-term immersion experiment is the longest duration of such scientific experiment and the results of this experiment are important for future work.

The key contributions of our work can be summarized as:

- We provide a new systematic requirements framework through combining the deficiency needs of human beings with the specific needs of VEs. Taking the basic office as a case, we have constructed an MR office system under the guidance of the systematic requirements framework.

- We design an 8-hour long-term exposure experiment according to the human circadian rhythm, which is the longest exposure test in the current scientific research experiments and its experimental data could help further study of the long-term immersion.

- We statistically evaluate the physiological, psychological and cognitive effects of long-term exposure in VEs, compare the requirements for the short-term immersion and the long-term immersion to find the differences.

The remaining part of this paper is structured as follows. Sect. 2 reviews the existing works related to our work. Sect. 3 introduces the needs framework in MR, which is different from that in the physical world. Sect. 4 describes the system design of an office environment based on the proposed needs framework. Sect. 5 shows the experimental design and detailed procedures, followed by the experimental results in Sect. 6. Finally, Sect. 7 gives the discussion and conclusion about this paper.

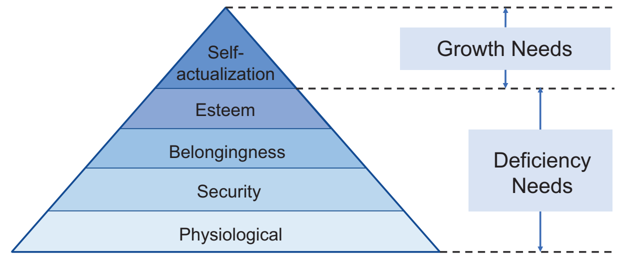


Figure 1: Maslow's hierarchy of needs.

2 Related Work

The work presented in this paper attempts to provide a requirements framework for long-term immersion, followed by a case study of MR office environments to verify this framework. A long-term immersion experiment is designed to evaluate this system and study the physiological, psychological and cognitive effects on users after long-term exposure in VEs. This section reviews the related literature on the theory of requirements for human beings, the requirements for VR, the work about the MR office, the evaluation of VEs, and the long-term immersion in VEs.

2.1 Needs Theory

Herzberg [19] proposed the two-factor theory in 1959 to describe the certain factors in the workplace that caused job satisfaction. This theory distinguished between the motivation factors and the hygiene factors, and concentrated on the factors that influence employees' job satisfaction and dissatisfaction. Alderfer [1] developed his ERG theory which included the existence needs, the relatedness needs and the growth needs. He suggested that more than one need might be activated at the same time, which meant that these needs should be more continuous than hierarchy level. McClelland [57] also proposed a need theory named McClelland Achievement Motivation Theory, which was also known as the Three Needs Theory. McClelland stated that people's motivation was directly linked to need and he identified three types of motivational need: need for achievement, need for affiliation, and need for power. Afterwards, the need for avoidance was added to this theory. However, when we consider the basic requirements for human beings, we should mention the theory of MHN, which is one of the most popular and often-cited theories of human motivation.

The theory of MHN as shown in Fig. 1 was postulated by the psychologist Abraham Maslow [56], it was a motivational theory in psychology, which expressed that the human actions were directed toward goal attainment. This theory was a key foundation in understanding how drive and motivation were correlated when discussing human behaviour. It indicated that there were certain requirements that all humans shared in order to be productive and happy, and these requirements could be classified into five levels, including physiological needs, security needs, belongingness needs, esteem needs, and self-actualization. Among these five levels, the first four layers of the pyramid are the most fundamental and basic ones, which are called "deficiency need". The individuals do not feel anything when these needs are met, but feel anxious when they are not [86]. Tay and Diener [85] tested the theory of MHN by analyzing the data of 60865 participants from 123 countries and their results showed that the need fulfilment was consistently associated with subjective well-being regardless of cultural differences. Their results also showed that we need all of the requirements without the hierarchy.

Although the theory of MHN has its disadvantages, it is still a very popular framework in motivation. The theory of MHN has been effectively applied in many fields, such as education, organization

[90], management [77], career choice [27], industrial construction [65], medicine [23], etc. The theory of MHN is also frequently applied to motivate the employee and guide the construction of a work environment. Duncan [24] used the theory to design and evaluate the hospitality houses to meet the guests' need. Chretien [17] used this theory to guide the construction of the social media in medicine and proposed the medicine hierarchy of needs pyramid. Hazeltine [34] and Elizabeth [48] also applied it to analyze the workers' needs and job-site environments.

Because of the effective and widespread use of the theory of MHN, we choose it to guide our work in this paper. The research condition in this paper is similar to that in Szocik's work [81], in which the environment on Mars is different from the physical world in our daily life. Our MR environment is also quite different from the physical world, so we think their work can be help us build our needs framework in MR.

2.2 Needs for Virtual Reality and Mixed Reality

Immersion, interaction and imagination are the basic characteristics of VR and MR. Therefore, most researches in VR focus on building highly integrated, immersive, interactive and comfortable VEs.

To meet the requirements of integration, the visual, auditory [68], haptic [50], motorial [26, 53, 62, 64, 73], olfactory [7] and even the multi-channels [25] have been studied. In order to realize high immersion, the use of depth cue [49], the perspective of users [79], the control of virtual body [76], and the way to navigation [5] are studied to conduct a more immersive environment. As for the realization of interaction, gesture interaction [60], linguistic interaction [38], gaze interaction [58], haptic interaction [22] and even brain-computer interaction have been studied.

In addition to the technical aspect of VR/MR, human factors for the comfortable use are also studied [80]. Such physiological indicators as visual discomfort [13, 31, 46, 47], simulator sickness [51, 61, 69, 75], physical fatigue [16, 67, 72] and such psychological factors as stress [3], loneliness [4, 52, 84], and emotional responses [44] have been investigated. The cognitive effects as the memory [70], the attention [8], etc., have also been studied.

