Affordances and Performance of the Limbic Chair in Embodied Virtual Reality Flying: A Comparison between Flexible Perching Interface and Existing Sitting and Standing Interface

by

Yaying Zhang

Bachelor of Engineering, Chongqing University, 2015

Bachelor of Art, Chongqing University, 2015

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Name:	**Yaying Zhang**
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Title:	**Affordances and Performance of the Limbic Chair in Embodied Virtual Reality Flying: A Comparison between Flexible Perching Interface and Existing Sitting and Standing Interface**
Examining Committee:	**Chair: Michael Filimowicz** Senior Lecturer
	Thecla Schiphorst Senior Supervisor Professor
	Bernhard Riecke Co-Supervisor Associate Professor
	Carman Neustaedter External Examiner Associate Professor
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Ethics Statement

Abstract

Virtual reality (VR) allows people to interact within virtual environments (VEs) to extend our own physiological and physical constraints, enabling us to conduct activities such as embodied flying that are impossible to do in the real world. Current research in academia and industry has developed three categories of VR flying interfaces: lying-based, standing-based and sitting-based, and each of these have specific physical constraints. For example, lying-based interfaces may cause neck fatigue, and sitting-based and standing-based flying interfaces constrain the user's lower body to a sitting position or to the ground requiring that their feet and legs are not free to move as if they were in the air. In this thesis, we explored a new kind of possibility to support VR flying: a "floating chair" – called the Limbic Chair. Two studies were conducted. In Study 1, an observational study, VR experts explored the affordances of Limbic Chair use as a VR flying interface: we explored participants' preferred VR flying navigation movement choices, and generated three considerations of using the Limbic Chair as a flying interface. In Study 2, we applied the results of Study 1 to the Limbic Chair in VR flying and queried into the experiential qualities of the VR flying experience as compared to standing and sitting on a normal chair. A one-factor between-subject experiment was conducted using both quantitative and qualitative methods in the Study 2. The result showed that the Limbic Chair received more votes than the normal chair and standing interfaces in "closest to people's imagined way of flying", but not significantly outrivaled the other two interfaces in other qualities. The deeper investigation revealed a disconnection between "likeness to flying" and "good flying experience". We proposed future study directions for further exploration on the VR flying supported by the Limbic Chair.

Keywords: Virtual Reality; 3D Locomotion; Flying

Dedication

For my mother and father who always support me and dedicated all their love to me.

You are the greatest mom and dad in the world <3.

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List of Acronyms

VR	Virtual Reality
VE	Virtual Environment
HMD	Head Mounted Display

Chapter 1.

Introduction

A crucial problem in virtual environments (VEs) research is how best to develop interfaces that allow for natural and effective user interactions within virtual space and objects (Usoh et al., 1999). Locomotion through virtual spaces is the most basic and important example (D.A. Bowman, Koller, & Hodges, 1997; Iwata, 1999). The locomotion mentioned in this thesis refers to the first person's viewpoint change in a virtual space. A user in virtual reality (VR) could perform a variety of locomotion types such as walking, steering, and flying. Among the these kinds of locomotion, flying is a most intriguing one because flying is an experience that we human beings had long dreamed of achieving (X. Tong et al., 2016). In human history, people have attempted various ways to fly in reality, like parachuting, skydiving, hand gliding, the design of airplanes, helicopters and so on. However, due to the structure of our physical bodies, it's hard (or impossible) for us to achieve truly embodied flying, in another words, we cannot fly like a bird, without external mechanical support. Fortunately, with the increasing power and affordability of virtual reality (VR) technology, we can now allow people to control their movements and experience their simulated environment in ways that are impossible in the real world. VR designers can replace the user's vision with any imaginary world, and enable the user to interact with the new world in novel new ways, including flying.

1.1. Virtual Reality (VR)

Virtual reality (VR) is a kind of media that immerses the user in a virtual three-dimensional environment and allows the user to conduct activities.

The interface for a VR system contains two components: 1) the system output, the virtual content that the VR system generates for the user to perceive, and 2) the user input, the user control and physical activities that the system receives from the user.

The firs component, **system output** is provided to the user in multiple perception channels: vision, audition, haptics and vestibular. The visual channel is an important channel used in the system output to provide immersion of VR. The visual output is mainly achieved by replacing the user’s vision with virtual imagery (to provide visual information, or visual cue, of the VE). The visual cue is often implemented with either a head mounted display (HMD) setting, or a projector display (360-degree projector screen that surrounds the user) (Figure 1.1). Both of the HMD and projector display replace the user’s vision of the real world with the virtual imagery as a main method of creating immersion. Other than vision, the VR system can also provide audio output (e.g. using speaker or headphones to provide artificial sound), haptic output (e.g. using fans to provide wind, or using vibrator attached to the user seat or hand controller to provide vibration), and vestibular output (e.g. in lying-based VR flying interface like Birdly™ (Figure 1.2), the lying platform will tilt corresponding to the user’s flying direction in the VR experience).

Figure 1.1. Example of HMD (left)[1] and Projector Display (right)[2].

[1] Image from ESA [CC BY-SA 3.0-igo (https://creativecommons.org/licenses/by-sa/3.0-igo)], via Wikimedia Commons

[2] Image by Elizabeth Lockwood Health.mil (United States Army) [Public domain], via Wikimedia Commons

Figure 1.2. Birdly[3].

In terms of the second component, the **user control**, or how a VR system receives the **input** from the user, there are multiple user input controls in the market that mainly contain three types: i) the controllers, ii) the motion-based controls, and iii) the combination of i) and ii).

The **controllers** are usually hand-hold devices that provide buttons/joysticks. The user holds the controller, and press the buttons or roll the joysticks to give instruction to the VR system. Figure 1.3 illustrated some examples of the VR controllers.

[3] Image from http://www.somniacs.co

Figure 1.3. VR Controllers.[4]

For the **motion-based controls**, the user conducts body movement to give instructions to the system. For example, the user may navigate in the VE by walking in the real physical space. Another example is hand gestures. For instance, a user may use hand swiping to navigate to the next page of a selection menu. The motion-based controls are usually implemented by gesture recognition, or position tracking of the user (Figure 1.4). The two kind of controls can be combined on one control device. The oculus rift controller can be an example. While holding the oculus rift controller, when the user's fingers close together and thus touch the buttons on the controller, forming a grabbing gesture, the controller recognizes this motion, and the virtual hand in the VR system form a grabbing gesture too (Figure 1.5).

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[4] Images from:

HTC Vive controllers and Oculus Rift controllers (first row): https://www.roadtovr.com/including-controllers-htc-vive-and-oculus-rift-could-be-evenly-matched-on-price-touch/;

Windows Mixed Reality Lenovo Explorer controllers (second row, first one): https://www.microsoft.com/en-au/windows/windows-mixed-reality;

Samsung Gear VR controller (second row, second one): https://winncomm.business/product/controller-for-gear-vr-samsung/;

Oculus Go controller (second row, third one): https://www.scan.co.uk/products/oculus-go-32gb-standalone-virtual-reality-headset-with-touchpad-controller-55-wqhd-display-snapdrago

Figure 1.4. The Motion Tracking Methods Used in VR Input.[5]

Figure 1.5. The Grabbing Gesture of Oculus Rift Controller.[6]

The job for VR interface designers is to design the system output (visual, audio, haptic, and vestibular feedbacks) and the user control (mapping from the user's instructions to the VR operations). In this thesis, we specifically look at the interface design of embodied VR flying. In the following section, we discussed the current VR flying techniques and their limitations.

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[5]Images from:

Opti Track: https://optitrack.com/hardware/;

Microsoft Kinect: https://www.telegraph.co.uk/gaming/news/microsoft-shutting-kinect-production/;

Structure Sensor: https://kuinoma.fi/fi/tuotteet/22679;

LeapMotion: https://www.leapmotion.com/press/#117

[6]Image from https://uploadvr.com/wp-content/uploads/bfi_thumb/hands-1000x562-n4ajirwlm5wr502mwfa647512i9ejs3vw1goiyu584.jpg

1.2. Existing VR Flying Locomotion Interfaces and Their Limitations

Designing flying locomotion interface in VR mainly has two purposes. One is to simulate the real aircraft flight, which emerged around 1930s for pilot training purpose(Page, 2000). The design concern of these kinds of systems is to replicate the exact operations and environment feedback of a real flight. But in this thesis, we discuss another purpose, VE locomotion, which is to facilitate flying navigation in a VE, in terms of the accuracy, efficiency, sense of flying etc.

Recently, there has been an increasing research interest on embodied VR flying interfaces that let users mimic the movement of flying. The essential design challenge here is to design a way of “flying” that is reasonable and natural, because nobody has ever experienced embodied flying in reality. Currently three kinds of interfaces are in the market or under experiment: lying-based, standing-based and sitting based (Figure 1.6). The **lying-based** interfaces allow the user to lie down in a prone position. It can provide bed-like support from the bottom (SOMNIACS SA, 2018), or suspend the user with strips (Ars Electronica Futurelab, 2018; Sproll, Freiberg, Grechkin, & Riecke, 2013; Thapan, 2016). The lying-based flying interfaces simulate embodied flying in the closest way, because it mimics the posture of the birds. The **standing-based** interfaces allow the user to stand on the ground, and use arms, head, or upper body to control the virtual flying (X. Tong et al., 2016). For the **sitting-based** interfaces, the user sits on a chair, and leans his/her upper body to interact (Bimberg et al., 2016).

However, no matter whether the interface is lying-based, standing-based or sitting-based, there are some limitations in each case. In the **lying-based** interfaces, the user’s head and limbs are often hanging in the air, which is not a common position that human bodies are used to. The gravity applied on the head and the limbs will cause easy fatigue to the user. Moreover, the lying-based interfaces are often expensive. With the **standing-based** flying interfaces, the user is less likely to feel fatigue. But since the user’s feet touches the ground, he/she may feel less like flying. In the **sitting-base** interfaces, the user is the least likely to get tired, and his/her feet can be off the ground or on the ground depending upon the interface design. However, the movement of the user’s legs are still limited by the seat, which decreases the degree of freedom, and thus the user will feel less feeling of flying freely.

Figure 1.6. The Lying-Based, Standing-Based and Sitting Besed VR Flying Interfaces[7]

1.3. The Limbic Chair

Recently, a new chair, called the Limbic Chair™ (shown in Figure 1.7), was released by the Limbic-Life Ltd (Limbic Life AG, 2018). The most unique and novel feature of this chair is that it provides the user with two separate supporting “shells” for each of the legs, and the shells are able to move independently in pitch (up/down) and yaw (left/right) rotations. As a result, while sitting on the Limbic Chair, the user can also move his/her legs. The user’s two legs can also move in different ways (e.g. lift one leg up and put one leg down at the same time). The chair has no backrest or armrests. So in theory, the stance that the Limbic Chair could provide the user who sits on it a new kind of stance that lies between sitting, in which the user has buttock support but limited leg movements, and standing, in which the sitter has no buttock support but some leg freedom. We call this new stance the “**flexible perching**” stance. The Limbic Chair also includes sensors that detect the pitch, yaw and roll rotational data of the two shells, which can be used to transfer the user’s leg movement to the console. As the Limbic Life company claims, the Limbic Chair is designed to provide the user with a “light, free and happy” experience (Limbic Life AG, 2018), which seems to closely align with what we want in VR flying. So there is a possibility that, with the Limbic Chair and the flexible perching stance that the Limbic Chair provides, that we can design a VR flying locomotion interface that provides a better VR flying locomotion experience.

[7] Images from http://www.somniacs.io (left), X. Tong et al., 2016 (middle), and Bimberg et al., 2016 (right).

Figure 1.7. The Limbic Chair.

1.4. Research Objective

To find out how the Limbic Chair can be used for VR flying locomotion interface design, we conducted two studies that are presented in this thesis.

In Study 1 (Chapter 3), an observational study, VR experts explored the affordances of Limbic Chair use as a VR flying interface: we explored participants' preferred VR flying navigation movement choices, and generated three considerations of using the Limbic Chair as a flying interface.

In Study 2 (Chapter 4), we applied the results of Study 1 to the Limbic Chair in VR flying and queried into the experiential qualities of the VR flying experience as compared to standing and sitting on a normal chair. (The experiential qualities included ease of control, feeling of presence, less simulator sickness, more joy, safety, comfort). In Study 2, a one-factor between-object experiment was conducted using both quantitative and qualitative methods. The results show that the Limbic Chair outrivaled other two interfaces in "likeness to people's imagined way of flying", but not significantly outrivaled the other two interfaces in other qualities. The deeper investigation revealed a disconnection between "likeness to flying" and "good flying experience". We propose future study directions for further exploration on the VR flying supported by the Limbic Chair.

Chapter 2.

Literature Review

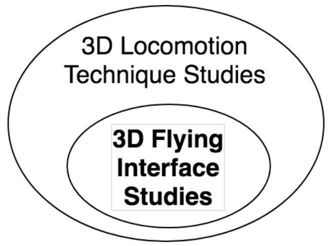

Figure 2.1. Literature Review.

In this literature review, we acknowledge that recently there has been an increasing research interest in embodied VR flying interfaces that allow users to mimic the movement of flying. The essential research design challenge is to design a way of “flying” that is reasonable and natural, because human beings cannot physically experience embodied flying in reality without additional affordances provided either by mechanical or digital technologies. Because our interest is in VR technologies we review the literature in 3D locomotion studies and 3D flying interfaces. The purpose of this chapter is to review the literature related to our research topic of 3D flying interfaces in order to propose a novel flying interface called the Limbic Chair.

In Section 2.1, we begin from the broadest topic of 3D locomotion studies. In this section, we introduced 3D locomotion technique studies.

In Section 2.2, we introduced 3D flying interfaces, which is a sub-category of the 3D locomotion technique studies (illustrated in Figure 2.1). We introduce i) the history of 3D flying interfaces, ii) the categories of the current 3D flying interfaces and iii) the relationship between these studies and the studies we did in this thesis.

2.1. 3D Locomotion Technique Studies

The 3D locomotion research described in this literature review refers to the change in first person’s viewpoint in a three dimensional virtual space. Locomotion through virtual spaces is one of the most primitive and important research concerns in VR (D.A. Bowman et al., 1997; Iwata, 1999).

A number of 3D locomotion techniques were proposed for different purposes. There are three primary goals of 3D locomotion in a VE: i) exploration, ii) search and iii) maneuvering (R. McMahan et al., 2014; Tan et al., 2001). For the goal of **exploration**, there is no specific target as its purpose is to gather information about the environment, or to explore for pleasure where the environment is joyful or stimulating. **Search** is defined by the user having a specific target, when he or she wants to locate a specific target in the environment. **Maneuvering** refers to the precise perspective control over a target. Maneuvering usually happens when the user wants to change to different views to observe an object, in order to gain more complete knowledge of it. Each of the three goals may require different techniques to be most effective (R. McMahan et al., 2014). According to McMahan et al., the locomotion techniques mostly fall into four categories in terms of the way of control: i) manual manipulation, ii) automated, iii) steering and iv) physical locomotion (R. McMahan et al., 2014). Below we described each of the four categories.

Manual manipulation is a kind of exocentric navigation (the user's visual perspective is not aligned with the navigation perspective), i.e. the user navigates using a VE representative object, like a map. It includes "camera-in-hand" technique, in which a user's hand is over a map acts as a camera specifying the imagery rendered for the display (Ware & Osborne, 1990). Alternatively, the "scene-in-hand" technique, in which the miniature of the environment itself is attached to the user's hand position (Ware & Osborne, 1990).

The automated, steering and physical locomotion techniques are egocentric (the user's visual perspective is aligned with the navigation perspective), i.e. the user conducts navigation in the VE directly without using an VE representative. **Automated** locomotion technique does not provide real-time control during the travel, but allows i) the users to designate the target position (target-based locomotion, e.g. (D.A. Bowman et al., 1997)), or ii) moving path before the actual travel (route-planning locomotion, e.g. (Doug A. Bowman, Johnson, & Hodges, 1999)). Instead, the Steering and physical locomotion allows the user to decide the real-time orientation and velocity during the traveling.

Steering refers to the control in which the user's body is relatively stationary, for example, when a person is sitting still while driving his/her car. The traditional controls like joystick control fit in this category. Other ways of steering could be using gaze (Doug A. Bowman et al., 1999) or using pointing (Kopper, Ni, Bowman, & Pinho, 2006) to direct the moving direction. Steering provides no motion cue (physical and vestibular cues that suggest self-motion) to the user. On the other hand, physical locomotion provides full motion cue (1:1 physical travel) or partial motion cues to the user (Kruijff & Riecke, 2017).

Physical locomotion refers to the control that requires the real movement of the users' body. "Real walking" is the most direct and natural physical locomotion, where the user conducts the same walking movement in the real environment as in the VE. One problem of the *real walking* method is that it requires the actual physical space to be big enough to fit the area of the virtual space, which sometimes is difficult to fulfill. Accordingly, some other methods have been proposed to solve the problem of limited physical space and enable the user to locomote infinitely within the limited space. For example, "redirected walking" (Razzaque, 2005) 'cheats' the user by varying the user's vision when he/she navigates, so that the user thinks he/she moves or rotates to some certain degree in the VE, but in the physical space he/she moves or rotates a smaller degree, thus the user always stays in the limited physical area. Another example is "walking in place (WIP)" (Slater, Usoh, & Steed, 1995), in which the user walks in place instead of walk to a different place in the physical area. The human joystick, or leaning-based locomotion technique is another commonly used physical locomotion that saves physical space (R. P. McMahan, Bowman, Zielinski, & Brady, 2012; J. Wang & Lindeman, 2012). In the leaning-based locomotion, the user sits or stands, and leans his/her body to the direction that he/she wants to navigate to. In this method, it seems that the user's body works like a "joystick" to control the navigation, so this leaning-based locomotion method is also called "human-joystick" locomotion.

The embodied VR flying interface we focused on in this thesis belongs to the **physical** locomotion category, and our goal is to design a natural flying interface that help the user easily and freely fly in the VE. Because it is not possible for human beings to perform real flying, our research uses partial motion cues embedded within the interaction design of our interface. We identified our locomotion goal as more aligned to the **exploration** and **search** goal, and less focussed on the maneuvering goal, because i) flying is a faster, larger range of locomotion compared to grounded based locomotion, and ii) we focus more on the users' moving through the environment, rather than staying at a smaller range of area maneuvering the viewpoint.

2.2. 3D Flying Interface Studies

3D flying interfaces are 3D locomotion techniques that allow the user to "fly" in the 3D VE, as distinct from ground-based locomotion (e.g. the "real walking" or "WIP" techniques that mentioned above).

Prior research in designing 3D flying interfaces for VR has two main purposes: i) aircraft flight simulation and ii) VE navigation. The studies for aircraft flight simulation, emerged in 1930s for pilot training (Page, 2000), and replicates the exact operations and environmental feedback of real flights. In this thesis, we discuss another purpose, VE navigation, which is to facilitate flying navigation in a VE, in terms of the accuracy, efficiency, sense of flying and so on.

Although it may seem that the exploration of ground-based locomotion research would have preceded flying locomotion research (because flying is not a common activity that humans can conduct, and flying includes one more direction of control, the z direction, than the ground-based locomotion), the flying locomotion research studies preceded grounded-based locomotion studies. The exploration of 3D flying interfaces came naturally with the emerging of the 3D locomotion technique studies, because the 3D locomotion in the VE that the pioneers studied was just like flying: it was smooth, free and not constrained by the gravity - as Chuck Blanchard said in 1993, "Nobody walks in VR, they all fly." (Hays, 1993). These initial flying studies emerged in the research literature over three decades ago.

For example, Ware and Osborne in 1990 (Ware & Osborne, 1990) compared a "flying vehicle," in which a user navigates the VE in a egocentric perspective to "scene in hand" metaphors in which a miniature of the VE itself is attached to the user's hand position. The study found the three metaphors all had their own constraints and affordances, and the "flying vehicle" performed better in conducting smooth movements. Many other researchers studied large scale area locomotion using different flying approaches. For example, Pausch (1995) proposed a "world-in-miniature" (WIN) method, a hand-held miniature representative of the VE with a movable object representing the user him/herself, to facilitate navigation in a large space, and found the WIP was useful for some common tasks in VE, but would confuse the user when the scene updates to the new scene after the navigation. Other researchers studied the reasonable speed of flying in VE. For example, Mackinlay (1990) proposed a method in which the moving speed became logarithmically slower when the user approaches to the target position (Mackinlay, Card, & Robertson, 1990). Ware and Fleet (1997) proposed a method to scale the flying speed changes in relation to the user's distance to the VE. The distance was defined in four ways: the user's point to the VE's far most sampling point, the nearest sampling point, the average distance from all the sampling points, weighted sum of the distances to all the sampling point. They found other than the far most sampling, the other sampling ways markedly improved the navigation (Ware & Fleet, 1997).

These early studies in 1990s and early 2000s focused on how to effectively navigate the 3D VE and conduct tasks like search and maneuvering (e.g. precise viewpoint control or navigation in large area). However, because the discussion of 3D flying interface was in its infancy, the corresponding technologies were not mature enough at the time, and therefore none of the flying interfaces proposed by these early studies provided motion cues to the user, and seldom did they explore on the "feeling of flying" that the interface could provide to the user. Restated, earlier research in VR flying did not explore techniques that could provide the user with an illusion that they were flying in the VE.

Therefore, in the later decades including the 2000s, few studies were proposed on the 3D flying interface in VR (later we call it "VR flying locomotion interface" or "VR flying interface"). Not until recently in 2010s, notably present because of the thriving development and growth of background technologies (e.g. the motion tracking technology, head mounted display, and unmanned aerial vehicle technology), that a growing number of researchers again cast their focus on the VR flying interfaces, and a variety of embodied flying interfaces that provided the user with flying motion cues emerged in the research literature. These interfaces began to provide the user with the feeling of embodied flying, in order to create more natural flying experience, more pleasure and excitement of flying, and/or better flying control. Below we introduce the categories of the recent embodied VR flying interfaces in terms of their i) system output and ii) user input (or user control).

In terms of the system's **output** to the user, the studies could fall into two streams: i) simulated VR flying, which gives the user the scenery generated by computer simulating system (e.g. (Heidelberger & Mossel, 2015; Sikström, Götzen, & Serafin, 2015; J. Wang & Lindeman, 2012)), and ii) telepresence VR flying, which gives the user real 360-degree imagery captured real-time by an unmanned aerial vehicle (UAV), or drone (e.g. (Higuchi, Fujii, & Rekimoto, 2013; Ikeuchi, Otsuka, Yoshii, Sakamoto, & Nakajima, 2014; Pittman & LaViola, 2014; Teixeira, Ferreira, Santos, & Teichrieb, 2014)).

In terms of the **user input**, or the **user control**, the researchers had explored several ways of embodied VR flying interfaces using different human body parts of in different bodily positions. The most popular method is to have the user lie down in a **prone position** with arms wide open, mimicking a bird, and to use the **arms** and **torso** tilting to control the flying. There are two ways to achieve this interface strategy. One way is to suspend the user by a physical handing device so his/her body is cradled in a prone position in mid-air, and then to use motion tracking technology (mocap, Kinect etc) to capture the gestures of the user (Eidenberger & Mossel, 2015; D. Krupke et al., 2016; Dennis Krupke et al., 2015; Perusquía-Hernández et al., 2017). Another method is to provide a bed-like support to the user to lie his/her body on. The bed-like support could be a simple low-cost setting, like cushion seats (Ikeuchi et al., 2014). Or it could use a more tailored device like Birdly (Cherpillod, Mintchev, & Floreano, 2017; Rheiner, 2014; SOMNIACS SA, 2018), a plane like platform for the user to lie on that allows whole body tilting, hand gesture and arm flapping.

However, because lying is not a common position that our human body is used to, the gravity applied on the neck and limbs readily causes fatigue to the user in this kind of interface. As a counter-strategy to have the user fly with his/her arms and/or torso in a prone position, there are also flying interface designs that use some part of the body in **standing** and **sitting position**. The most common way is to use the **head** position to control the flying (the head joystick flying interface) (Higuchi et al., 2013; Pittman & LaViola, 2014; Teixeira et al., 2014). Sometimes the leaning of the **torso** is used as the flying control (Bimberg et al., 2016). (Note that the head control also involves the leaning of the torso.) In addition, Wang et al. studied how to use **feet** to control flight, using metaphors of skating and skiing (J. Wang & Lindeman, 2011, 2012; Jia Wang & Lindeman, 2012). Tong et al. studied the use of **arms** to control the virtual flight (Xin Tong et al., 2014). In all, the use of **head** and leaning **torso** were often designed with the **sitting** position, while the use of **feet** and **arms** were often designed with the standing position. This could be explained biomechanically as the sitting position provides a closer center of gravity for the user to balance their body, which allows a larger degree of tilting; while in the standing position, the user's body is not bent, which opens up more freedom to use limbs.

The research study of the performance and affordances of the Limbic Chair that is proposed in this thesis is a new kind of device that provides the user with a new "flexible perching stance" that lies between the standing stance and the sitting stance, because it provides seat support, while allows a greater free range of lower body movements. Moreover, it could provide a sensation of "floating" as the lying-based interfaces could provide. So there is a possibility that the Limbic Chair can provide better VR flying experience to the user than the other interfaces. But the affordance of the Limbic Chair as a VR flying interface has yet to be examined. The premise and motivation of our exploration of the potential of the Limbic Chair as a VR 3D flying interface resulted in our conducting the 2 research studies in this thesis which explore the affordance of the Limbic

Chapter 3.

Study 1: The Affordance of the Limbic Chair as A Virtual Reality Flying Interface

3.1. Objective

The Limbic Chair is a new interaction technology that has recently been developed by Limbic Life Ltd. and has been adopted in the consumer market primarily for office use (Limbic Life AG, 2018). While Limbic Life is interested in also exploring VR applications there are currently no academic studies which explore the viability of the Limbic Chair (or similar interfaces) for use in VR flying interfaces. Our research goal is to explore its affordance (utility/usefulness), to understand its strengths and weaknesses, in order to propose an interface design for VR flying locomotion using the Limbic Chair. To study these goals, we proposed the following research questions:

RQ1. How do users experience the affordance quality of the Limbic Chair in terms of: ease of learning, ease of control, comfort, safety, enjoyment and intuitiveness?

RQ2. How could the Limbic Chair be used to support flying locomotion in VR?

RQ2.1. What movement choices do participants make to use the Limbic Chair to support flying locomotion in VR?

RQ2.2. What are the comparative strength and weakness of the Limbic Chair in supporting VR flying in relation to existing embodied VR flying interfaces that use leaning-based interface while sitting or standing (later we call them “sitting interfaces” and “standing interfaces”)?

3.2. Method

We adopted a qualitative observational method to answer our research questions. In Study 1 we asked the participants to experience sitting on the chair and then without VR visual feedback, imagine how they would use the Limbic Chair in a VR flying scenario. Study 1 contains three phases: 1) a guided experience phase, 2) an optional free exploration phase and 3) an interview about the experience.

In phase 1, the **guided experience**, we gave each participant the same structured list of flying navigation instructions and asked them to conduct that movement using the Limbic Chair and to imagine the corresponding visual scene.

In phase 2, the **free exploration phase,** which was more exploratory and unstructured, the experimenter and the participants explored freely without the navigation instructions.

Finally, in phase 3 of Study 1, we conducted an **interview** that asked participants about: i) their experience of the affordance qualities of the limbic chair in phases 1 and 2; ii) their experiential like/dislike about the overall sitting experience and the flying navigation movements; iii) the comparison of the Limbic Chair with sitting and standing interfaces[8], and iv) their rationale for i), ii) and iii) above.

Figure 3.1. Study 1 Procedure: Affordances of the Limbic Chair.

3.2.1. Participants and Experiment Setting

Because we relied on the participants to provide insights to their experiences of the flying interface design of the Limbic Chair, we required capable participants who were familiar with or had expertise in VR and 3D interface design. We specifically invited VR researchers as our participants for the study. Because the VR researchers are familiar with VR and interface design, they can better imagine the VR scene as required by the experiment, and they can better analyze the advantages and disadvantages of the Limbic Chair interface. We invited five VR researchers (age 25-48, M = 33.6; all male) from the iSpace lab (which focuses on VR interface design) in the School of

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[8] The participants answered their opinions about the comparison of the Limbic Chair with sitting and standing interfaces based on their previous experience with sitting and standing.

Interactive Arts and Technology at Simon Fraser University. We defined VR expertise based upon the length of time these participants had experience with VR game play, development and/or research experience. Participant expertise ranged from four months to over twenty years of VR gameplay, development and/or research experience. The mean level of experience was 5.1 years. All participants had used the Limbic Chair in a short period of time for 2-15 minutes each time, 3-10 times in all, but hadn't explored the chair systematically or reflectively.

The experiments for Study 1 and 2 were conducted in the iSpace lab, in the School of Interactive Arts and Technology at the Simon Fraser University Surrey campus. The iSpace lab is a quiet closed laboratory space of about 20 square meters. During Study 1, the participants wore an HTC Vive headset and sat on the Limbic Chair for both the guided experience and the free exploration phase. (see Figure 3.2). Although no imagery was displayed in the headset during Study 1, we asked the participant to wear the HTC Vive headset in order to adapt the participant to a "VR" setting and to help him/her to imagine the feeling of a VR flying experience. During the interview phase (phase 3), the participant removed the headset and stepped off the Limbic Chair, so that he/she could better describe his/her first-person experience and also reflect upon his/her overall assessment regarding their movement choices. By having the participant conduct the interview sitting next to the Limbic Chair also provided an opportunity for a third-person view of their recent activity on the limbic chair.

Figure 3.2. The experiment setting for guided experience and free exploration phases.

3.2.2. Guided Experience and Free Exploration

3.2.2.1. Guided Experience

In the guided experience phase, the participant was first asked to sit on the Limbic Chair and to move freely until they felt adapted to the Limbic Chair's movement. Then the participant was asked to put on the HMD, HTC Vive headset. The experimenter asked the participant to imagine a place that they would like start the imagined flying experience. The experimenter informed the participant of the goal of the experiment (to explore VR flying interface design with the Limbic Chair). The experimenter orally gave a set of flying navigation instructions one by one, and let the participants conduct an exploration of the corresponding movement while sitting on the chair while imagining that corresponding visual feedback was displayed in the VR headset. We do not display visual feedback, so that no imagery would interfere with the participants' imagination – we want the participants to explore using the Limbic Chair without being imposed any constraint on the visual feedback corresponding to their choices of movement.

The flying navigation instructions that the experimenter suggested to the participants were:

1) Take off;
2) Fly up;
3) Fly forward (speed up, speed down);
4) Turn (left, right);
5) Stop and stay in the air;
6) Spin around;
7) Fly back;
8) Fly down;
9) Land.

The order of the navigation instructions was designed to articulate a complete flight process from take-off to landing.

While conducting movements, the participants were asked to “think out loud” – to describe their VR flying locomotion experience and to describe why they conducted any specific movements. During this period, the experimenter asked clarification questions to help the participant explain more concretely. In this phase, the participants’ movements on the Limbic Chair were video recorded. The experimenter also took notes while communicating with the participants during the experience.

3.2.2.2 Free Exploration

Directly following the guided experience, the participants entered the free exploration phase during which the participant stayed on the Limbic Chair, reflected on the flying movements, and moved in any way that they preferred. During the Free Exploration period, the participants may provide verbal comments out loud from an overall perspective, and also may propose new ideas on the interface design. During Study 1, when any valuable design ideas were suggested from any of the previous participants, the experimenter suggested further exploration of these design interactions so that later participants could examine these potential interactions as part of the VR flying design.

Same as the guided experience phase, the participants’ movements on the Limbic Chair were also video recorded, and the experimenter also took notes while communicating with the participants during the experience.

3.2.3. Interview

Directly following the guided experience and free exploration phase, the participants took part in an interview conducted by the experimenter. During the interview, the participants were first asked about the basic information (their height, their prior experience using the Limbic Chair, their expertise utilizing VR based on their prior experience of VR research, development, or gameplay).

Following the introductory questions, participants were asked about questions regarding their experiences of the *affordances* of the Limbic Chair:

Part 1: Participants' experience of the affordance quality of the Limbic Chair in phase 1 and phase 2 (the participant was asked to give a score from 0 to 10, and then describe the reason for their score). The affordance qualities were:

- Comfort
- Ease of learning
- Ease of control
- Safety
- Enjoyment
- Intuitiveness

Part 2: Participants' experiential like/dislike about the overall sitting experience with the Limbic Chair, and about the flying navigation movements with the Limbic Chair

- Which part of the overall sitting experience did you like/dislike most? Why?
- Which flying movement did you like/dislike most? Why?

Part 3: The comparison of the Limbic Chair with sitting and standing interfaces:

- How do you think the Limbic Chair can be good/bad as interface for flying comparing to other chairs?
- How do you think the Limbic Chair can be good/bad as interface for flying comparing to standing?

The questions were all open ended, and the participants were encouraged to express their opinion freely. The experimenter asked follow-up questions when clarification was needed, or in order to lead the current conversation to deeper understanding of the flying experience. The interview was audio recorded, and the experimenter also took notes.