Meanwhile, researchers also focus on the basic physical needs in VR environments, such as grasping real objects in VR environments [15, 33, 92, 99], eating in VR [45, 83], as well as other basic movements have also been studied.

Although there are so many studies focusing on VR/MR, they mostly concentrate on one point and lack systematical exploration. There are a lot of studies focusing on the human factor issues in this field, but most of these researches are concerned about short-term immersion. The effects of long-term immersion are still under-researched.

2.3 A Vision of Mixed Reality Office

There have existed researches investigating the use of VR for work. E.g. Wilson [95], in Information Society Technologies (IST) project, designed a VE named Virtual and Interactive Environments for Workspaces of the Future (VIEW of the Future) and discussed its human factors. Their system could design, test and train in assembly for different groups of user partners by using a movable stereoscopic projection screen. Also in the IST project, Hoffmann [37] used the desktop VR system with CAD or modelling software to create office workplaces based on user requirements. These workplaces could continuously work for 30 minutes or more without inducing negative physical and psychological effects. Although these workplaces of IST project could meet the issues of human factors and combine some complex applications about work, such systems couldn't meet the needs of long-term continuous use. Except these studies, there are other researches using VR to create a virtual workspace to enable direct manipulation of a shape model on a computer, which is similar to manipulating a real 3D object. Hirata et al. [35] constructed a virtual workspace and provided a tactile feedback to the fingertips while an object was being held. Grajewski et al. [28, 29] utilized HMDs to create a realistic immersive educational simulation of a workplace for assembly operations with the aid of haptic and VR systems. They used virtual prototypes to replace the physical ones for training the future operators or improving ergonomic quality of the workplace. This workplace could train assembly operations, but this system had few functions and could not consider human factors. Microsoft Research is also interested in the MR office, but their focus is on the input and output modules [30]. All of the researches in VR office focus on different aspects, and some of them also mention the issues of human factors. However, none of the studies have touched the systematical requirements, and all of them lack the theory to guide the system design.

2.4 Long-Term Immersion in Virtual Environments

Steinicke and Bruder [12] had conducted a self-experiment to investigate how human's cognition, perception, and behavior change over time in a fully isolated virtual world. In which one male participant was exposed to an immersive VE for 24 hours. The participant wore the HMD on his head during the entire experience except the break time. Their results showed that the participant's simulator sickness had been significantly increased during the experiment. But the sense of presence was rarely affected over time. The latency and low resolution of the HMD increased the simulator sickness. And the participant was worried about the place and plausibility illusion. Nordahl [71] also investigated the simulator sickness of two participants when being exposed to the VEs for a total of 12 hours. Up until now few studies investigated the effects of long-term immersion and their results are not statistically significance due to the adoption on only one or two participants.

3 Needs Framework in Mixed Reality

MR systems utilize the physical elements to augment the VEs. The VEs must be comfortable and healthy, and they must meet the fundamental needs of humans. The connection between the virtual world and the real world should be increased as much as possible, while the switch between these two worlds need to be minimized to reduce the discomfort. Therefore, the needs framework for long-term immersion must include the deficiency needs of human beings, the specialized needs for VEs and the functional needs for the special functions. In this paper, we use a long-term immersion office environment to verify our framework, so the functional needs in this paper are actually the office needs.

Our needs framework combining the deficiency needs of participants with the special characteristics of working in VR for long-term use of VR is shown in Fig. 2. It includes the deficiency requirements for humans, the functional requirements for office work and the specialized requirements for VEs. Strictly speaking, the functional requirements and the specialized requirements also belong to the deficiency needs because they are proposed to satisfy participants' needs. For the purpose of clarity, we describe these two requirements respectively in the following parts.

3.1 Deficiency Needs in Virtual Environments

In this paper, we discuss the deficiency needs in VEs. More strictly, we only focus on the first three layers of the MHN theory, i.e. the physiological needs, the safety needs and the belongingness needs. In the VEs, the scenes are controlled by the designers, so the relaxing environment is also important. We therefore expand the belongingness needs to the emotional needs. We do not discuss the esteem needs and the self-actualization needs in the basic needs of long-term immersion, resulting from their complexity and personalization. In summary, the deficiency needs in this paper include the physiological needs, the safety needs and the emotional needs.

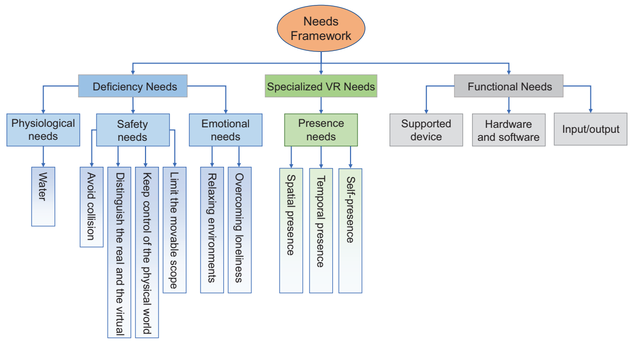


Figure 2: The need framework for long-term immersion.

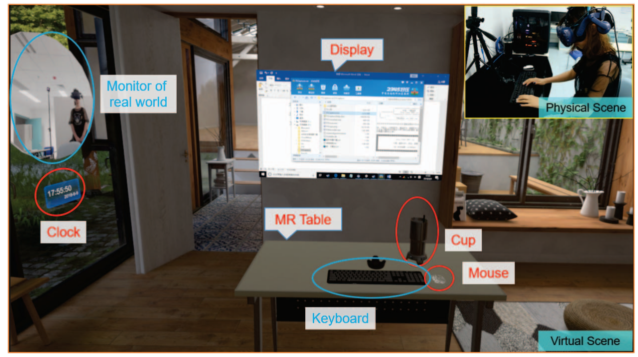


Figure 3: The environment of MR office.