3.3. Analysis and Findings

An analysis which was mainly based on qualitative methods was conducted to answer our research questions. As illustrated in the Figure 3.4, We found the answer to the RQ1, "how do the users experience the quality of the Limbic Chair in terms of: ease of learning, ease of control, comfort, safety, enjoyment and intuitiveness", in the part 1 questions in our interview data, "participants' experience of the affordance quality of the

Limbic Chair in phase 1 and phase 2”. We found the answer to the RQ2.1, “what movement choices do participants make in order to navigate the interaction of VR flying in the Limbic Chair”**,** in both our guided experience and free exploration video record data and part 2 in the interview data, “Participants’ experiential like/dislike about the overall sitting experience with the Limbic Chair, and about the flying navigation movements with the Limbic Chair”. For the RQ2.2, **“**what are the comparative strength and weakness of the Limbic Chair in supporting VR flying in relation to existing sitting and standing VR flying interfaces?**”**, we investigated the answer from the part 3 of the interview data, “the comparison of the Limbic Chair with sitting and standing interfaces”. Based on our results in RQ2.1 and Q2.2 we concluded the RQ2, “how could the Limbic Chair be used to support flying locomotion in VR”. The findings for each research question were reported in below subsections.

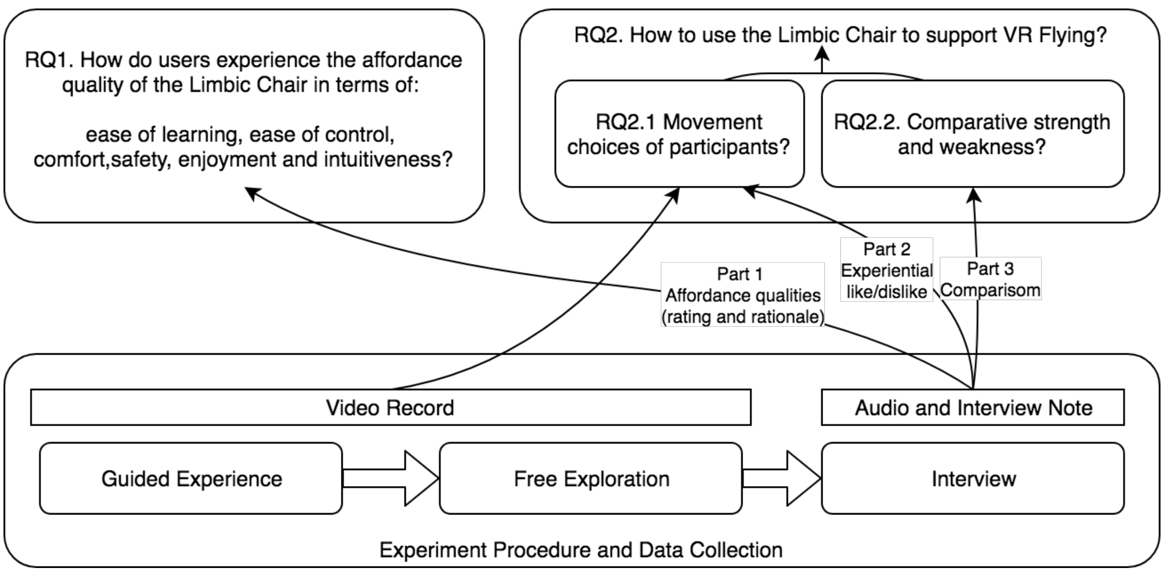

Figure 3.3. Data Analysis: Links between Data and Research Questions.

3.3.1. RQ1: The Affordance Quality of the Limbic Chair

In the part 1 questions in our interview data, “participants’ experience of the affordance quality of the Limbic Chair in phase 1 and phase 2”, we asked our participants to rate the affordance quality items (i.e. comfort, ease of learning, ease of control, safety, enjoyment, and intuitiveness), and to explain the reasons for the rating.

Rating data was analyzed in a quantitative manner to gain an overall view of the participants' experience towards the affordance quality of the Limbic Chair.

The affordance qualities were rated in a scale of 0-10. However, to keep the interview open-ended, we did not require a single score for each affordance quality (comfort, ease of learning, etc.). The participant was able to give multiple scores for different condition cases, or give no score if they thought the affordance quality couldn't be concluded by any score). Figure 3.4 shows an overview of the scores. When there were multiple scores given by one participant for an affordance quality, we retained all scores and counted each as a different entry.

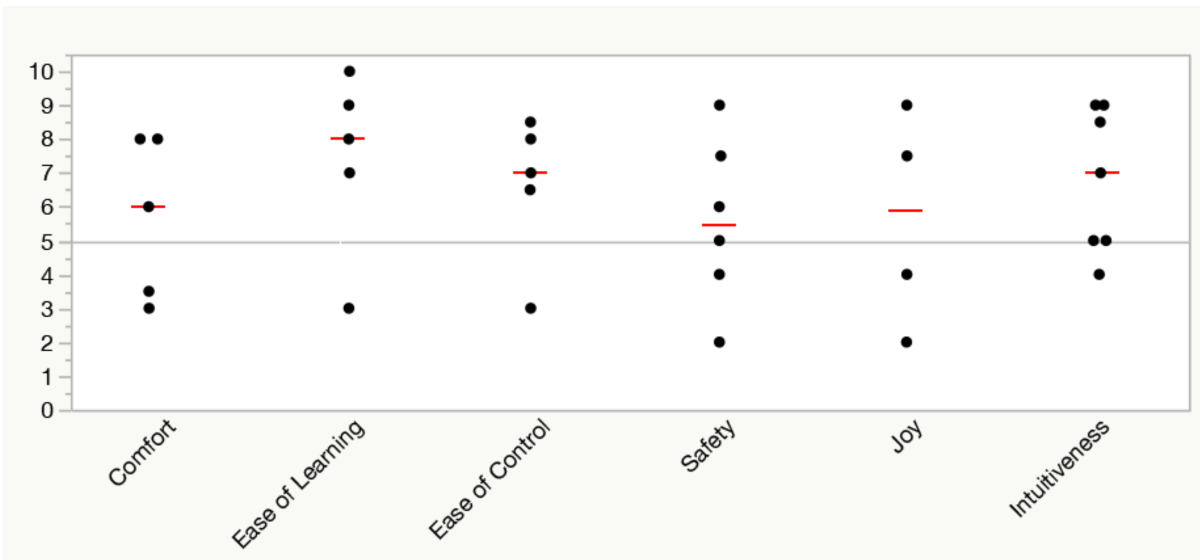

Figure 3.4. Participants' Rating of Affordance Qualities.
Red bars identify the median rating score of each affordance quality.

In all, the participants' experience about the affordance quality of the Limbic Chair was not unified. For each item, there was a large difference between the lowest score and the highest score. But overall, participants gave more higher scores (scores that are over 5) than lower scores (scores that are below or equals to 5), especially in the affordance qualities items "ease of learning" and "ease of control". But notice that this only implied a preliminary overview, and was not a statistical analysis, because we have not considered the individual difference in which some participants are higher markers in general and would give marks higher than 5 even they held negative opinions.

Following the quantitate analysis of the scores, we conducted a qualitative analysis to investigate the *reasons* why the participants gave the scores for the affordance quality items. We did the open coding of all the interview data (annotating sentence by sentence), followed which an axial coding on all the participants over every interview questions to generate categories about people's experience on the affordance quality of the Limbic Chair. Lastly, we performed selective coding to draw out the participants' experience about the affordance quality of the Limbic Chair.

For the ***affordance quality of comfort***, two participants gave higher scores (score > 5) because that the Limbic Chair brought more leg movement (so that it was more "enjoyable" and "adaptive"). The other three participants gave lower scores (score <= 5). The problem of "sliding" was mentioned twice – the participants may slide down the seat when they leaned forward. Two participants complained about the seat material ("the seats were hard"), and the design ("the two seats hurt the buttock"). One participant complained that siting would take extra effort to maintain balance.

For the ***affordance quality of ease of learning***[9], most of the participants gave a higher score (score > 5), because they thought the sitting was "obvious enough" or they had watched the online demonstration video. One participant gave a lower score (score <= 5) because that he thought it took time for the user to practice and get used to the Limbic Chair.

The participants had various opinion on the ***affordance quality "easy of control***"[10]. One participant gave a high score (score of 8.5) because of the freedom provided from the Limbic Chair; meanwhile, another participant gave the lowest score (score of 3) saying that there were "too many things to adjust". Two participants both mentioned that it would be better if there were something under the feet when the user sat on the Limbic Chair. This later became one setting that we provided the participant to experience in the free exploration phase in the later experiments. In addition, two

[9] The ease of learning is both for the ease of learning the sitting on the Limbic Chair, and the ease of learning to use the Limbic Chair to control the VR flying.

[10] The ease of control is both for the ease of control the sitting on the Limbic Chair, and the ease of control to use the Limbic Chair to control the VR flying.

participants mentioned that the limit on the rotation of yaw direction hindered the degree of control.

For the ***affordance quality of safety***, four out of five participants agreed on that backward movement on the Limbic Chair did not feel safe, because they were not sure to what degree when they could move backwards without falling out from the chair. In fact, it was unlikely for the user to fall back unless he/she lean very hard to it, because there are locks under the moving shells (the two seats that the user put legs on) that limit the shells' tilting backwards to a maximum degree. But even though we described this feature to the participants during the interview they still had the concern of falling back. This inspired us to put the Limbic Chair against a wall after the first participant. But having the wall behind did not fully diminish the users' concern, because when the participant had the headset on, they didn't know how far the wall was behind them. Only one participant appeared to trust the design and reckoned that the chair "can't hurt". In addition to falling back, one participant suggested that leaning forward was less safe when his feet were suspending than when he could touch the ground.

For the ***affordance quality of joy***, two participants gave positive feedback and regarded it as "playful", "new and fun". But other two participants stated it differently. One participant thought it was "more work than fun", suggesting that although the Limbic Chair was novel and playful, it required extra effort to adapt and control. One other participant gave the lowest score (2) because he thought that "it was just a chair, and if it was not comfortable, there was no fun".

When we asked about how ***intuitive*** the sitting movements on the Limbic Chair were as in a VR flying locomotion interface, the participants' answer was not unified. Two participants disagreed that the Limbic Chair could be used for VR flying intuitively. One participant thought that the position of "sitting" itself was not intuitive for flying. But this participant agreed that the Limbic Chair was more intuitive than the other chairs. Another participant thought that in the air was not like in the water, where a person could move up or down by pushing the water. Instead, there must be other extra some pushing force, like a jet pack. He couldn't imagine that force by just sitting and moving on the Limbic Chair. However, one participant highly agreed that the Limbic Chair flying movement was intuitive in up/down and forward/backward directions, but not the rotation navigation movements, because the chair could not rotate physically. The remaining two participants gave a moderate opinion. One said that it was intuitive in general but could be improved if the user could know the maximum movement range of each direction. Another said that it was not intuitive for maneuvering tasks, in which the user need precise locomotion control, but good for the big range of flying locomotion.

To conclude, the results revealed that the **leg freedom** the Limbic Chair provided contributed to the comfort, ease of control and intuitiveness (as a tool for flying). The **sliding (when tilt down the legs) issue, the hard touch shells, and that the Limbic Chair could hurt sitter's buttock** were the most noticeable drawbacks that decreased the comfort of the Limbic Chair sitting experience. And the safety experience was largely affected by the **lack of the back support**, giving that the user could more easily lean back on the Limbic Chair than the other normal chairs due to the leg freedom, and that the user has less awareness of his/her leaning position with the VR headset on. The Limbic Chair's **new design on the leg movement mechanism** did make it more playful and fun as perceived by some participants. But it also required extra effort from the user to learn and control the more flexible movements provided by the Limbic Chair.

But we also noticed that some participant's experience on the downside of the Limbic Chair may result from the fact that our participants did not have enough time to learn sitting on the Limbic Chair. For example, if the participants sat in the Limbic Chair at a right angle, the Limbic Chair might fit the user's thighs well enough and would not hurt the user's buttock. If the participants were more experience in manipulating the degree of freedom provided from the Limbic Chair by a longer period of practice, he might not feel spending extra effort because he already got used to it. But whatsoever that indicated the complexity of the Limbic Chair and less ease of learning.

3.3.2. RQ2: How the Limbic Chair could be used to support flying locomotion in VR

To investigate how the Limbic Chair could be used to support flying locomotion in VR, firstly, we analyzed the **video data** from Study 1 *guided experience* and *free exploration* phases to understand participants' choice of movements, and explored the issues observed from the participants' choice and corresponding solutions.

Secondly, we analyzed the **part 2 of the interview data**, which recorded participants' experiential like/dislike regarding the overall sitting experience and the flying navigation movements with the Limbic Chair.

Thirdly, we analyzed the **part 3 of the interview data**, which recorded participants' experience of the Limbic Chair as a VR flying interface as compared with participants' previous perception of sitting and standing VR flying interfaces. Based upon the analysis of this data, we summarized and concluded ways in which the Limbic Chair could be used to support flying in VR.

The analysis and findings were illustrated in the three subsections below.

3.3.2.1. Video Data Analysis: Participants' Choice of Movements for the Flying Navigation Instructions

To analyze the video data, we extracted the participants' movement choices for each flying navigation instruction, and annotated movement choices with participants' "think out loud" comments while doing the navigation movement. The participants' movement choices for the flying navigation instructions displayed in images in Appendix B. We then observed and compared the movement choices for:

1) each participant, and

2) each navigation instruction

in order to generate suggestions and considerations for using the Limbic Chair to support flying in VR. The "think out loud" comments were coded to understand the movement choices and inspire new solutions.

Table 3.1. Video Data Analysis: Participants' Navigation Movement Choice Overview

		P1	P2	P3	P4	P5			P1	P2	P3	P4	P5
Take Off	Arms	X	X				Land	Arms	X	X			
	Legs	X	X	X				Legs	X	X	X	X	X
	Core							Core	X	X	X	X	X
	Head							Head	X	X	X	X	X
Fly Up	Arms	X	X			X	Fly Down	Arms	X	X			
	Legs	X	X		X			Legs				X	
	Core	X	X	X	X			Core	X	X	X	X	X
	Head					X		Head	X	X	X		X
Fly Forward	Arms	X	X			X	Fly Back	Arms	X		X		
	Legs		X	X	X			Legs					
	Core		X	X	X	X		Core	X	X	X	X	X
	Head							Head					
Turn	Arms						Spin Around	Arms					
	Legs		X		X	X		Legs		X		X	X
	Core	X	X	X	X	X		Core	X	X	X	X	X
	Head							Head					
Stay and Stop in the Air	Arms												
	Legs												
	Core												
	Head												

The five participants are represented by P1 to P5. "X" represents this participant utilized the corresponding body part for the movement. Green color indicates the participant liked this movement. Orange color indicates the participant disliked this movement. The navigation movements that are related (i.e. take off/land, up/down, forward/backward, and turn/spin) were put in the same row.

In this subsection, we expand upon our analysis for the participants' movement choices for every flying navigation instruction. This analysis was based upon the video data. We categorized the participants' movement choice by assessing the usage of these four body segments separately. The four body segments are: arms, legs, core (or torso/upper body), and head. The final summary of data analysis for the body segment usage choices for all flying navigation instructions is illustrated in Table 3.2 above, which summarizes the 9 movement choices of 1) take off, 2) fly up, 3) fly forward, 4) turn, 5) stop and stay in the air, 6) spin around, 7) fly back, 8) fly down, and 9) land.

1) **Take off:** For the **legs**, two participants (P1, P2) chose to lift their feet off the ground. Oppositely, one participant (P3) stepped his feet down to push himself up, and consequently, he stood up from the seat. Other two did nothing on the legs. For the **arms**, two participants (P1, P2) chose to raise their hands, while the other three participants did not use arms.

2) **Fly up:** For the flying up navigation instruction, the participants showed a tendency to change their bodies from a “bended” form to a “straight” or “vertical” form: with the body straight and the legs down. Four participants (P1, P2, P3, and P4) made their **upper body** straight as if they were “reaching up”. For the **legs**, P1, P2 and P4 tried to stretch their legs (pressed their legs down), trying to “push their body up”. But these participants also mentioned that when they stretch their legs, the legs touched the ground and the feeling of flying was decreased. The other two participants (P3 and P5) chose to kept their feet floating.

   P5’s choice was different from all the other participants on the legs and upper body. He did not make any attempt to straighten his back or legs. Instead, he used **head** direction (looking up) to fly upwards, while keeping his back relaxed.

   For the **arm** use, three participants (P1, P2, and P5) chose to raise their arms to fly up. The other two did not use arms.