Figure 4: MR cup for drinking.

Physiological needs are the most basic needs that sustain the human life. It includes the human metabolic needs and the basic needs. Metabolic demand is the minimum requirement for human survival, including food, air, water, sleep, and excretion, etc. The basic needs mainly include clothing, shelter, and sexual needs. The most basic and important thing combining the physiological needs and the conditions of VEs is to solve the problem of drinking water in VEs, because water is necessary for human lives and people need to drink water frequently. If we cannot drink in VEs, we have to frequently switch from the virtual world to the physical world, which would cause discomforts. The other physiological needs can be solved in the physical environments due to their low frequency or privacy.

Safety needs are important in VEs because of the inconsistency between the real world and the virtual world. Safety needs include life safety, financial security, physical and mental health, and accidental avoidance. When wearing HMDs in a VE, there are four needs that should be met to ensure the users' life safety, physical and mental health. Firstly, avoiding collision can ensure life safety and physical safety. Such physical objects as desks, chairs, cups, and other real objects, are necessary for long-term work, so these physical objects must be consistent with their 3D models in VEs to avoid collisions. Secondly, the model of physical objects and the virtual objects need to be distinguished to prevent falls and reduce the feeling of insecurity. This distinction can avoid such damage as falling down when sitting in a virtual chair. If users do not know which object is physical, they would feel insecure because of their fear of collision and harm. Thirdly, users must keep control of the physical world even though they are immersed in the VEs. This control can not only reduce users' panic, but also benefit users' adaptation and adjustment when they return to the physical world after a long period of exposure to VEs. It can decrease users' discomfort and reduce the cognitive load caused by environmental switch. Finally, the users' range of motion needs to be limited to avoid collision. In order to ensure the users' financial security, the functions in the VE must be good enough to keep the users work effectively. The details of the needs for working effectively are described in the functional needs.

The emotional needs in VEs include two aspects during long-term immersion. Firstly, a pleasant and relaxing VE is important to relax bodies during long-term immersion. Reducing loneliness and isolation in VEs must also be considered in long-term immersion because the long-term immersion in the virtual world will lead to a feeling of loneliness and reduce the social connection, and those feelings are detrimental to users' health [39, 98].

3.2 Specialized Needs for Virtual Environments

In addition to the deficiency needs in VEs, there are some special needs related to the VEs. Among all the requirements of VR/MR, the presence needs are essential for long-term immersion. Except the concept of "being there" (spatial presence), the temporal presence and the self-presence also need to be considered during the long-term exposure to the VEs. Spatial presence is the cognitive feeling of being in a place [78], which not only includes the sense and perception of the space where users stay, but also includes the accurate judgment of their positions and the distances in the virtual space [5]. In VEs, the mismatch between the visual cues and the objects will influence users judgement of space, or even induce spatial perception disorder [9, 82]. Temporal presence is vital to human's life although we cannot clearly feel it in the real world. It affects people's life schedule and their cognitive state [87]. Living in a world that cannot accurately judge time will both affect people's cognition of time and the synchronization of human's psychological clock [40]. Therefore, it is important to add cues for users to estimate time in the VEs. In consideration that in most VEs, we cannot see our body and lack the sense of self, we need to consider self-presence in VEs. Self-presence is defined as users' mental model of themselves inside the virtual world, including physical self-presence and inner self-presence [6]. Physical self-presence is the sense of users' own body, which includes embodiment and ownership. Embodiment indicates that users can feel that they have a body, and ownership indicates that users can feel that the body belongs to themselves [20, 63]. Therefore, we need to add some cues for self-presence in VEs.

3.3 Functional Needs for Work

Except those needs for long-term immersion in mixed environments, the functional needs must also be considered. In this paper, the functional needs are applied to ensure effective work. These needs include the devices for working, the hardware and software systems, and the effective input and output systems. The devices include computers, chairs, desks and display devices. The hardware and software systems are similar to their real office counterparts. In order to make the system input more effective, we design an MR I/O system using keyboards and mice for work because of their effectiveness and stability.

4 Mixed Reality Office System

In order to verify whether the proposed needs framework is sufficient to support long-term exposure to VEs, we design an MR office environment for a normal work routine. The MR office environments include the physiological system, the safety system, the emotional system, the functional system and the presence system based on the needs framework. Many of those needs are solved by the works of previous researchers, and many of them are solved by ourselves. Fig. 3 illustrates the whole MR office environment. In this section, we present each part of this MR office system in the following order: Firstly, we provide the core technical issues of this part. Secondly, we present the current solutions of those issues. Finally, we describe the approach that we have adopted.

4.1 Physiological Sub-system

Based on the requirements of long-term immersion, the physiological sub-system aim to solve the problem of drinking water in VEs. The core technical issue of this problem is to accurately grasp the physical objects in VEs. Numerous studies focus on virtual grasping [14, 33, 42], but most of them are interested in grasping virtual objects with tactile or force feedbacks. In order to reduce the complexity of interaction and increase the freedom of users, we solve this problem with the help of model-matching.

A virtual model of the physical cup is built for users to visually perceive the physical cup in the VEs. A tracker is fixed under the bottom of the physical cup as shown in Fig. 4 for real-time tracking and precise localization. The capacity of this cup is 591 ml, and the weight is 350 g. The cup can be tightly closed with a lid, and users can drink water through a straw to prevent water spalling out during careless collision. The triangular tracker is fixed under the cup to maintain stability and effectively tracking of the position of the cup in real time.

4.2 Safety Sub-systems

In order to meet the safety needs, the safety sub-system includes four parts.

Firstly, in order to keep consistency between the real objects and the virtual objects, we build the virtual models for every physical object in the VEs and use trackers to track them. In this environment, a desk, a chair, a cup, a keyboard and a mouse are included both in the physical world and in the virtual world.

Secondly, in order to separate the model of real objects from the virtual objects, we highlight the 3D virtual models of the real objects when pressing the lateral button of the handle. In the VEs, there are more virtual objects than real objects, so it is more convenient to highlight the 3D models of real objects in VEs, this will also be helpful to remember the few real objects. Users can use it to remind themselves at any time when they are confused and forget the real objects.

It is also important to maintain familiarity and control of the real environments, so we use a monitor in the virtual office shown in Fig. 3 for users to keep connection with the real world. We use a camera to shoot the real environment and map it to the monitor in the VEs to make users keep connection with the real world.

Finally, the issue that the range of motion in the VEs must be consistent with the real environment, is solved by setting the room boundary using HTC VIVE Pro's own room setting system. These designs can effectively prevent collisions and accidents in the VEs to protect users as much as possible.

(a) (b)

Figure 5: Virtual Environments. (a) Relaxing environment with green forest. (b) Monitor for overcoming loneliness.

4.3 Emotional Sub-system

The pleasant and relaxing VEs and the loneliness and isolation reduction units are the basic requirements of emotional sub-systems.

Since office environments will obviously affect both job performance and job satisfaction [10], a pleasant and relaxing working environment can effectively recover users from stress and depression [18, 89]. Previous studies showed that such natural elements as forest and park are beneficial to staff's physical and mental health and can increase staffs' job satisfaction and organizational commitment [2]. The artificial nature has the same effects with the real nature. Therefore, the MR office environment is set to a green forest environment as shown in Fig. 5 (a). The office is located on the lawn surrounded by a number of trees and flowers.

The loneliness and isolation reduction unit aims to reduce loneliness and keep connection with the real world. In the MR office environments, we use an image window to keep connection with the real world and use music to keep the environments alive. We choose an area in the physical environment as the connecting area. A camera is set to capture the person who enters this area and transmits this image into the VE. The user who immerses him/her-self in the VE can communicate with this person through the image window to keep connection with other people and overcome loneliness. Fig. 5 (b) illustrates the loneliness and isolation reduction system.

4.4 Functional Sub-system

4.4.1 Basic Devices for Work

In order to support long-term work, such basic devices as desks, chairs and computers are necessary. In the proposed VR office system, we use a table to place keyboard, mouse, cup, and HMDs. An ergonomic chair is used for long-term comfortable sitting. A computer is used to render the scene and a HMD is used to display the office interface.

4.4.2 Supported Unit

The VR office environments run on a desktop computer with the following configuration: Intel Core i7-6700K, dual-core chips of NVIDIA GeForce GTX 1080Ti, 16 GB RAM. The resolution of the computer is 1920×1080 pixels. The HMD used for the experiment is HTC Vive Pro, which includes the head-mounted display unit, the position posture tracking unit as well as the handle controller unit. The resolution of monocular display is 1400 x 1600 pixels, and the binocular resolution is 2880 x 1600 pixels. The refresh rate of the display is 90 fps and the delay is 22ms. The accuracy of position and posture tracking system is 0.1 degree with active movement.

4.4.3 MR Input/Output Unit

Nowadays keyboards and mice are among the most familiar and effective input devices for office systems, so we use the common keyboard and mouse for users' tasks. Many existing researches focus on how to effectively use the keyboard in VEs. Mehring et al. [59] used the combination of a keyboard and a glove for typing tasks in VR, and Wu et al. [96, 97] combined a keyboard with haptic feedback to enhance human-computer interaction in an immersive

Figure 6: Mixed Reality I/O System.

VR environment. However, they are not suitable for long-term work because of increasing interactive redundancy. In the proposed MR office environment, we design a MR keyboard without using glove for the purpose of freedom and effective typing. The MR input/output (I/O) system is shown in Fig. 6.

The hardware of the MR I/O system contains a real keyboard, a real mouse, a tracking device for keyboard and a tracking chip for mouse. The software contains the module for hand segmentation and the module for hand-keyboard and mouse fusion. We use a RealSense camera to capture the RGB image and the depth image to capture the current depth view of the user. We then segment the hand area and put a virtual keyboard and a virtual mouse according to their real positions. Afterwards, we fuse other virtual elements with the virtual keyboard and add the segmented hand image into the VEs. This system is effective and accurate, and it can greatly improve the freedom of long-term work. The detailed setup is similar to the work of Jiang et al. [41].

4.5 Presence Sub-system

Spatial presence, temporal presence and self-presence are necessary in VEs. Spatial presence is mostly influenced by the VEs. In our MR office environments, we construct a high-fidelity MR office environment which is similar to the real environments and control the light carefully to make the environment realistic. The familiar objects in VEs will increase the spatial presence of users.

As for the temporal presence, some researches use such indirect cues as the change of sunlight, or the sunrise and sundown [74] to remind the changes regarding time. In our system, we use a digital clock to remind the date and the time. The clock is shown in Fig. 3.

The self-presence in this sub-system is achieved with two methods. The first one is that users can see their hands when they are working, playing and drinking. The second one is that users can see themselves through the monitor to recognize their own existence.

5 Experiment

The long-term experiment is designed to evaluate whether this MR work environments can support long-term immersion in MR based on a normal biological rhythm, as well as to the effects of long-term immersion on participants. These efficiency and effects are compared with those in the physical environments. Before the long-term exposure experiment, we have conducted a short-term preliminary experiment to measure the efficiency of the MR office environments and evaluate the discomfort of users, which is also served as a comparison for long-term immersion experiments. The study on the short-term exposure [32] is the foundation of the long-term immersion experiment.

5.1 Participants

30 participants are recruited to participate in the experiment. A within-subject method is adopted in the experiment to exclude individual difference. Three participants quit the experiment when they conducted experiment in the physical environment. The first one quit the experiment because he feels the task is boring. The second one is too tired to finish the tasks because of the lack of sleep at noon. The third one feels uncomfortable because of long-term use of computers. Finally, 27 participants (15 males and 12 females) finished both the task in MR office environments (MR office group) and in the real office environments (RE office group).