3) **Fly forward:** Four out of five participants (P2, P3, P4, and P5) chose to lean their **upper body** forward to fly forward. The participants who chose to use **arms** in the “flying up” movement (P1, P2, and P5) continued to use arms in the navigation movement of flying forward. Two of them (P2 and P5) put their hands back-down to the sides, forming a reversed “V” shape. One participant (P1) kept his upper body straight but raised his right hand forward, mimicking the “superman” pose. He was also the only participant who did not lean his upper body forward, because his already had his one arm raised forward. Similarly, as in the “flying up” navigation movement, participants tended to put down their **legs** but found this movement choice reduced the feeling of flying.

   For the navigation instruction of “speed up”, the four participants (P2, P3, P4, and P5) who leaned their **upper body leaned more**. The ones who put **arms** back put their hands back more. And the P1 who previous raised one **arm** forward to “fly forward” also changed to the same pose as the other four participants, and leaned his **upper body** forward (and also put down his arms backwards). When participants leaned more, the problem that arose when the feeling of flying is reduced when touching the ground became more obvious so that the participants would have to struggle to crunch their body to lift their legs off the ground with their upper body leaning forward, or suffer the feeling of floating and put legs on the floor to support their balance in the pose. One participant almost fell down the seat when he was trying to lift his legs. For the navigation instruction of “speed down”, the participants’ movements were to lean less of their upper body and reduce the movement range their arms.

4) **Turn:** For the turning movement, three different ways of using the **upper body** were adopted by the participants: i) tilt or lean the upper body to the side (P3, P5), ii) rotate the upper body (P1), and iii) the combination of i) and ii) (P2, P4). For the **legs**, two participants (P4, P5) chose to raise up the leg on the same side of the turning direction, and to press down the leg on the opposite side (e.g., when rotating to the left, the left leg was raised up and the right leg was pressed down). So the leg movement looked like the “skiing” movement when one uses one leg to push his/her body to a side to rotate. We noticed that this was a unique movement that a participant can conduct with the Limbic Chair, but hardly with standing or normal chair sitting stances. Although not explicitly mentioned, the P2 also used similar leg movement. **Arms** were not specifically used for turning, but many of the participants naturally slightly raised the arms to keep their balance.

5) **Stop and stay in the air:** For “stopping”, the participants were unanimous in their choice of movement. None of the participants intended any movement for the body segments. They sat straight and rested their arms and legs naturally.

6) **Spin around:** Spinning is a navigation movement that combines the turning and flying upward/forward movement, and would not necessarily happen in a flying application. But we adopted this movement in our navigation instruction list to stimulate the participants’ exploration of the Limbic Chair, and to see how the participants would behave and experience a complex movement. In this movement exploration, the participants moved in a similar way to how they moved in turning: either by rotating the **upper body** (P1, P2, P3) or

tilting the **upper body** (P4, P5). **Legs** may form a “skiing” like movement as described in the “turning” movement. P2 complained that the Limbic Chair was not as rotatable as a swivel chair. He said that because there was no visual feedback in the VR headset, and the chair was not rotatable, the spinning movement was not convincing.

7) **Fly back:** To fly backwards, all participants leaned back their **upper body** backwards to move back. Two participants (P1, P3) also raised their **arms** forward – P3 described this position as “being hit and flying back”. Participants’ **legs** were naturally hanging.

8) **Fly down:** All participants chose to crunch their **upper body** for flying downwards. In addition, other than P4, all the participants look down with their **heads**. While P4 emphasised the use of **back (upper body)** bending and used it as the main method of downwards flying, while for other participants, the crunching happened naturally when they looked down with their **heads**. No participants mentioned the particular use of **legs**, other than P4, who intentionally bended his back and also raised his thighs to a horizontal level to lower his body down, all the other participants had their legs kept relaxed and dropped down, forming a natural oblique degree to the horizontal plane. P1 and P2 also put their **arms** down.

9) **Land:** For the participants, the “landing” was similar to the “flying down” but with an extra foot motion. All participants said they would put their **feet** on the ground when they “land” in the VE. P2 proposed two different ways of landing. One was direct going down and landing when it got close to the ground – like a “helicopter”. Another one was to bank and glide down, then to touch the ground – like a “plane”.

Issues and Solution Explorations:

We found two issues of using the Limbic Chair in our experiments: 1) fear of falling back (5/5 participants) and 2) sliding when pressing the feet down (4/5 participants). Here we explained the issues and how we explored the solutions for them.

Issue One: Fear of Falling Back. The **“fear of falling back”** happened when the participant wanted to lean back to navigate backward. Owing to the lack of the backrest of the Limbic Chair, the participant had to use his abdominal muscles to maintain balance of the body when he leaned backwards, which is not a common movement that a person normally conducts in daily life and may cause discomfort. Moreover, the participants would be afraid of losing balance, falling back and getting hurt. We noticed that from the experiment for the second participants and then moved the chair against a wall for the later participants (the Limbic Chair was not directly up against the was, and a distance was left between the chair and the wall, so that the participants can still lean back but will touch the wall when they lean back more than an certain extend). But the participants still had certain fear, even with a wall behind them, because when they were wearing the headset, they were uncertain about the distance between themselves and the wall. Additionally, this fear was very firm in that it remained even after we explained to the participants that the chair had a lock to prevent the shells tilting back over a maximum degree, and that it was impossible for the chair to actually fall back.

Figure 3.5. Hard support (left) and soft support (right) in the free exploration phase.

Issue Two: Sliding When Pressing Feet Down. The "**sliding**" issue came from the unique leg-free moving mechanism of the Limbic Chair. Since the Limbic Chair allows the user to move their legs in the pitch direction, the users can tilt their thighs up and down. When the participant did movement for "flying forward" and "flying upward", they may tilt down their thighs and thus the seats form a sloping angle. Because the material of the Limbic Chair shells is hard and smooth, it was easy for the participants to slide down the seats and touch the ground with their feet. So the participants may struggle to have their feet off the ground to hold their balance and avoid sliding. One participant said in our experiment "I need something under my feet (to prevent sliding)". We observed this phenomenon from the second participant's experiment. So in later experiments, we applied two feet support settings in the free exploration phase of the experiment: the hard support setting and the soft support setting (Figure 3.4).

For the hard support setting, we put a cardboard box under the participant's feet. For the soft one, we put a stack of pillows under the participant's feet. P3, P4 and P5 tried the two settings in the free exploration stage of their experiments. The **hard support** did not help with the problem. According to our participants, the hard support felt the same as the ground, and would block the users' leg movement, because it was higher than the ground. However, we received all positive feedbacks from the **soft support** setting. The soft support provided both a certain degree of support from the feet, so that the user wouldn't slide down, and a degree of movement for the user to still move their feet. One participant said it felt like "cloud". Another two participants commented that they felt like "flying" with the soft support and had better control over the movements with the soft support. Not being in direct contact with the ground and creating a cognitive/perceptual framework of movability has been shown to enhance self-motion perception in a prior study by Riecke et al (Riecke, Feuereissen, & Rieser, 2009).

3.3.2.2 Interview Data Analysis (Part 2, participants' Experiential Like/Dislike): Participants' Overall Experience of the Flying Navigation Movements with the Limbic Chair

Following our video analysis of movements in Study 1, we analyzed the qualitative data in the interview. We performed the open coding of all the interview data (annotating sentence by sentence). Example codes include "feeling", "mechanism", "device", etc. Then we performed an axial coding on all the participants over every interview questions to generate categories about the participants' overall experience on the of the flying navigation movements with the Limbic Chair, and the comparative strength and weakness of the Limbic Chair in relation to sit on a normal chair and standing. Axial groupings included "freedom", "floating", "rotation", "comfort", "safety", etc. Lastly, we performed selective coding to draw out the findings, which were illustrated below. We analyzed two parts of the interview transcripts. In this **subsection, 3.3.2.2**, we analyzed **part 2 of the interview data** which recorded participants' experiential like/dislike regarding the overall sitting experience and the flying navigation movements with the Limbic Chair, and **revealed the participants' overall experience of the flying navigation movements with the Limbic Chair**. In **subsection 3.3.2.3**, we analyzed **part 3 of the interview data**, which recorded participants' experience of the Limbic Chair as a VR flying interface as compared with participants' previous experiences of sitting and standing VR flying interfaces, and **revealed the comparative strength and weakness of the Limbic Chair in supporting VR flying in relation to sit on a normal chair and standing**.

We analyzed the participants' explanation about what movement they liked or disliked (in the Interview Part 2). The participants' experiential like/dislike movements about the flying navigation movements with the Limbic Chair was shown above in Table 3.2.

We found that the "**flying back**" was the least liked navigation movement that three participants (P2, P3 and P5) mentioned it as the most disliked one. The fear of falling back was the main reason for this, which confirmed our finding in the section 3.3.1, the affordance quality of the limbic chair, that the concern of falling back of the Limbic Chair when leaning back effected the participants' feeling of safety in the Limbic Chair sitting experience.

Other than the "flying back" navigation movement, participants' preferences were not unified. There were likers and dislikers for all the other movements. For the **moving up and down**, P1 and P2 liked them because that they were "easy" and that the they can change the angle of the thigh and core to control. Whereas the P4 and P5 disliked moving up/down because P4 disliked crunching his back, and P5 thought that the chair did not allow moving up and down so he used arms.

For "**flying forward**" P2 disliked it because of the sliding issue, while P3 liked it because he thought it was "the safest and easiest" navigation movement. These two participants both experienced sliding issue when "moving forward", but P3 chose to put his feet on the ground while P2 insisted on suspending his legs. Thus we identified the sliding problem as a threat for the forward navigation movement to be comfortable for the user – and we explored the solution with soft support, reported in the last subsection, Problems and Solution Explorations.

In the "**turning**" movement, participants all used their upper body (core) either rotate or lean to a side, and three of the participants (P2, P4, and P5) used one leg up and one leg down. The three leg users all gave opinions on this turning movement, two of which (P4 and P5) liked the turning due to the leg movement, but the P2 disliked the turning, because he wanted the whole chair to rotate, like a swivel chair.

3.3.2.3 Interview Data Analysis (Part 3, Participants' Experience of the Limbic Chair Compared with Sitting and Standing): The Comparative Strength and Weakness Of The Limbic Chair In Supporting VR Flying In Relation To Sit On A Normal Chair And Standing

Table 3.2. The Strengths and Weaknesses of the Limbic Chair as a VR Flying Interface Comparing to Sitting on a Normal Chair or Standing

	Limbic Chair vs Normal Chair						Limbic Chair vs Standing					
		P1	P2	P3	P4	P5		P1	P2	P3	P4	P5
Strength	**Freedom**	X	X	X	X	X	Less Tiring			X		X
							Floating	X	X			
							Comfortable		X			
							Less Motion Sick				X	
							Safer (being steady)		X			
Weakness	**Unsafe**	X	X	X	X		**Unsafe**	X	X		X	
	Rotation				X	X	**Rotation**		X	X	X	
	Discomfort					X	Less intuitive		X	X		
	Skirt Unfriendly		X				Less Freedom					X
	Expensive		X									

"X" indicates the participant had the corresponding opinion.

Table 4.4 displayed a conclusion of the participants' opinions towards the comparative strength and weakness of the Limbic Chair towards the sitting and standing interfaces. We found out that:

Comparing to **sitting on a normal chair**, the Limbic Chair was **good** as a flying interface that it provides more freedom, or more leg movements (from all participants). It was **bad** in safety (from P1, P2, P3, and P4) and the lack of full chair rotation (from P4 and P5). Discomfort (P5), skirt-unfriendly (P2) and expensive (P2) was some minor disadvantages reflected in the participants' interview.

Comparing to **standing**, the participants held different opinions. Participants thought the Limbic Chair was **good** as a flying interface in that it was less tiring than standing (P3, P5) and that it provided a sense of floating (P1, P2). In addition, P2 suggested that the Limbic Chair was more comfortable than standing. Moreover, P4 believed that the Limbic Chair could cause less motion sickness because it allowed the user to constantly conduct micro movement (Hale and Stanney, 2014). As to the **disadvantage**, P1, P2, and P4 thought the Limbic Chair was more unsafe than standing (while P2 suggested that the Limbic Chair could be safer than standing in terms of being steady). P2, P3 and P4 also complained about that the Limbic Chair did not have the full physical rotation as the standing could do. P2 and P3 thought the Limbic Chair was less intuitive as a flying interface comparing to standing, because they thought "flying shouldn't be sitting". In addition, P5 thought the standing has higher degree of freedom in movements than the Limbic Chair.

To gain an overview of the comparative strength and weakness of the Limbic Chair, the participants thought that, as a VR flying interface, the Limbic Chair provided more leg freedom than sitting on a normal chair. But the participants thought that the Limbic Chair was more unsafe than sitting on a normal chair or standing. Moreover, the participants thought the full physical rotation that they were able to conduct with the normal chair or standing was a limitation of the Limbic Chair.

3.3.2.4. Considerations on How to Use the Limbic Chair to Support Flying Locomotion in VR

As stated above, our analysis of the data included video and interview data analysis. The summary of this analysis has been presented in tables 2.2 and table 2.3. As a result of the issues, strengths and weaknesses, we reviewed possible solutions that could provide design challenged for VR flying. This next section reviews our design considerations regarding how the use the Limbic Chair to support flying locomotion in VR.

We considered how to use the Limbic Chair to support flying in VR based on our analysis of the participants' movement choices for the flying navigation movements and participants' overall experience of the flying navigation. We generated some considerations that suggested our design of using the Limbic Chair to support flying in VR:

Consideration 1. Leverage the leg freedom provided by the Limbic Chair, especially on the forward and turning navigation movement. Allow the user to press down their legs when they lean forward to fly forward. Let the user to raise one leg up and step one leg down (like the skiing movement) to help tilting their body to a side to conduct turning movement.

Consideration 2. Use soft support under the user's feet for safety and easier control. Direct contact with the ground will decrease the feeling of flying and constrain the user's leg movements. Not being in direct contact with the ground and creating a cognitive/perceptual framework of movability has been shown to enhance self-motion perception (Riecke et al., 2009). A soft feet support could also prevent the user from sliding forward when they lean forward or reaching up the upper body, while still provide the leg freedoms supported by the Limbic Chair.

Consideration 3. Provide back support to the Limbic Chair to reduce the fear of the user falling backwards from the Limbic Chair when they lean backward. Feeling unsafe when leaning backwards was the biggest threat to the experience with the Limbic Chair as a potential VR flying locomotion interface, according to our study. In Study 1, we tested one solution with a wall as back support to the Limbic Chair. It to some degree reduced the fear of falling backwards, but not fully, because when wearing the VR headset, the participants were less aware of the wall back (e.g. not sure how far away was the wall from them, or forgot that there was a wall behind). We assume it might be ideal to have a soft back support, that lets the user be aware of its existence, which reduced the fear of falling back, but also allows the user to lean back to a certain degree. It might also be ideal to have a back support that follows or aligns with the user's back movement when the user tilt his/her back to a side, so that the user continues to feel the back support when his/her vision was replaced by VR.

3.4. Discussion and Limitation

In this section, we concluded the goal, method and the findings of Study 1, and discussed the contributions and limitations.

In this Study 1, we investigated into the Limbic Chair's affordance qualities and how the Limbic Chair could be used to support flying in VR. We designed an observational experiment to "let the user do the design". We invited experienced VR researchers as the participants for the experiment to experience sitting on the Limbic

Chair and using the Limbic Chair for flying navigation movements. We then interviewed the participants about their experience with the Limbic Chair and the flying movement.

The analysis showed, in terms of the affordance quality, the Limbic Chair's unique leg freedom was a prominent advantage that contributed to it's comfort, ease of control and intuitiveness as a VR flying interface. But it had some noticeable issues resulted from its lack of the back support, the sliding issue, hard touch and buttock hurting issue. In addition, we also noticed that Limbic Chair's novel moving mechanism brought to the user the playfulness and control challenge at the same time. In terms of how to use the Limbic Chair to support VR flying, we generated three considerations on how the Limbic Chair could be used to serve the VR flying purpose: 1) leverage the leg freedom provided by the Limbic Chair; 2) provide soft feet support for the user; 3) provide back support for the user.

Study 1 contributes to the knowledge space by exploring a novel new technology, the Limbic Chair, and its possibility to be used in VR flying locomotion interface design. The leg-free stance that the Limbic Chair could provide allows the user to rest on a seat and move his/her feet freely at the same time, which fills in the gap of the existing VR flying locomotion interfaces with the sitting stance and standing stance that the user can either rest on a seat but has limited leg movement (sitting stance) or be able to move legs freely but not able to rest on a seat (standing stance). VR flying locomotion interface designers can learn from our experience, and build VR flying interface with flexible perching stance with the Limbic Chair or similar equipment.