The average age of those 27 participants is 24.04 ($SD = \pm 2.244$) years old. The average time of working in computer is 7.11 ($SD = \pm 2.592$) hours in their daily life. 85.3% of them ($n = 23$) have experienced HMDs before the experiment. 44.4% of them ($n = 12$) suffer from a carsickness or seasickness occasionally, and the others never suffer from a carsickness or seasickness. 7.4% of them ($n = 2$) seldom suffer from motion sickness when they are watching 3D movies while the others never. The level of their myopia is less than 500 degrees. The subjects slept well and had a normal work-rest schedule during the month before the experiment. They do not have any auditory and visual impairment, mental retardation, history of visual disease and brain injury that might affect the results either. None of them suffer from claustrophobic and depression. The participants are asked to avoid driving cars or other heavy machines within 2 or more hours after the experimental session. This study is approved by the local ethics committee, and all participants provide the written informed consent after the complete description of the study.

5.2 Stimuli

The most basic operation of computer-based work is the operation of the keyboard and the mouse. Accordingly, we design four tasks: texture input (only keyboard is used), image classification (only mouse is used), document correction (frequent keyboard use with occasional mouse use), and the keyword searching (occasional keyboard uses with frequent mouse use). In order to avoid the empirical effects, the tasks in the physical environment are matched with the tasks in the MR office.

The phrases for texture task are taken from the work of Mackenzie et al. [54] in 2003. The source includes 500 phrases and these phrases have similar performances. The phrase set does not have punctuation and it contains only lowercases (uppercases can be ignored and replaced with lowercases). In our experiment, 500 phrases are randomly assigned to the two environments.

The images for the image classification task are downloaded from the ImageNet database [21], including five categories: flower (177 images), fruit (946 images), car (1309 images), cat (1083 images) and human (1015 images). Images appear randomly during the experiment. And subjects under both the real environments and the VEs use the same image database.

Documents used for document correction in the MR office environment and the real office environment are selected from different chapters in the same book written by one author. The book is named "The Story of Sahara", which is written by Echo Chan. Those two documents have the same number of errors, including spelling mistakes, repetition, reverse order and missing words. Subjects need to read this document and correct the mistakes.

In the keywords searching tasks, subjects need to search the explanation and the image of the keywords and finish it in the Microsoft PowerPoint. This task imitates the popular web search. However, in order to avoid the impact of network instability, we prepare the keyword explanation documents and the keyword image document. Therefore, the subjects search the keyword in documents instead of searching in the web and then make keywords in Microsoft PowerPoint. The template of PPT is fixed, including the title (the keyword), the explanation and a figure about the keyword. 130 keywords are matched and assigned to two groups, such as “virtual reality” in MR group and “augmented reality” in RE group. Such keywords as rose and coffee etc. are used frequently, while some other are not, like Kronosaurus. Subjects need to evaluate their familiarity with every keyword.

5.3 Experimental Procedure

A comparative-study for normal work routine (from 9:00 am to 5:00 pm) is designed to verify whether the requirements framework can support the long-term immersion. The whole experiment contains three parts, including the training test, the MR office test and the real office test. In order to avoid the empirical effects, all participants randomly start the MR experiments or the real experiments at first. Then they conduct another test after one-week's recovery.

Before the first experiment, the participants are trained to familiarize with the experimental procedure and experience a game with HMDs for thirty minutes to evaluate their reactions on VEs. The experimental procedure of 8 hours' test is shown in Fig. 7. For the MR office test, participants need to continuously wear HMDs during the whole experiment except the lunch.

Before the test, we evaluate participants' baseline states through objective measurements and subjective measurements. Every 90 minutes is served as a stage, including 40 minutes' task, 20 minutes' attention task, 10 minutes' subjective measurements, and 20 minutes' rest [54]. Document correction which combines the use of keyboard and mouse is the first task because the moderate difficulty can help participants to familiarize with the system. The second task is keyword searching with less cognitive load. Text input is the third task which happens after the lunch and rest when the participants are quite familiar with the MR keyboard and have enough recovery. The last task is image classification. It is the easiest task when the participants are really tired after one day's work. Subjective measurements are measured after every one hour's work and objective measurements are measured before participants wear the HMDs and after thay take off the HMDs. As a result, the participants have a total of 7 times of subjective tests and 4 times of objective tests during the one day's experiment.

5.4 Measurements

Simulator sickness questionnaire (SSQ)is used to measure participants' physiological effects. The positive and negative affect survey (PANAS) is used to measure participants' psychological indicators. The presence questionnaire (PQ) is used to investigate the presence of the office system. The system usability scale (SUS) is used to evaluate the availability and accessibility of the system.

Simulator Sickness Questionnaire SSQ is designed by Kennedy et al. [43] and includes 16 items. Every item has four levels, in which level 0 represents the state of ”absolutely not” and level 3 represents the state of ”completely yes”. SSQ can test four symptoms about simulator sickness: nausea, oculomotor, disorientation and the total symptoms.

Positive and Negative Affects Survey PANAS is designed by Watson et al. [93] in 1988 and consists of 20 items and every item has five levels. Level 1 represents the state of ”absolutely not” and level 5 represents the state of ”completely yes”. This scale can evaluate participants' positive state and negative state.

Presence Questionnaire PQ is designed by Usoh et al. [91] in 2000 and consists of 6 items. Each item has 7 levels, in which level 1 represents the state of ”absolutely not” and level 7 represents the state of ”completely yes”.

System Usability Scale SUS is designed by John et al. [11] in 1996 and includes 10 items with 5 levels. Level 1 represents the state of ”absolutely not” and level 5 represents the state of ”completely yes”.

6 Results

In this paper, we use the number ”X” to stand for the X times to measure the symptoms, in which the number of ”1” represents the participants' baseline before the test. ”2” represents the stage after document correction, ”3” represents the stage after keywords search, the ”4” represents the stage after dinner and rest, ”5” represents the stage after texture input, ”6” represents the stage after image classification and ”7” represents the stage after the whole experiment. We use the capital letter to represent the abbreviations for each symptom, e.g. the capital letter of ”N” represents the symptom of nausea and ”N1” represents the first time to measure the symptom of nausea.

6.1 Analysis of Physiological Effects

The results of SSQ were shown in Fig. 8. The horizontal axis stood for the times to measure the symptoms, and the vertical axis represented the average score of the symptoms. The higher the score was, the severer the symptoms were. The results indicated that the SSQ symptoms in both the MR office and the physical office were positively correlated with the working time. The mean score of SSQ increased with the working time, which means that the longer the working time is, the severer the simulator sickness is. In a word, with the increase of working time, participants became more and more discomfort.

The result of analyzing the data with the repeated-measurement difference analysis showed that during one day's test, the symptoms of nausea (N) ($F(6,26) = 6.050, p < 0.001$), oculomotor (O) ($F(6,26) = 20.168, p < 0.001$), disorientation (D) ($F(6,26) = 11.602, p < 0.001$) and the total score ($F(6,26) = 15.391, p < 0.001$) in MR office environments had significant difference over time. For the RE office group, the symptoms of oculomotor ($F(6,26) = 12.997, p < 0.001$), disorientation ($F(6,26) = 5.545, p < 0.001$) and the total score ($F(6,26) = 7.318, p < 0.001$) had significant difference over time. However, the symptom of nausea ($F(6,26) = 1.717, p = 0.120$) in RE office had no significant difference with the increase of time. After the first task (document correction), the symptom of oculomotor ($p = 0.001$) in RE office group had significant difference compared with the baseline. The other symptoms (nausea, disorientation and total symptom) had no significant difference. However, in MR office group, all of those symptoms had significant difference between the second score and the baseline. After the second task (keyword searching), the symptoms of nausea ($p = 0.026$) and oculomotor ($p = 0.035$) in RE office group had significant difference, and the symptom of disorientation had no significant difference between D3 and D2. But in MR office environments, the symptoms of oculomotor ($p = 0.017$) and disorientation ($p = 0.010$) had significant difference, and the symptom of nausea had no significant difference between N2 and N3. After the lunch, all of these symptoms had a tendency to be relieved, but none of these symptoms was recovered to the baseline. Except the symptom of nausea in the RE office environments, all the other symptoms had a significant difference between the fourth measures and the baseline ($p < 0.05$), which meant that a lunch and rest at noon could help the participants to recover from the discomfort, but couldn't recover to their best states. For the third task (texture input), only the symptom of oculomotor had significant difference both in RE office environments and in MR office environments between O4 and O5. The other symptoms had no significant difference. For the fourth task (image classification), all of those symptoms under both two environments had no significant difference ($p > 0.05$). What interested us is that all symptoms between the sixth measure and the final measure were relieved. The symptom of oculomotor both in RE office environments ($p = 0.027$) and in MR office environment ($p < 0.001$) had significant difference. The results showed that the symptom of oculomotor become severer quickly with the increase of time, while it recovered more quickly than other symptoms.

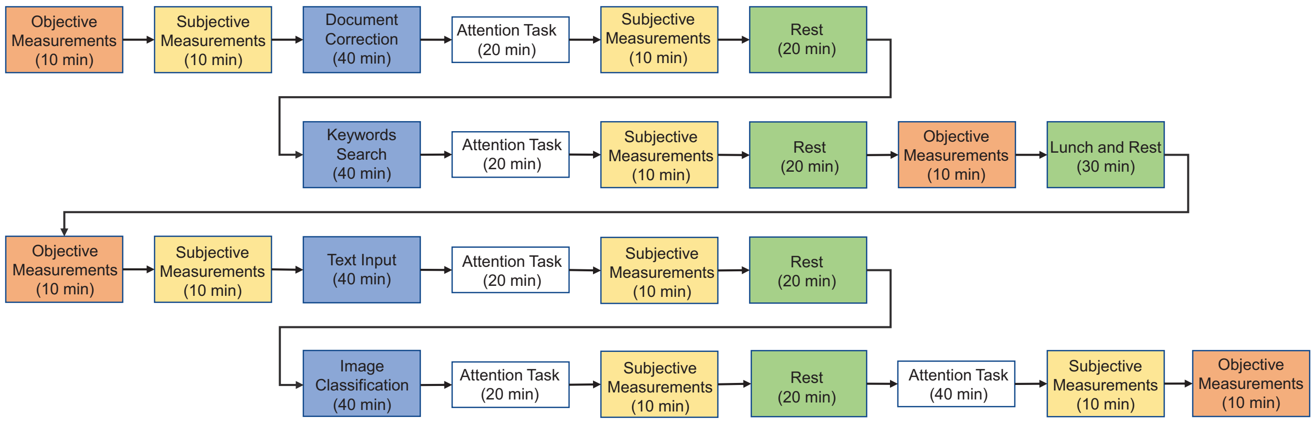


Figure 7: Experimental Procedure.

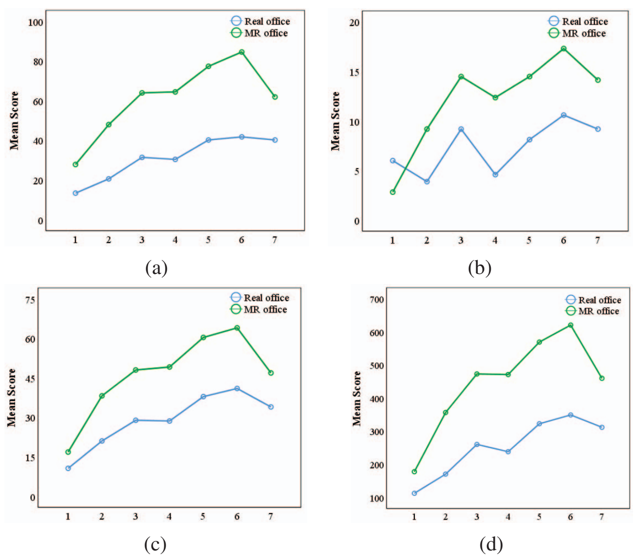


Figure 8: Results of physiological effects. (a) The symptom of disorientation. (b) The symptom of nausea. (c) The symptom of oculomotor. (d) The total score of SSQ.