Study 1 also gave us insight into how we could propose a second study to test out some of our findings in comparison to standing and sitting interfaces. In our second study (described in Chapter 4), we adopted the design of the VR flying locomotion interface with the Limbic Chair in real VR flying application, and compared the VR flying locomotion experience provided by the Limbic Chair with that provided by the normal chair and the standing interfaces.

However, we were also aware of the limitations of the Study 1, with the major one being a small amount of participants. Because we required our participants to be experienced in VR research, in order to better imagine the navigation movement in VR and to suggest the VR interface design, our choice was limited to five participants.

Although we hadn't reached a saturation status of the data, qualitative data analysis can require fewer participants for the purposes of validity, provided a number of obviously repeated responses from the participants towards the experience of the Limbic Chair sitting and the preferred navigation movement. We hypothesize that this could be both that the complexity of the Limbic Chair caused the participants' different opinions, and that there were not enough participants invited to the study. We couldn't say that with a larger participant base we would find uniformed responses on the experience of using the Limbic Chair, but the data may show more tendencies, and thus we may be able to generate more insights towards the VR flying locomotion experience with the Limbic Chair. In Study 1, we were able to generate some considerations to suggest the use of Limbic Chair in the VR flying locomotion, but not able to confidently confirm the effective interface design for every flying navigation movement. More design space remained to be explored. One augmented way is to also recruit novice participants other than expert participants. Although experts could provide more professional design advice, their comments might be effected by their previous VR interface knowledge, instead of purely induced by the Limbic Chair sitting experience. Different insights could be revealed if we also included novice users.

In addition, in our interview, we asked the participants to rate the affordance qualities of the Limbic Chair, but the actual scoring wasn't consistent (we allowed the participants to give multiple score, or no score, as long as they explained their choices). So in section 3.3.1, in the quantitative oriented analysis, when we illustrate the overview of the participants' opinion towards the affordance qualities by the scoring, the weight of the opinion for each of the participant was not equal. The overview analysis based on the scoring could only be a reference, and could not reflect the exact overview of the participants' opinion. We should not force the participants to give one score for each affordance quality item, but it might be good to pre-design multiple conditions for each affordance quality item (e.g. safety when legs off the ground, safety when legs on the ground, safety when there is a back wall, safety then there is no back wall).

Also, although our participants had at least five minutes of previous Limbic Chair sitting experience before the experiment, and around twenty minutes of the Limbic Chair sitting during the experiment, the sitting experience time was probably too short, considering the Limbic Chair is novel and very different from other normal chairs. As we found in the response from the participants, some participants reported that there was a discomfort of sitting, like buttock stuck by the Limbic Chair seats when they moved legs. This may be caused by the unfamiliarity of the Limbic Chair sitting movement and may be prevented if the sitter had used the Limbic Chair for a longer time and knew how to use the chair. This also may be due to the size of the Limbic Chair, which can be ordered in different sizes to adapt to the unique structure and size of various participants' bodies. We also heard complains that the Limbic Chair required extra effort to control, which may not be a problem if the participants were more experienced. But whatsoever that indicated the complexity and less ease of learning of the Limbic Chair. On the other hand, we could also consider using movement experts, such as dancers, as the participants. Movement experts have been trained in using bodies, and expressing body movement in novel ways. So movement experts could possibly get used to the Limbic Chair movement more easily, and might yield more insights on the experience using the Limbic Chair as an embodied VR flying interface.

Moreover, in the Study 1 interview, we asked the participants about the comparison between the VR flying locomotion experience with Limbic Chair and with normal chair or standing. However, the participants did not experience the flying movement instruction with the normal chair or standing as a part of the experiment of Study 1. The comparison made by participants was based on participants' previous memory and previous perceptions, but not experienced directly in the Study 1 experiment. This may be a possible threat to the validity of the comparison. To correct for this threat to validity and to explore how participants actually experience the difference in flying interfaces, in the Study 2, we designed a within-subject experiment incorporating three sections of experience using the three kinds of interfaces for VR flying: 1) the Limbic Chair, 2) a normal swivel chair, and 3) standing without a chair.

Chapter 4.

Study 2: The Performance of the Limbic Chair as a Virtual Reality Flying Interface: Comparing the Limbic Chair, Sitting on a Normal Chair, and Standing

4.1. Objective

Based on the findings in Study 1, we conducted Study 2 that adopted the Limbic Chair in a flying locomotion interface for real-time VR application, and compared its performance with that of the normal swivel chair[11] (later we call it “the normal chair”) flying locomotion interface and standing flying locomotion interface. This study is to deeply investigate the interface of VR flying locomotion with the Limbic Chair, and to explore whether the Limbic Chair brings more ease of control, a better feeling of presence, and less simulator sickness symptoms to the user in the VR flying experience, compared to flying interfaces based on standing or normal chair. To study these goals, we proposed the following research questions:

RQ1. Does the Limbic Chair interface provide the user with more ease of control, more feeling of presence, less simulator sickness, more vection, more joy, more safety, more comfort, and can be used for longer time for the user in the VR flying experience comparing to sitting-based and standing-based flying interfaces?

RQ2. How does the Limbic Chair interface provide more/less control, more/less feeling of presence, and less/more simulator sickness symptoms, more/less vection, more/less joy, more/less safety, more/less comfort, and can/cannot be used for longer time for the user in the VR flying experience comparing to sitting-based and standing-based flying interfaces?

RQ3. How can we improve the VR flying locomotion interface design using Limbic Chair?

[11] We used a swivel chair with a backrest but without an armrest in order to prevent the chair form hindering the user’s sideway movement

4.2. Method

We adopted a mixed (quantitative and qualitative) research method to examine whether the Limbic Chair interface provides to the user with more ease of control, more feeling of presence and less motion sickness symptoms than the interfaces of standing or using a normal chair, and explored the reasons behind the differences. We invited participants to experience three phases of VR flying with each phase using a different interface: 1) the Limbic Chair interface, 2) a normal chair interface and 3) a standing interface. In the three experience phases, we encouraged participants to actively explore and search the VE using each of the flying locomotion interfaces. After each section, we used a questionnaire to collect the participants' ratings about the VR flying experience and the flying locomotion interfaces. The questionnaire asked for the participants' ratings regarding the ease of control, feeling of presence and simulator sickness symptoms. Before the experiment, we used a pre-experiment questionnaire to collect basic demographic information. After the experiment, we interviewed the participant regarding their overall experience of the three interfaces.

4.2.1. Participant

A total of 18 participants (age: M = 21.6 years, SD = 2.68, range = 19–29, 8 males and 10 females) were recruited from the participant pool of Simon Fraser University and received partial course credit or compensation for their participation. The experiment was conducted in iSpace lab, in the Simon Fraser University Surrey campus, which is a closed space with approximate an area of 20 square meters.

4.2.2. Experiment Setting

The participants wore an HMD (HTC Vive) during the experience. During the experiment, participants used three kind of flying interfaces (the Limbic Chair, normal chair, and standing). Before, at the end of, and after the experiment sections, the participants were asked to leave the experiment area in order to complete the questionnaire on a different table provided with another computer. We collected valid data from 18 participants (age: M = 21.6 years, SD = 2.68, range = 19–29, 8 males and 10 females).

4.2.3. Flying Interfaces

To make the three phases comparable, we adopted the same leaning-based flying control developed by the iSpace lab (Hashemian & Riecke, 2017, p. 360; Kitson, Hashemian, Stepanova, Kruijff, & Riecke, 2017) for the three interfaces. Based on this leaning-based flying control, we developed the three interfaces for the Limbic Chair, normal chair and standing in this experiment. Here we describe the iSpace lab's leaning based flying interface, and the detail designs of our three flying interfaces that adopts this leaning-based flying interface.

4.2.2.1. The Leaning-Based Flying Control by iSpace Lab

In this subsection we introduce the i) user control mechanism of the Leaning-based flying control by iSpace lab (below we refer it as "leaning-based flying control"), the ii) computational algorithm of the leaning-based flying control, and iii) how we adopted the leaning-based flying control in our three flying interfaces.

As to the **user control mechanism**, first, to fit every user's body size, iSpace lab's leaning-based flying control utilized a calibration process for the user. Following the calibration, the user could lean their body to a direction that corresponded with the flying to that direction in the VE. For example, the user can lean forward to move forward in the VE, bow down to move downwards, or reach both forward and downward to dive down in the VE. The more the user leans toward a direction, the greater the speed is in the VE.

As to the **computational algorithm,** in the leaning-based flying control's software system background, the computational algorithm compares the user's current head position with the calibrated initial head position, and calculates the corresponding moving velocity based on the vector that points from the initial position to the current position. A maximum speed is set to prevent the user from moving too fast. The maximum forward/backward and sideways velocity was 10 m/s. The speed was mapped with exponential transform function from the distance between the head position and the initial position, which means that the simulated translational velocity was related exponentially by the power of 1.53 – to its deflection.

As to how we adopted the leaning-based flying control in our three flying interfaces in our Study 2, we adopted the leaning-based flying control that our three interfaces share the same control mechanism and computational algorithm, but we adapted the different interfaces with different flying control sensitivities: for the two sitting positions (the Limbic Chair and the normal chair), the flying control sensitivities (the multiplier from the mapping of the head offset to the velocity) were higher (15) than the standing position (10), because they had less range of movement than standing. Other than the flying control sensitivities, the participants' lower body position and alignment were the critical essential difference of the flying experience of the three interfaces we compared. The participants either sit on the Limbic Chair, or sit on a normal chair, or stand, which provided different tactile material experiences and movement dynamics to the legs. These nuances of the lower body also in turn affected the movement of the upper body and the feeling of whole body movement.

4.2.2.2. Flying Interface Design for the Normal Chair and Standing.

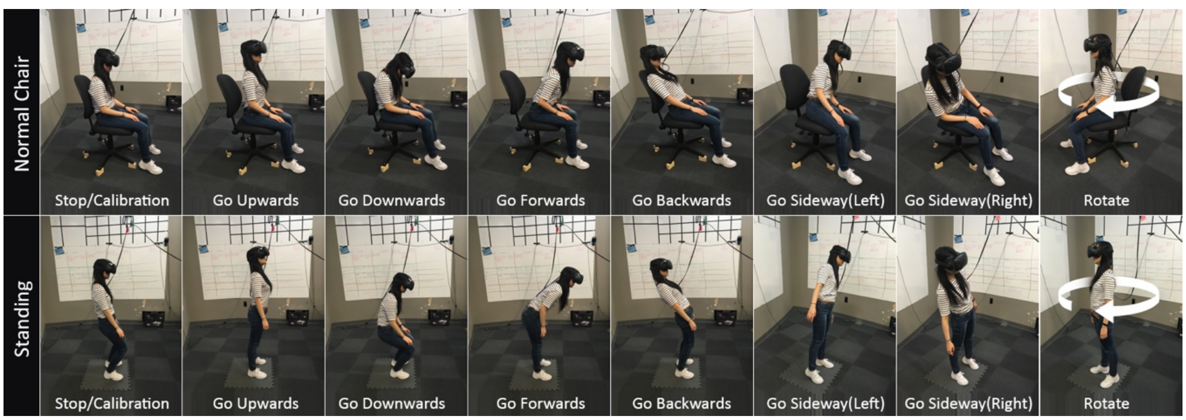

Figure 4.1. the Normal Chair (first row) and Standing (second row) Setting and Flying Operations.

In this subsection, we discussed the i) setting, ii) user control mechanism (calibration and moving control) of the normal chair interface and the standing interface.

As to the **settings**, in the normal chair flying interface, we adopted a swivel chair with a backrest but without an armrest. We used a chair without armrest to prevent the chair form hindering the user's sideway movement. We used a chair with backrest because it was indicated in previous study that the backrest provided safer experience in VR navigation (Kitson, Hashemian et al 2017). To prevent the chair from moving around, we replaced the chair wheels with wood blocks. The height of the chair was adjusted for each participant. In the standing flying interface, participants stood on a 60cm * 60cm pad. The pad was used to prevent the participant from walking around. The participants were asked to move back to the center if they stepped on the edge of the pad.

As to the **user control mechanism**, to calibrate, our participant needed to find a middle position that allowed him/her later to go both upwards and downwards, which is usually a position that was lower than the normal sitting straight or standing straight position. To calibrate for the normal chair position, our participant needed to lower down the body by relaxing and bowing the back. But he or she shouldn't lay to the backrest of the chair for the initial position, in order to be able to lean backwards after the calibration. Instead, his/her upper body was straight, though bowed. To calibrate for the standing position, our participant needed to lowered down the body by either slightly kneel down or bow the back. To fly forward and backward for the normal chair position and the standing position, our participant leaned the upper body to the corresponding direction. To go upward, the participant straightened the upper body to reach upwards. For standing, he/she could also toe the feet to reach higher. To go down, the participant bended the upper body to lower down their position. For standing, he/she could also kneel down. When the participant leaned his/her upper body to a side, he/she would move sideway in the VE. To rotate, the participant rotated the chair in the chair interface or his/her own body in the standing interface.

4.2.2.3. Flying Interface Design for the Limbic Chair

Figure 4.2. the Limbic Chair Setting and Flying Operations.

In this subsection, we discussed the i) setting, ii) user control mechanism (calibration and moving control) of the Limbic Chair interface.

Based on Study 1 of the affordance of the Limbic Chair (Chapter 3), we created this Limbic Chair flying **setting**. The Limbic Chair was put against the wall. The base of the Limbic Chair was five to ten centimeters away from the wall, according to the participant’s height. This was to make sure that the participants would have space to move backwards, but still be able to touch the wall if he/she leaned too far backwards. A stack of pillows was put under the participant’s feet. This was to provide a soft support, that could both provide balance support the participant from below, and provided feeling of flying and floating by providing more moving range to the feet.

As to the user control mechanism, we made use of the degree of flexibility that the Limbic Chair provided to the participant to help our flying. To calibrate, the participant did not need to bow the back to lower down the body, instead, he or she sat straight and slightly lower the hip using the rotation of the shells. To fly up, the participant would reach his/her head up by pressing down the Limbic Chair shells, and step down on the pillow to push his/her hip and the whole body up. To go down, the participant tilted the two shells reversely, lowered down his/her hip, and bow the back. To turn left, the participant tilted the upper body to the left side. To support the tilting, the participants were required to lift the left leg by tilting the shield up, and press down the right leg by tilting the shield down. The movement looked like skiing. Flying forward and backward were similar to the other two positions, the participant leaned the body to the corresponding direction. The Limbic Chair interface can not conduct 360-degree physical rotation as the normal chair and the standing interface do. So different from the normal chair and standing interfaces, the Limbic Chair interface uses body tilting to perform turning in the VE, and it does not allow the user to locomote sideway. This different might be a confound to evaluate the flying experience between three flying interfaces.

4.2.4. Procedure

Our experiment procedures followed an order of “Pre-Experiment Questionnaire” – “Experiment” – “Post-Experiment Interview”, as illustrated in the figure (Figure 4.3)

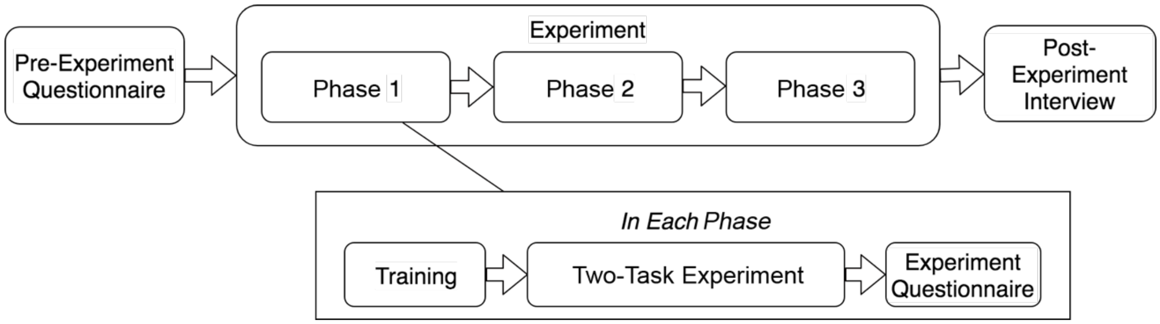

Figure 4.3. The Procedure of Study 2: the Performance of the Limbic Chair.

4.2.3.1. Pre-Experiment Questionnaire

Before the three experiment phases, participants were asked to fill in a pre-experiment questionnaire, in which they are asked to provide basic information (gender, height, gaming experience etc., explained in the “4.2.4 Data Collection” section).