Results of two-way ANOVA showed that the environments (the real office environment and the MR office environment) had significant influence on the symptoms of SSQ. The symptoms of nausea ($F(1,24) = 6.011, p = 0.047$), oculomotor ($F(1,24) = 11.369, p = 0.003$), disorientation ($F(1,24) = 8.565, p = 0.007$) had significant difference between both two groups. The results showed that the MR office environments induced severer symptoms of nausea, oculomotor and disorientation than the real office environments.

6.2 Analysis of Psychological effects

Fig. 9 showed the results of PANAS in those two environments. With the increase of working time, the positive affects (PA) had been continuously decreased in both two environments. And the negative affects had few changes in these two systems.

Result of two-way ANOVA showed that the environments (the real office environment and the MR office environment) had no significant influence on both the positive affect and the negative affect.

Repeated-measurement difference analysis showed that the positive affect ($F(6,26) = 18.127, p < 0.001$) in RE group had significant difference with the increase of time, while the negative affect ($F(6,26) = 3.746, p = 0.698$) had no significant difference. The results were similar in MR office environments, which showed that the positive affect had significant difference ($F(6,26) = 27.066, p < 0.001$) and the negative affect had no significant difference ($F(6,26) = 2.074, p = 0.059$). The results indicated that the long-term work could reduce participants' positive emotions, but did not have influence on their negative emotions. The comparison of each task, both in MR office group and in real office group showed the same changes that the tasks after a long-time break (the first task and the third task) caused a significant drop in participants' positive emotions ($p < 0.01$) while the other task (the second task and the forth task) did not cause significant difference ($p > 0.1$). It was interesting that the positive emotion in MR office groups had a significant increase during the last task. The difference between PA6 and PA7 in MR office group was statistically significant ($p = 0.015$), while the real office group had the same tendency but had not significant difference ($p = 0.099$). The results showed that the long-term work would decrease participants' positive emotions in both two environments, but the end signal would make participants' positive emotions rise rapidly.

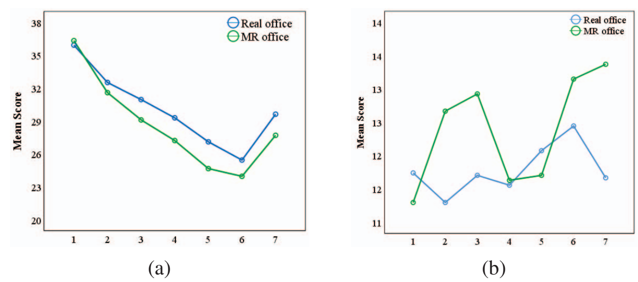
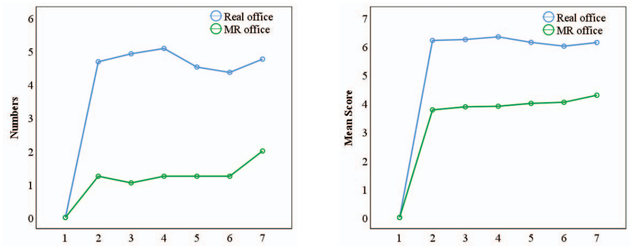


Figure 9: Results of psychological effects. (a) The change of positive effect. (b) The change of negative effect.

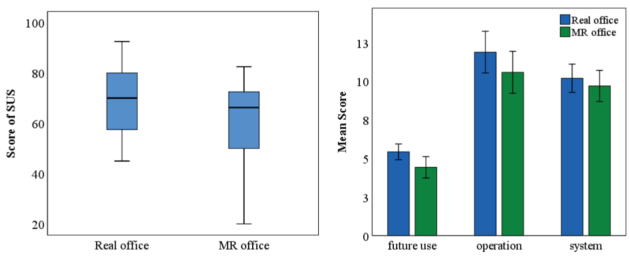
6.3 Analysis of the Sense of Presence

The presence questionnaire was used after every task and tested a total of six times, whose results were shown in Fig. 10. The higher the score was, the stronger the sense of presence was. And the data was analyzed by logistic regression rather than normal regression. The column "PQ Count" showed the mean of the SUS count of "6" or "7" scores among the 6 questions and the column "PQ Mean" uses the mean score across the 6 questions. The results of two-way



(a) (b)

Figure 10: Results of presence. (a) Results of PQ Count. (b) Results of PQ Mean.



(a) (b)

Figure 11: Results of system usability. (a) The score of SUS. (b) The score of each indicator.

ANOVA showed that the PQ count had a significant difference in those two environments ($p < 0.001$), while no significant changes with time. The count in MR office environments was significantly lower than the count in the real office environments. The results also showed that the PQ mean score in the MR office environment was significantly lower than the real office environments. Those results were mainly reflected in Q3 (Did the office space seems to be more like naturally?), Q5 (Was the office space similar to other places that you have been visited?) and Q6 (Did you feel you actually in the office space?). All of those questions were about the theme that remembered the VE as a 'place'. The results showed that the unfamiliarity with the virtual office environments reduced participants' feeling of presence.