4.2.3.2. Experiment

After the pre-experiment questionnaire, the participants conducted three phases of the VR flying experiment. In every phase, they used one of the three interfaces (the Limbic Chair, the normal chair and standing) to experience the effect of the interface on flying in VR. The order of the three interfaces was designed using 3*3 Latin Square to counter-balance the interference effects and learning effects. Each phase of the three phases of the experiment contains three sessions: 1) the training session, 2) the two-task experiment session, and 3) the experiment questionnaire session. Below we explained the three sessions in the experiment phase.

4.2.3.2.1 The Training Session

Every phase of the three experiment phases began with a training session to make sure that the participant managed to use the corresponding interface to control the navigation.

In the training session, the experimenter firstly demonstrated the corresponding interface that the participant was going to use in this training session of experiment. After the demonstration, the participant replaced the position of the experimenter to be ready to use the interface (sit on the Limbic Chair, sit on the normal chair, or stand on the pad). Then the experimenter helped the participants to calibrate the interface, and trained the participants to conduct the basic flying navigation movements using the interface. The navigation movements included “flying up”, “flying down”, “flying forward”, “flying backward”, “turning”, “moving sideway” (the Limbic Chair interface does not include moving sideway), and “stop”. The calibration process may be redone for the participant to nicely conduct all of the flying navigation movements. In the end, the experimenter asked the participant to conduct more complicated navigation movement like “fly to the tree on the hill”, “rotate around the tree”, “fly back to the rock”, to make sure that the participant had managed the interface. When the participant successfully followed the given instructions and reckoned he/she was ready to conduct the real experiment, the experimenter triggered the two-task experiment session.

Figure 4.4. Training Scene.

The training scene (the VE that was used in the training session) was identical for all the three sessions (Figure 4.4). The art style of the training scene was designed to be low-polygon and relatively simple. This was to avoid spoiling the participant with too much visual information, to help the participants focus on the interface movement learning, and to clean up the visual memory between the three phases of experiments.

4.2.3.2.2 The Two-Task Experiment Session

Following the training session, the participant entered the actual experiment scene for evaluating the flying interfaces. We designed two tasks for the actual experiment. The goal of these two tasks was to let the participants experience the VR flying with the corresponding interface and give the valid evaluation. There are three goals of 3D locomotion techniques: exploration, search and maneuvering(R. McMahan et al., 2014). We designed the task 1, the photo taking task, to stimulate the participant to explore the VE using the corresponding interface. In the task 1, the participant was asked to act as tourist, explored the VE and took two pictures. The experimenter explained that the pictures would be sent to the participants as a souvenir to the virtual "trip". We designed the task 2, the chest hunting task, to stimulate the participant to search in the VR. In the task 2, the participant searched the virtual area to find a hidden treasure chest within three minutes. In the task 2, the participant had to first actively survey the whole VE to locate the treasure chest, and then to engage in more precise movement to navigate closer to the chest to open it (the chest opened when the participant's location was close enough to it). When the participant found the chest, or the three minutes' time was over, the two-task experiment ended. We did not design tasks for the maneuvering task, because we identified our locomotion goal as more aligned to the **exploration** and **search** goal, and less focussed on the maneuvering goal, because i) flying is a faster, larger range of locomotion compared to grounded based locomotion, and ii) we focus more on the users' moving through the environment, rather than staying at a smaller range of area maneuvering the viewpoint.

Figure 4.5. The Task 1, Photo Taking task (left), and the Task 2, Chest Hunting Task (right).

To maintain the participant's interest for exploration, three different environment scenes were used for the two-task experiment sessions in the three phases. Due to the complexity of shuffling the scene order, every phase used a fixed scene. We examined the effect of the scenes to the experience rating. The assumption of normality of distribution was approved using Shapiro-Wilk test, all ps > 0.05, except the DVs of Simulator Sickness (Snow Mountain scene, Lake scene, Night scene), Joy (Lake scene, Night scene), Safety (Snow Mountain scene, Lake scene, Night scene), and Vection (Snow Mountain scene). But because ANOVA is robust when the group sizes are the same, we can still use normal ANOVA. Mauchly's test shows that the assumption of sphericity was not violated (all ps > 0.05). An ANOVA test showed **no significant difference** between the data with different scenes (all ps > 0.05), which indicated that the different scenes do not have a significant effect on the DVs. Because we used a fixed order of the scene for each phase, this test result also indicated that there was no significant order effect in our experiment.

The experiment scenes differed from the training scene, in that they were relatively high-resolution, of realistic style, and had more details for the participants to explore. Three experiment scenes are snow mountain (phase 1), lake (phase 2), and night (phase 3). The scene themes were decided by an informal survey about “if you were enabled with the power of flying for 15 minutes, where do you want to go”. The top places were: in the cloud over the mountain, “over where I live”, and the north pole to watch the aurora. So we created the snow mountain scene, with floating cloud over the mountain, the lake scene, which is a typical natural Rocky Mountains scene with lake and surrounded forest and snow mountain, that our participants (Vancouver residents) are familiar with, and the night scene, an imaginary scene with night desert and aurora. For the night scene, although it is darker than the day scenes, its still visible in the VR head set, and no participant reported visibility problem of the scene.

Figure 4.6. The Experiment Scenes of Phase 1(Snow Mountain), Phase 2 (Lake), and Phase 3(Night).
Pictures were taken in the real experiment by the participants.

4.2.3.2.3 The Experiment Questionnaire Session

Right after each two-task experiment session in each phase, the participants were asked to finish an experiment questionnaire evaluating the experience. The answers that participant answered in the sections were visible and editable in the later phase(s), in order to remind the participant about his/her rating for the previous interface(s), so he/she had a reference for the current questionnaire that was under evaluating. If the participant thought his/her answer for the previous flying interface should be higher or lower comparing with the current flying interface, they can change the answer. This was to help the participants to keep a consistent evaluation standard through out the long time of experiment. The questionnaire question details were described in “4.2.4 Data Collection”.

4.2.3.3. Post-Experiment Interview

After all the three phases of experiment, an interview was conducted to collect the participants' overall opinions about their experience in the three interfaces and the whole experiment. In the interview, participant was asked both closed and open-ended questions. The experimenter asked follow-up questions to clarify and further understand participants' opinion. (interview question details were described in "4.2.4 Data Collection")

4.2.5. Data Collection

In the experiment, we collected data in the i) pre-experiment questionnaire, ii) the experiment questionnaire, and iii) in the post-experiment interview. We also collected data in the form of the photographs taken by participants in task 1 and noted the durations of task 2, the time each participant spent to find the treasure chest. Below, we explain the details of the questions appearing in i) the pre-experiment questionnaire, ii) the experiment questionnaire and iii) the post-experiment interview. We also provide a rational for the reasons we chose these questions.

4.2.4.1. Pre-Experiment Questionnaire

In the pre-experiment questionnaire, we ask for the participant's basic information prior to the start of the experiment. The goals of the pre-experiment questionnaire are 1) to understand the participants' demographic information, 2) to exam possible confounds for the experiment result, and 3) to prepare the baseline for the experiment questionnaire prior to the experiment (Kennedy et al, 1993) (i.e., the source rating for the NASA Task Load Index (TLX) (Hart & Staveland, 1988) and to evaluate the participants' simulator sickness symptom level with the Simulator Sickness Questionnaire (SSQ) prior to the experiment) (Kennedy, Lane, Berbaum, & Lilienthal, 1993). Data was collected using an online survey. The full questionnaire of the pre-experiment questionnaire is attached in the Appendix C.

The questions we asked were (We annotated the questions for the Pre-experiment questionnaire as "PRE"):

PRE01 - Age

PRE02 - Gender

PRE03 - Height

PRE04 - Vision (normal/corrected with contact lenses/corrected with glasses)

PRE05 – Most Frequently Played Video Gaming Platform

PRE06 – Video Gaming Experience Level

PRE07 - HMD Experience Level

PRE08 - The Limbic Chair Experience Level

PRE09 - Sense of Direction

PRE10 - Fear of Height

TLX Source Rating and SSQ

4.2.4.2. Experiment Questionnaire

The experiment questionnaire asked questions in four areas: ease of control, feeling of presence, simulator sickness symptoms and other (Joy and Likeness to Flying). The full experiment questionnaire is attached in the Appendix D. Below we explained how we chose these questions.

Ease of Control Questions

To understand the ease of control of the flying interfaces, we referred to the Control Factor questions from Witmer and Singer's Presence Questionnaire (Witmer & Singer, 1998) and NASA's Task Load Index (TLX) (Hart & Staveland, 1988). We adopted the Presence Questionnaire and the TLX because these are broadly used, and are a validated questionnaire for the evaluation of the ease of control of the general digital systems. In addition to these, we also added our own questions. The ease of control questions included:

- The Control Factor Questions from Presence Questionnaire (Witmer & Singer, 1998), from 0 to 10 scale (We annotated the questions in this sections as "PQ", meaning the control factors questions from Presence Questionnaire):

PQ01 - How much were you able to control events?

PQ02 - How responsive was the environment to actions that you initiated (or performed)?

PQ03 - How natural did your interactions with the environment seem?

PQ04 - How natural was the mechanism which controlled movement through the environment?

PQ05 - How much did your experiences in the virtual environment seem consistent with your real - world experiences?

PQ06 - Were you able to anticipate what would happen next in response to the actions that you performed?

PQ07 - How completely were you able to actively survey or search the environment using vision?

PQ08 - How much delay did you experience between your actions and expected outcomes?

PQ09 - How quickly did you adjust to the virtual environment experience?

PQ10 - How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

PQ11 - How much did the control devices interfere with the performance of assigned tasks or with other activities?

- NASA TLX (Hart & Staveland, 1988), from 0 to 10 scale (We annotated the questions in this sections as "TLX"):

TLX01 - Mental Demand (0 as "low" - 10 as "high")

TLX02 - Physical Demand (0 as "low" - 10 as "high")

TLX03 - Temporal Demand (0 as "low" - 10 as "high")

TLX04 - Performance (0 as "good" - 10 as "bad")

TLX05 - Effort (0 as "low" - 10 as "high")

TLX06 - Frustration (0 as "low" - 10 as "high")

Above are broadly used, validated questionnaire questions to evaluate the ease of control of the general digital systems. Beside them, we also asked questions specifically designed for the tasks of this experiment:

- Other questions, from 0 = "strongly disagree" to 10 = "strongly agree" (We annotated the questions that's not included in the classical questionnaires as "OTR". Some OTR questions are in other sections):

OTR01 - Task difficulty of locating the chest (to find where it is) was high.

OTR02 - Task difficulty of opening the chest (to move close to the chest) was high.

OTR09 - I could imagine using the interface for longer time periods.

OTR13 - I have the freedom to move (physically using this position).

OTR14 - I have the freedom to move (in the virtual environment).

Feeling of Presence Questions

The Igroup Presence Questionnaire (IPQ) (Schubert, 2003) is widely accepted to evaluate the feeling of presence for a VR experience. We adopt the IPQ to evaluate the feeling of presence. 0 = “strongly disagree” to 10 = “strongly agree”. (We annotated the questions in this sections as “IPQ”).

IPQ01 - In the computer generated world I had a sense of "being there"

IPQ02 - Somehow I felt that the virtual world surrounded me.

IPQ03 - I felt like I was just perceiving pictures.

IPQ04 - I did not feel present in the virtual space.

IPQ05 - I had a sense of acting in the virtual space, rather than operating something from outside.

IPQ06 - I felt present in the virtual space.

IPQ07 - How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?

IPQ08 - I was not aware of my real environment.

IPQ09 - I still paid attention to the real environment.

IPQ10 - I was completely captivated by the virtual world.

IPQ11 - How real did the virtual world seem to you?

IPQ12 - How much did your experience in the virtual environment seem consistent with your real world experience?

IPQ13 - The virtual world seemed more realistic than the real world.

In the questions, IPQ03, IPQ04, IPQ07, and IPQ09 were reverse questions. IPQ07, IPQ08 and IPQ09 were asking the same question in different ways.

Beside the IPQ questions, we asked about the participants feeling about vection (the feeling of self-moving perceived by the participants), from 0 = “strongly disagree” to 10 = “strongly agree”:

OTR03 - I had a strong sensation of self-motion through the space with the interface.

Simulator Sickness Symptoms Questions

For the evaluation of the participant’s simulator sickness symptom, we adopted the Simulator Sickness Questionnaire (SSQ) from Kennedy et al (1993), which is broadly used to evaluate the simulator sickness for VR experiences. 0 = “none”, 1 = “slight”, 2 = “moderate”, 3 = “severe”. (We annotated the questions in this sections as “SSQ”)

SSQ01 - General discomfort

SSQ02 - Fatigue

SSQ03 - Headache

SSQ04 - Eye strain

SSQ05 - Difficulty focusing

SSQ06 - Salivation increasing

SSQ07 - Sweating

SSQ08 - Nausea

SSQ09 - Difficulty concentrating

SSQ10 - Fullness of the Head

SSQ11 - Blurred vision

SSQ12 - Dizziness with eyes open

SSQ13 - Dizziness with eyes closed

SSQ14 - Vertigo

SSQ15 - Stomach awareness

SSQ16 - Burping

Other Questions

Because we look at embodied VR flying locomotion, instead of ground-based VR locomotion, which is an experience that the participant couldn't experience in daily life, so other than the three main topics above, we also looked at some other aspects, including:

1) Joy: The degree the participants enjoyed the flying. From 0 = "strongly disagree" to 10 = "strongly agree".

OTR10 - I enjoyed exploring the whole scene using this interface.

OTR11 - I enjoyed the flying experience using this interface.

OTR12 - I feel fresh/excited/delighted/relaxed during the flying experience using this interface.

2) Which interface provided the closest experience to the participants' imagined flying experience. From 0 = "strongly disagree" to 10 = "strongly agree".

OTR08 - Flying with this interface is close to the way I would imagine to fly.

3) Safety. From 0 = "strongly disagree" to 10 = "strongly agree".

OTR06 - I feel safe using this interface to fly.

4) Comfort. From 0 = "strongly disagree" to 10 = "strongly agree".

OTR07 - My position (posture) was comfortable

5) Longer Time Use. From 0 = "strongly disagree" to 10 = "strongly agree".

OTR09 - I could imagine using the interface for longer time periods.

All the data for the experiment questionnaire were collected using an excel table, showing the questions as rows, three phases as columns, in order to facilitate the participant to easily compare and correct the scores for each phases.

4.2.4.3. Post-Experiment Interview

In the post-experiment interview, the participant was asked to give preferences about the overall experiment experiences and the reason for the preferences. The questions regarding the three flying interfaces included: 1) the participant's most liked and disliked flying interface, 2) the interface that provided the closest experience to the participant's imagined flying experience 3) how the experience with the Limbic Chair interface is different than that provided by the other two interfaces and 4) their rationales of 1), 2) and 3).

Other than these, one question was also asked about the participant's preference towards the experiment scene in order to exam whether the different scene had a confounding effect on participants' rating towards the interfaces. Moreover, participant was also asked to give opinion on the most enjoyed and dislike experience in the whole experiment experience. This is to exam whether the participants were actively exploring and searching the scene as expected, and whether there was any unexpected flaw in the experiment design. The full interview question sheet is attached in the Appendix D.

The questions asked in the post-experiment interview are (we annotated the questions in this sections as "POST"):

POST01 - Which interface do you like most? Why?

POST02 - Which interface do you dislike most? Why?

POST03 - Which interface do you think is closest to your imagined way of flying? Why?

POST04 - What do you think is the difference (good part and bad part) of the Limbic Chair comparing to the standing and normal chair, in terms of the flying experience? Why?

POST05 - Which part in the experience did you enjoy most? Why?

POST06 - Which part in the experience did you dislike most? Why?

POST07 - Which scene did you like most? Why?

POST08 - Any other suggestions and comments?

The questions were given to the participants in verbally by the experimenter. According to the participant' responses, the experimenter asked follow-up questions to understand the participants' opinions and the reasons behind. The interview was audio recorded, and the experimenter also took notes of the participant's responses during the interview.

4.3. Analysis and Findings

We analyzed the data with both quantitative and qualitative methods.

There were two types of quantitative data that we collected: i) the "rating" data (collected in the experiment questionnaire) and ii) the "voting" data (collected in the interview preference questions). We analyzed the **rating data** with one-way ANOVA methods, and analyzed the **voting data** with its distribution and chi-square test of goodness-of-fit. We used a "color coding" method to code our participants who had the same experiential preferences towards the interfaces into a same colored category.

Then we coded the **qualitative data** (collected in the interview rational questions) within a same colored category to explain deeper into the reasons behind the participants' choice.

We presented our findings of the **rating data analysis**, **voting data analysis**, and **qualitative data analysis**.

4.3.1. Rating Data Analysis

We looked at these dependent variables (DVs): 1) the **ease of control** of the flying experience, 2) the **feeling of presence** of the flying experience, 3) the **simulator sickness** perceived by the participants 4) the **vection** perceived by the participants, 5) the **joy** perceived by the participants, 6) the **safety** of the flying experience, 7) the **comfort** of the flying experience, and 8) the degree that the participant could imagine **using the interface for a longer time**.

For each DV, we first used Shapiro-Wilk test to exam the assumption of normality, and Mauchly's test to exam the assumption of Sphericity. The full analysis result was present in Table 4.1. All DVs were approved by the Shapiro-Wilk test. All DVs other than the DV of **joy** passed the Mauchly's test. For the DV of **joy**, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.68$). Then we conducted one-way ANOVA to exam the variation between the three interfaces. The result showed that the three flying interfaces had ***no significant difference*** in the DVs of 1) ease of control, 2) feeling of presence, 4) vection, 5) joy, and 8) longer time use. Three DVs of 3) simulator sickness ($F(2, 34) = 6.71$, $p = 0.0035$), 6) safety ($F(2, 34) = 4.64$, $p = 0.02$) and 7) comfort ($F(2, 34) = 7.13$, $p = 0.0026$) showed ***significant difference*** between the three flying interface groups. For these three DVs, we conducted Tukey HSD post-hoc test to dig out the detail of the difference and used Cohen's d to indicate the effect size. The post-hoc test result was also present in Table 4.1.

Table 4.1. The Analysis Result of the Rating Data[12]

Ratings	LC	NC	S	Ratings	LC	NC	S
1) Ease of Control (overall)[13] 0-10 scale	M = 6.49, SD = 0.91	M = 6.73, SD = 1.01	M = 6.38, SD = 1.27	5) Joy 0-10 scale	M = 6.67, SD = 2.37	M = 7.63, SD = 2.02	M = 6.65, SD = 2.56
	Shapiro-Wilk test approved (all ps > 0.05). Mauchly's test approved ($\chi^2(2)$ = 5.62, p = 0.06).				Shapiro-Wilk test approved (all ps > 0.05). Mauchly's test violated ($\chi^2(2)$ = 9.97, p = 0.007).		
	F(2, 32) = 0.66, p = 0.53				(Univar G-G, ε = 0.68) F(1.37, 23.23) = 1.24, p = 0.29		
2) Feeling of Presence (overall)[14] 0-10 scale	M = 6.14, SD = 1.42	M = 6.63, SD = 1.13	M = 6.37, SD = 1.18	6) Safety 0-10 scale	M = 7.33, SD = 2.06	**M = 8.44, SD = 1.65**	M = 6.72, SD = 2.05
	Shapiro-Wilk test approved (all ps > 0.05). Mauchly's test approved ($\chi^2(2)$ = 2.40, p = 0.30).				Shapiro-Wilk test approved (all ps > 0.05). Mauchly's test approved ($\chi^2(2)$ = 4.84, p = 0.08).		
	F(2, 34) = 1.00, p = 0.38				**F(2, 34) = 4.64, p = 0.02** (between NC and S: p = 0.013, d = 0.85)		
3) Simulator Sickness (overall)[15] 0-3 scale	**M = 0.32, SD = 0.28**	M = 0.14, SD = 0.16	M = 0.24, SD = 0.30	7) Comfort 0-10 scale	M = 5.39, SD = 2.03	**M = 7.44, SD = 1.95**	M = 5.11, SD = 2.74
	Shapiro-Wilk test approved (all ps > 0.05). Mauchly's test approved ($\chi^2(2)$ = 0.54, p = 0.77).				Shapiro-Wilk test approved (all ps > 0.05). Mauchly's test approved ($\chi^2(2)$ = 0.41, p = 0.81).		
	F(2, 34) = 6.71, p = 0.0035 (between LC and NC: p = 0.0024, d = 0.71)				**F(2, 34) = 7.13, p = 0.0026** (between NC and S: p = 0.0042, d = 0.95; between NC and LC: p = 0.0121, d = 0.84)		
4) Vection 0-10 scale	M = 6.36, SD = 2.23	M = 5.89, SD = 2.00	M = 6.67, SD = 2.06	8) Longer Time Use 0-10 scale	M = 5.56, SD = 2.71	M = 6.61, SD = 2.83	M = 5.22, SD = 2.56
	Shapiro-Wilk test approved (all ps > 0.05). Mauchly's test approved ($\chi^2(2)$ = 0.49, p = 0.06).				Shapiro-Wilk test approved (all ps > 0.05). Mauchly's test approved ($\chi^2(2)$ = 1.75, p = 0.42).		
	F(2, 34) = 2.04, p = 0.15				F(2, 34) = 1.68, p = 0.20		

LC = Limbic Chair, NC = Normal chair, S = Standing

[12] the bold items highlight the significant DVs. The bold mean values are the highest mean scores for the corresponding DV.

[13] Overall score of Ease of Control = sum of all the PQ questions (PQ01 to PQ11) + OTR04 + OTR05 + OTR09 + OTR13 + OTR14. (P04 was excluded in the Ease of Control tests, because P04 had one answer included in this item missing).

For the DV of **simulator sickness**, although all interfaces gained low scores (all means < 0.5, 0-3 scale), the stat analysis showed that the Limbic Chair interface (M = 0.32, SD = 0.28) gained significantly higher score (p = 0.0024) than the normal chair interface (M = 0.14, SD = 0.16), meaning that the normal chair caused least sickness to the participants, while the Limbic Chair caused the most. The effect size showed that it was a moderate effect (d = 0.71). No other significant difference detected in other pairs of comparison.

For the DV of **safety**, the normal chair interface (M = 8.44, SD = 1.65) gained significantly (p = 0.013) higher score than the standing interface (M = 8.44, SD = 1.65). The effect size showed that it was a large effect (d = 0.85). No other significant difference detected in other pairs of comparison.

For the DV of **comfort**, the normal chair interface (M = 7.44, SD = 1.95) significantly provided more comfort over both the standing interface (M = 5.11, SD = 2.74, p = 0.0042, d = 0.95) and the Limbic Chair interface (M = 5.11, SD = 2.74, p = 0.0121, d = 0.84). The difference was bigger between the normal chair and that standing than that between the normal chair and the Limbic Chair. Both of the effect size indicated large effect.

In all, the **normal chair interface** had the best performance. The **standing interface** was the least safe and the least comfortable one, while the **Limbic Chair interface** cased most, although not much, simulator sickness.

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[14] Overall score of Feeling of Presence = sum of all the IPQ questions (IPQ01 to IPQ13, with IPQ03, IPQ04, IPQ07, and IPQ09 reversed) + OTR03.

[15] Overall score core of Simulator Sickness = sum of all the SSQ questions (SSQ01 to SSQ16).

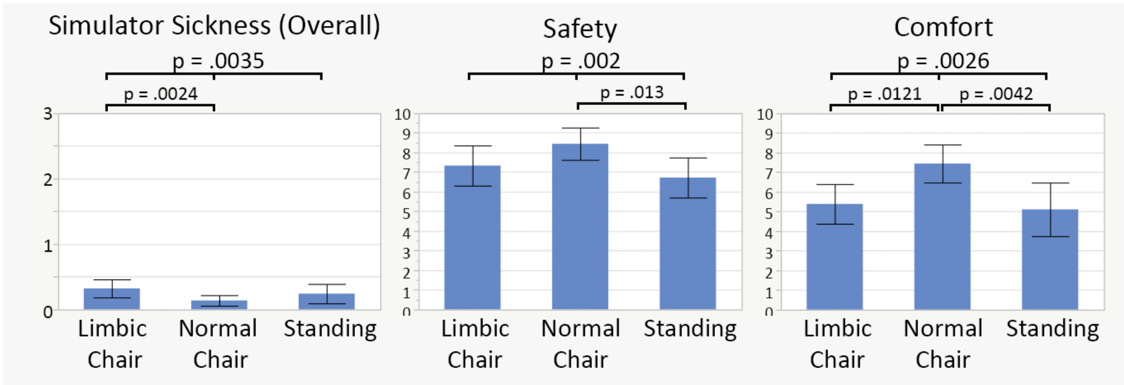

Figure 4.7. The Mean Scores of Significant Items.
Each error bar is constructed using a 95% confidence interval of the mean.

We rejected our hypothesis that the Limbic Chair interface provides the participants with better VR flying experience in terms of more ease of control, feeling of presence and less simulator sickness, vection, joy, safety, comfort and longer time use. We conclude the finding 1:

Finding 1. The Limbic Chair interface caused significantly and moderately more **simulator sickness symptoms** to the participants than the normal chair interface. The normal chair interface was perceived significantly and largely **safer** than the standing interface. The normal chair interface was rated as more **comfortable** than both the standing interface and the Limbic Chair interface. There was no other difference between the three interface groups detected in other DV aspects.

4.3.2. Voting Data Analysis and Color Coding

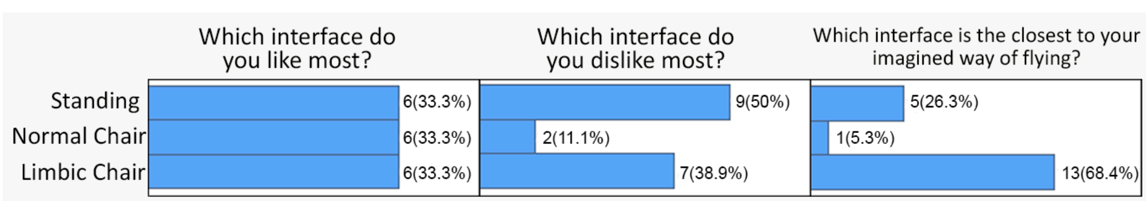

Figure 4.8. The Distribution of The Voting Data (Count And Percentage). [16]

We asked three voting questions in the interview illustrated in Figure 4.8.

For the first voting question, "POST01 – Which interface do you like most?", the choices were evenly distributed. Each interface had 6 votes (33%) from the participants.

[16] For the voting of the interface that is "closest to imagined way of flying", there were 19 votes in total, because because one participant voted for both the Limbic Chair and standing.

For the second voting question, “POST02 – Which interface do you dislike most?”, the normal chair was the least likely to be disliked (only 2 votes, 11%). Standing (9 votes, 50%) and the Limbic Chair (7 votes, 39%) was similar.

For the third voting question, “POST03 – Which one do you think is closest to your imagined way of flying?”, the vote for the Limbic Chair (13 votes, 68%) was significantly more than the others (standing: 5 votes, 26%; normal chair: 1 vote, 5%).

The voting result showed, the normal chair interface, which earned the best scores in the rating analysis, was truly the least disliked interfaces (only 11% participants chose it). However, it did not show any advantage in winning the best place for the liked most interfaces (the three interfaces gained equal votes). The standing interface did perform the worst in the rating, and it was indeed the most disliked interface. And the Limbic Chair performed the best as the interface that provides the closes experience to the participant’s imagined flying experience (later in this thesis, we refer participant’s choice for this question as “the participant’s choice of *likeness to flying*”, or “the participants thought this chosen interface was *like flying*”) (68% of the votes). A chi-square test of goodness-of-fit confirmed the voting for the “closest feeling to flying” was not equally distributed ($X^2(2, N = 18) = 12.64, p = 0.0018$).

Interestingly, we found that there was a relationship between the like/dislike preference of the interface (POST01, POST02) and the likeness to flying (POST03). In Table 4.2, we listed out the distribution table of the participants for their choice of like/dislike preference (in the three columns), and their choice of likeness to flying (in the two rows):

Table 4.2. Distribution of the Participants in the Limbic Chair’s Voting Question Answers

	liked LC the most	neither like nor dislike LC	disliked LC the most
Chose LC as most like flying	P00, P01, P04, P05, P16, P18	P03, P07, P08, P11, P12	P14, P19
Did not choose LC as most like flying	None	None	P06, P10, P13, P15, P17

The voting questions includes the likeness to flying (POST03) and the like/dislike preference of the Limbic Chair (POST01, POST02). LC = the Limbic Chair. P00-P19 indicates the participant’s ID.

As illustrated in the Table 4.2, To more easily visualize the participants' choice and refer to the categories in later discussion, the participants' IDs in the same cell were coded in the same colors (green, purple, orange and red). In later discussions, we will use the same color code to refer to the group of participants.

It was not surprising to see that all the participants who chose the Limbic Chair as their liked most interface (the first column, in color green, 6 people, 33.3%), also thought the Limbic Chair was most like flying. The people who disliked the Limbic Chair most (the third column, in color orange and red, 7 people, 38.9%), they mostly thought the Limbic Chair as most like flying. But it was interesting that, all the people in between (the second column, in color purple, 5, 27.8%) all thought that the Limbic Chair interface as most like flying. In fact, even if someone disliked the Limbic Chair (in the third column, 7 people, 38.9%), two of them (in color orange, 11.1%) voted the Limbic Chair as most like flying.

Finding 2. Most participants thought the Limbic Chair interface provided **the closest experience to their imagined flying experience**. Interestingly, this holds true even if some participants might like other kind of interfaces best.

From these findings, curiosities were raised that provided possible reasons for our findings:

1) What was the strong power of the Limbic Chair interface, that let so many participants say "yes, it is flying", even if they may not like this interface the most?

2) Why did some participants regard the Limbic Chair interface experience as closest to their imagined experience of flying, but didn't vote this flying interface as their favorite?

3) Most of the participants who disliked the Limbic Chair interface also did not consider the Limbic Chair interface provided the closest experience to flying. Why they were different than other participants? Why didn't they think the Limbic Chair's experience was like flying? Was it the same reason that they didn't like the Limbic Chair most? Can we resolve the problem so they would think the Limbic Chair interface as their liked most interface?

In the qualitative data analysis (4.3.3), we used these questions as clues to motivate further investigation.

4.3.3. Qualitative Data Analysis

To find out the answers to the three curiosities noted above, we investigated more deeply into the qualitative data.

We firstly coded all the qualitative data regarding the participants' comments on the three interfaces to reveal the categories of the participants' opinion toward the Limbic Chair interface. The data we coded included 1) the reasons for the participants' choices of their liked and disliked most interfaces (POST01, POST02), 2) the reasons for their choice of the closest way of flying (POST03), and 3) the differences between the Limbic Chair experience and the other interfaces (POST04). We generated the main pros and cons categories of the Limbic Chair from all the opinions and organized them into Table 4.3 by the pros and cons categories for the Limbic Chair with the color coded participants' ID in these categories. There were opposite or related categories (e.g. "comfortable" and "uncomfortable", "new and fun" and "not familiar"). For those categories, we put them in the same row in the table to make easier comparison.

Table 4.3. The Pros and Cons Categories of the Limbic Chair Interface.

Pros		Cons	
Comfortable	P00, P05	Uncomfortable	P13, P06, P14 P12, P15, P11
Safe	P00	Unsafe	P08, P18
New and fun	P00, P01, P16, P04, P03	Not familiar	P15, P08, P14, P03, P07
Natural	P04, P08, P17, P18	Not natural	P15
Control and Movement	(More control) P00, P05, P12, P07 (More movement) P15, P03, P05, P18, P19,	Control and movement	(Hard to control) P08, P14, P15, P10 (More complicated movement) P13, P14, P15
Floating	P11, P14, P16, P18, P19		
Turning (like)	P08, P03, P05, P04, P16, P12,	Turning (dislike)	P13, P15, P17, P19
		Slow	P13, P10, P15, P17

Secondly, we did a secondary re-coding on sub-sections of the data for each of the curiosities we listed above to re-exam the deeper reasons. We illustrate our analysis below.

To figure out ***the first curiosity, "What was the strong power of the Limbic Chair interface, that let so many participants say "yes, it is flying", even if they may not like this interface the most?",*** we specifically investigated into the ironic group of participants that thought the Limbic Chair as most like flying, but chose other interfaces as their favorite interfaces (the purple and orange group).

The purple and orange group's reasons for choosing the Limbic Chair experience as most like flying:

P03: "use **legs**" "**floating**" "have to **use one side of the body** to **turn**, more like flying"

P07: "**legs** can move" "**floating**" "have to keep my balance"

P08: "use **legs** to cooperate with my upper body" "use **leg** and waist to **turn**"

P09: "**suspending** in the air" "**legs** can move" "**turning** is also like how I would fly"

P12: "**turning** is fast and responsive"

P14: "**floating**" "it feels new. S and NC feels so common, so they are not like flying."

P19: "I feel I'm swing in the space" "my legs were in the air suspending, I felt **floating**."