6.4 Analysis of System Usability

The System Usability Scale was used to evaluate the usability of the MR office environment and the real office environment. There were 26 valid data items for SUS analysis resulting from one participant forgetting to finish the scale. Paired sample T-test showed that the total score of SUS had no significant difference between those two environments ($p = 0.052$). But there was a tendency that the real office ($score = 68.75 \pm 13.365$) was more useful than the MR office ($score = 61.73 \pm 15.112$) as shown in Fig. 11 (a). The total ten indicators of SUS had been divided into three themes, as shown in Fig. 11 (b), which were the system indicators (indicators of integration, complexity, inconsistency, and cumbersomeness), operational indicators (easy to learn, easy to use, need to be supported and the need of train) and the index about the future use (frequency to use and confidence about the system). The results of the paired sample T-test showed that the indicators about the future use had a significant difference ($p = 0.016$), which means that the participants would like to use the real office system in the future. The indicators about the system in these two groups had no significant difference ($p = 0.312$). And there was a tendency that the operation in RE group was more convenient than MR group ($p = 0.085$). The indicators of being easy to use, easy to learn and need to be trained were consistent in both two groups, but the MR office group showed a higher score of the need for the support of a technical person ($p = 0.051$). The results showed that the reason why the participants were not confident in using MR may be the current complex setup (need help from staffs) of the virtual reality device rather than the MR system itself.

6.5 Analysis of Requirements Meeting

Through directly interviewing the subjects after the experiment and indirectly observing and recording the unconscious behavior of the users throughout the whole experiment, we compared the differences between the 40-minutes' short-term immersion and the 8-hours' long-term immersion. The short-term experiment [32] we conducted before the formal long-term experiment was a small test, which exploited the same setup of hardware, similar kind of tasks, and similar subject group.

For the physiological needs, the participant in the short-term immersion are not reflected. Even there is a cup for water, none of them drink water during the whole test. But the physiological system in long-term immersion actually worked. The participants in both the physical office environments and the MR office environments had drunk water. But it was interesting that the participants drank water when the task was finished, which was not similar to the normal work routine that we drank at anytime.

For the safety needs, the consistency between the real objects and the virtual objects, the control of physical environments, the limitation of the movable scopes all have worked both in the short-term immersion and the long-term immersion. What's more, in the two experiments, all participants only used the function that distinguishes the models of real objects from the virtual objects at the training stage. This phenomenon may be caused by the few models of real objects, which allows users to remember these distinctions at once.

For the emotional needs, the relaxing environments worked. The participants in short-term immersion were more enjoyable in the MR environments (50%) than the real environments (22%) (the others enjoyed both two environments). For those participants in long-term immersion, they said that they saw the virtual green yard for relaxing and recovered when they were tired during the whole experiment. 83% of them said that the VEs made them more concentrated. However, the function of reducing loneliness was ignored in short-term exposure and include in long-term exposure. The participants in long-term immersion chatted with the experimental workers.

This MR office environment was designed for basic computer operations, so all the functional systems had been used in both two experiments. As for the presence needs, we used the eye-tracker to capture users' gaze point. The temporal presence could be evaluated by the frequency of users gazing the clock. The self-presence could be evaluated by the time when users saw their virtual hands and it can be tested by the questionnaire.

7 Conclusion

In this paper, we propose a needs framework for long-term immersion in VEs by combining the deficiency needs of Maslow's hierarchy of needs with the special characteristics of virtual environments. The deficiency needs in VEs for human beings, the specialized needs of VR/MR, and the functional needs for the specific function of long-term immersion have been discussed. A case study of MR office environment is designed based on the needs framework. A long-term exposure experiment is conducted to verify these needs and evaluate the physiological, psychological and cognitive effects on users for long-term immersion.

By comparing the long-term exposure experiment with the short-term exposure experiment, it can be concluded that the physiological needs (like drinking water) and the belongingness needs (like communicating with others) are necessary for long-term immersion, but can be ignored during short-term immersion. The safety needs, which are reflected in avoiding collision, distinguishing the model of physical objects and the virtual objects, keeping control of the physical world, and limiting the movable scope in VEs, must be met in both the short-term immersion and the long-term immersion. Similarly, the requirements of relaxing environments of the emotional needs should be satisfied under both two conditions. The spatial presence needs should be met under both two conditions, while the temporal presence needs and the self-presence needs are only required by the long-term immersion.

However, there are still certain limitations in our work. Firstly, we only discussed the needs of drinking water in the physiological needs, but many people have a habit to eat snacks during their long hours of work. Therefore, it is necessary to include the need of eating food in the physiological needs. This shows the disadvantage of our method of drinking water, which uses a tracker and a virtual model with the physical cup for drinking water. This method is effective under the condition that we do not need to see the details and the objects are few. But it is not suitable for the situation where we cannot build the model for the food. Therefore, we will use the method of image classification to solve this problem in the future.

Secondly, the collision avoidance of our work is solved by building the model for every physical object, but the real scene is so complicated and changeable that we could not build the model for every changeable object. A more effective way is to build the virtual models of the physical environments and overlap it to the VEs in real time. This method is related to the technology of large-scale tracking in VEs.

Thirdly, in order to overcome the loneliness and reduce the feeling of isolation, we use a camera to capture the person in the physical world and render it to the VEs. But this function only works when the person walks into the fixed area. Therefore, a freer way needs to be adopted to meet this need. At the same time, users will also feel isolated because no people are in the virtual world. Therefore, multi-personal environments and remote-cooperated environments also need to be adopted in the future.

In addition, we list the needs of presence, including the spatial presence, the temporal presence and the self-presence in this paper. We believe that those presences are important, but we still do not know their clear impacts. The effects of temporal presence and self-presence need further study.

Finally, all the scenes and objects in the MR office system are set by the designers, and users cannot choose the appearance of the virtual objects in front of their eyes. This is a passive MR office system that users cannot participate in it. In the future, a more active method should be adopted to replace this method.

Although there are still limitations with our work, we believe that the needs framework for long-term immersion proposed in this paper could be a guideline for the future's design of long-term MR immersion systems.

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