From the responses, we found that there were the three common reasons that these participants chose the Limbic Chair experience as most like flying: the 1) leg freedom (4/7), 2) feeling of floating (5/7), and 3) turning mechanism (4/7). We here explain them one by one.

For the **leg freedom**, due to the special construction of the Limbic Chair, the participant's legs could move up and down in the pitch direction, and rotate left and right in the yaw direction, instead of being limited by the seat as the normal chairs, or limited by the ground as the standing position. This increased the feeling of flying to the participants.

The **feeling of floating** could have came from the moving shells and the pillow put underneath the participant's legs (for instance, P11 said "The Limbic Chair has more floating feeling, like swing, nothing underneath me, because the pillow was really soft, so I felt the floor wasn't really firm"). Without the feet touching the ground or limited by the seat, the participants feel the feeling of floating, and thus this increased their feeling of flying.

The **turning mechanism** was also a large contribution to the feeling of flying. In our design of the Limbic Chair interface, the participant could not move directly side ways, but could slowly rotate in the VE while he/she tilted the body to a side. With the Limbic Chair interface, the participant can raise one leg up and press one leg down like the skiing pose to help them lean to a larger degree (Figure 4.9). These participants found this turning mechanism was the reason for choosing the Limbic Chair interface as the interface that provides the closest experience to flying. Also, in the locomotion experience, the turning movement would be often combined with the forward movement, making a banking curve. These participants found it natural and more like flying.

Figure 4.9. Turning for the Limbic Chair.

The same reason applied for the green group, who liked the Limbic Chair interface most and also voted it as like flying most. So we concluded our second finding:

Finding 3. There were three reasons why most participants thought the Limbic Chair was like flying: **leg movement, turning and feeling of floating**.

For our ***second curiosity: "Why did some participants regard the Limbic Chair interface experience as closest to their imagined experience of flying, but didn't rate this flying experience as their favorite?"*** We investigated into the same purple and orange group, and their reason for choosing not the Limbic Chair as their favorite interface.

The purple and orange group's reasons for their favorite interface (in the brackets next to the participant ID are the participant's choices of their favorite interface. LC = Limbic Chair, NC = Normal Chair, S = Standing):

P07(NC): "more **familiar**"

P08(NC): "**comfortable**" "safe" "**familiar**"

P09(NC): "more **relaxed**"

P12(NC): "**comfortable**"

P03(S): "**easy** to move" "no chair to limit my freedom" "bigger moving range" "high-tech, new… but not **familiar**"

P14(S): "the control is more free" "**simple** and easy" "**not complicated**"

P19(S): "the body moving range is bigger" "I can move around **as I wish**"

It was very obvious that, for the participants who regard the Limbic Chair interface as most like flying, but chose other interfaces as their favorite interface: they prefer the normal chair interface, because it was more **familiar** to them, and they sat more **comfortably** than the Limbic Chair interface; they preferred the standing interface, because they have larger range of movement, and they can move "**easier**", while the Limbic Chair interface was more "**complicated**", which we considered as also a consequence of "**unfamiliarity**" to the Limbic Chair.

So here we recognized the "**unfamiliarity**" as the biggest threat for the Limbic Chair interface to become the participants' favorite interface. Of course this was due to the **novelty** of the Limbic Chair – none of the participants had ever used it before the experiment. We found this kind of novelty reflected in almost every participant's response. However, the participants who chose the Limbic Chair as their favorite interface, the green group, would mention this **novelty** in a positive way, they thought it was "new and fun":

P00: “It was my first time experience. It was **interesting**.” “This one (the Limbic Chair) has some **special** mechanism.”

P01: “it was more **interesting**”

P04: “I feel like another animal” “I **feel like a fish or flying like a dragon**”

P16: “the Limbic Chair was more **fun**, although the normal chair was more comfortable.”

So we conclude our finding 4:

Finding 4. The **endurance to the novelty** of the Limbic Chair was the watershed for the participants to favor the Limbic Chair, or not: if the participants like the novelty, they will like the Limbic Chair most, if the participants don’t, they may choose other interfaces.

At last, we had the ***third curiosity: “The participants who disliked the Limbic Chair most mostly did not consider the Limbic Chair interface provided the closest experience to flying. Why they were different than other participants? Why didn’t they think the Limbic Chair’s experience was like flying? Was it the same reason that they didn’t like the Limbic Chair most? Can we resolve the problem so they would think the Limbic Chair as the best?”***. To answer this curiosity, we looked at the red and orange group, who disliked the Limbic Chair interface most.

The red group’s reasons for disliking the Limbic Chair most:

P06: “will **fall** when moving forward”

P10: “hard to control” “**slow**”

P13: “I feel I’m gonna **fall**” “it’s not natural to **turn**”

P15: “not **familiar**, so hard to **control**” “**turning** was **slow**”

P17: “hard to **turn**” “I move **slow**”

The orange group’s reasons for disliking the LC most:

P14: “have to consider the **balance**” “**too sensitive**”

P19: “**turning** was not convenient”

In the responses, the participants mentioned several times their dislike about the **turning** of the Limbic Chair interface. They either thought the turning was **slow**, or **not familiar** with the skiing-like movement (putting one leg up, one leg down while tilting the upper body to a side), which the participants performed for the turning. When we investigated into other responses that those participants gave, we found that the dislike of **turning** also influenced their opinion to the control/movement of the Limbic Chair interfaces. Actually, this was confirmed by the table of the pros and cons categories of the Limbic Chair interface (Table 4.3) that the dislikers mainly disliked the Limbic Chair's turning mechanism and the slow speed: the red color mainly clustered in the right-bottom corner, where the "turning" and "slow" categories located.

So here we conclude the finding 5:

Finding 5. The incompatibility to the **turning** mechanism (either considering it as **unfamiliar** or too **slow**) made the participants dislike the Limbic Chair interface the most.

4.4. Discussion and Limitation

In this section, we concluded the goal, method and the findings of the Study 2, and discussed the contributions and limitations of the Study 2.

In this Study 2, we investigated the performance of the Limbic Chair as a VR flying locomotion interface comparing to the sitting and standing interface. We conducted a one-way repeated measure experiment comparing the flying experience provided by the Limbic Chair interface, the normal chair interface and the standing interface. We used questionnaires to collect quantitative data, and an interview to collect qualitative data. We found that the Limbic Chair interface did not provide significantly better overall experience comparing to the sitting and standing interface, but it clearly provided the participant with more feeling of flying with its special mechanism.

Here we discuss the contributions of the Study 2. Previous studies on VR flying locomotion interfaces focused mostly on the effectiveness of task completion time and accuracy (e.g. Pittman et al., 2014), and usability issues like ease of control, comfort, motion sickness, intuitiveness, fatigue and fun (e.g. Higuchi et al., 2013). But those features are all common with grounded-based VR locomotion interfaces, and few had talked about the "feeling of flying" that the user perceives, which is unique about VR "flying" locomotion. The only study we know of, from Cherpillod et al in 2017, had cast light on the user's feeling of flying in the flying experience, and found that their lying-based interface provided greater feelings of flying than a hand-held remote controller. However, they did not explore further how the interface provided the feeling of flying, and did not compare the feeling of flying between interfaces that are all embodied and provide motion cues.

Our study provided a deeper understanding of the feeling of flying that users perceive in a VR flying experience. The Study 2 contributed to the knowledge space by revealed that the Limbic Chair interface provided more feeling of flying comparing to the normal chair and standing interfaces. This feeling of flying was closely related to the sense of floating, that came from the leg movement with soft feet support and the turning mechanism provided by this new stance. The VR flying locomotion interface designers could refer to our experience and adopt the Limbic Chair in their designs.

Moreover, the Study 2 result showed a disconnection between "close to the feeling of flying" and "preferred experience of flying", i.e. the Limbic Chair interface gained most vote for the likeness to flying, but due to the unfamiliarity and discomfort, some of the participants may not choose its as their favorite flying interface. In theory, this disconnection could have two possible reasons. One, these participants may not like flying, when they really can. Two, these participants like the feeling of flying, but they think some other factors were more important. We argue that the reason is a mixture of the two.

We agree with the first possible reason, because as indicated in the analysis result, the leg moving provided by the Limbic Chair interface brought the participant with more ***freedom***, but also required more ***effort*** from the participant to hold balance. Similarly, the leg suspension introduced the ***feeling of floating***, but also the feeling of being ***unsafe*** for some participants. Moreover, some participants thought the novelty of the Limbic Chair interface was ***new and interesting***, while other participants considered the same novelty as ***unfamiliar and weird***. So we see that there are some **"two-sided-coin" effects** inherently bonded with the embodied flying experience.

We also agree with the second possible reason, because other than these two-sided-coin aspects (leg freedom - extra effort, novelty - unfamiliarity, and floating - unsafety), we also saw some issues caused by the hardware design, or that the participants did not sit and move on the Limbic Chair in a right way. For example, the participants may slide from the chair, the Limbic Chair's seats were too hard for some participants to sit comfortably, or sometimes the Limbic Chair stuck the participant's buttock when he/she moved his/her legs. We found that all the participants who had this kind of comments did not choose the Limbic Chair experience as their favorite. This means that for these participants who noticed these defects of the Limbic Chair, these aspects were more important than the feeling of flying itself. Later VR flying locomotion designers could consider to improve the interface design from those aspects.

In addition, in the study we also revealed that the flying speed and turning mechanism played an important role in participants' evaluation to the flying experience. As shown in Table 4.3, most of participants who disliked the Limbic Chair interface the most mentioned that they disliked it because they thought the **moving speed** of the Limbic Chair interface was too slow. But the participants who did not choose the Limbic Chair interface as the most disliked interface never mentioned that the Limbic Chair interface's speed was slow. So which speed we should choose is an interesting question to explore further. For the **turning mechanism**, our results showed that the same turning mechanism was both the reason for the likers to like the Limbic Chair interface most, and the reason for the dislikers to dislike the Limbic Chair interface most. The difference of turning of between the Limbic Chair interface and the other two interfaces are 1) for the Limbic Chair interface, the participants could use the leg freedom provided by the Limbic Chair to support their leaning to a side to turn; 2) the Limbic Chair interface does not provide 360-degree physical rotation as the interface with the normal chair and standing. From our speculation, both of the two differences have effects on the participants' experience about the turning mechanism of the Limbic Chair interface - especially the lack of physical rotations, which previous studies have found crucial for spatial updating/awareness(Riecke et al., 2010). However, few studies had ever focused on the flying speed and turning mechanism, and no one had provided an analysis of the relationship between the flying speed and the flying experience or between and the turning mechanism and the flying experience. From the result we got from this Study 2, we hypothesize that the turning mechanism is a personal preference, but the speed of flying is related to the participant's previous height, VR experience or gaming experience, and can be customized by it to provide the better experience. Deeper study could to be done to explore these two aspects.

However, we were also aware of limitations of the Study 2:

Firstly, in the Study 2, we used the Limbic Chair to form a new posture between standing and sitting, but the Limbic Chair could also work as a sensor to detect the pitch, yaw and roll rotation data of the two shell seats, and send the signal to the VR system. This orientation sensor of the Limbic Chair could be used to detect leg gestures to control the flying. For example, when we detect "one leg raising, one leg pressing" by the pitch, yaw and roll changes of the two legs, we conduct the rotation movement. In our Study 2, due to that the data is noisy and that the limited time we had, we haven't explored the possibility of using this feature to enhance the flying control for the participant. But more thoughtful usage of the Limbic Chair as an input device could be conducted in future works.

Secondly, the training time for the participants to adapt to the Limbic Chair movement was too short (5-10minutes), giving that the Limbic Chair's moving mechanism is novel and relatively complicated. As we noticed in the experiments, some discomfort about the Limbic Chair flying experience might be reduced if the participant sat in a correct way. For example, for some participants, if he/she sits more backwards, he/she may not encounter the buttock stuck issue. But due to the complexity of the Limbic Chair and the limited experiment time, although we already considered the training of the participants for the Limbic Chair sitting, the time was still not enough for the participants to master the chair movements. It would be ideal if the participants could be given hours-long trial, or separate days of training session before the real experimental session, in order for the participants to better adapt to the novel chair movement. It might be ideal, in the training, to both 1) allow the participants to freely explore the Limbic Chair and get adapt to the sitting with the Limbic Chair even without VR setting, and 2) train the participants to use the Limbic Chair flying interface in the training scene in VR, until they manage the Limbic Chair flying interface.

Moreover, to reduce the complexity of shuffling the scene order, we adopted the same scene for each phase of the experiment. To examine whether the scene difference affected the experiment result, we conducted ANOVA tests and found no significant difference between the results of the three different scenes. But the scene could still be a confound, especially giving that we asked the participant about the preference of the environment scene in the post-experiment interview (Snow Mountain: 3; Lake: 12; Night 4[17].), and the Lake scene was preferred by the participants. A chi-square test of goodness-of-fit showed the voting for the "liked most scene" was not equally distributed ($X^2(2, N = 19) = 7.18, p = 0.028$). To improve, pilot test on the scene preference and adjustment on the scene could have been conducted to reduce the effect of the scene preference. If the time and number of participants are sufficient, shuffling the scene order could also be conducted.

Lastly, in the study, we did not asses the inter-rater reliability. Due to the limited time and resources, the interview data were only coded by one researcher. Hereby the coding result could be affected by the researcher's personal bias. This might pose a threat to the rigour and reliability of the study.

[17] The total count of the voting is 19, because one participant voted for both the lake and the night scene.

Chapter 5.

Conclusion and Future Studies

Flying is an activity that human beings have long dreamed about achieving and VR is exactly a means to help us realize embodied human flying. Recently, many researchers and designers had proposed designs of VR flying locomotion interfaces in both academia and industry, including lying-based flying interface, sitting-based flying interface and standing-based flying interface. But current technologies continue to have limitations in providing optimal affordances and performance of VR flying interfaces. A lying-based flying interface allows the user to lie prone much like a bird, which, while it is the most intuitive interface most easily causes fatigue because it necessitates positioning the human into a challenging body position to maintain and can create muscle fatigue. The sitting and standing based flying interfaces create less fatigue, but they also provide less sense of floating, because the users' leg movement is limited by the sitting position or the floor.

In this thesis, we investigated the possibility of a new kind of device – the Limbic Chair as a VR flying interface. This chair has a novel design that provides two movable separate sitting segments for each half of the buttocks which frees each of the user's legs by supporting separate movement for each of the user's legs in pitch, yaw and roll directions, and thus provides the user with both leg freedom and less fatigue. This is a very recent device that to our best knowledge, has not been explored in a research setting. In our two studies we explore how the Limbic Chair can be used for VR flying. In our (Study 1) we explore the affordances of the Limbic Chair as a VR flying interface and examine how it can optimally be used it as a VR flying interface as was illustrated in Chapter 3. Based upon our results of Study 1, we followed with Study 2, in which we applied the Limbic Chair flying interface to a real VR flying application to investigate its performance, in comparison with the sitting and standing flying interfaces in terms of ease of control, feeling of presence, sickness symptoms joy, likeness to flying, and we investigated the reasons for our results. This was described in Chapter 4.

In our **Study 1**, we adopted a qualitative observational method, in which our participants, VR interface design experts, experienced the Limbic Chair and conducted their preferred movement on the Limbic Chair following flying navigation instructions. We used an interview to investigate the participants' i) experience of the affordance qualities of the limbic chair in phases 1 and 2; ii) experiential like/dislike about the overall sitting experience and the flying navigation movements; iii) the comparison of the Limbic Chair with sitting and standing interfaces, and iv) their rationale for i), ii) and iii) above. We found that, in terms of the quality, the Limbic Chair's unique leg freedom was a prominent advantage that contributed to its comfort, ease of control and intuitiveness as a VR flying interface. We noted usability issues of lack of the back support, sliding, hard touch and buttock hurting. We also noticed that Limbic Chair's novelty brought both playfulness and control challenge at the same time. we explored participants' preferred VR flying navigation movement choices, and generated three considerations of using the Limbic Chair as a flying interface: 1) leverage the leg freedom provided by the Limbic Chair; 2) provide soft feet support to the user; 3) provide back support to the user.

With the findings of Study 1, we conducted **Study 2**, in which we applied the Limbic Chair flying interface to real VR flying application to investigate its performance, (including the experiential qualities included ease of control, feeling of presence, less simulator sickness, more joy, safety, comfort) in comparison with the sitting and standing flying interfaces. We collected quantitative data to investigate the participants' attitudes to the three interfaces and qualitative data to explore the reasons behind participants' experience with the three interfaces. The results of Study 2 showed that the Limbic Chair outrivaled other two interfaces in "likeness to people's imagined way of flying", but not significantly outrivaled the other two interfaces in other experiential qualities. We found a disconnection between "close to the feeling of flying" and "good experience". We also realized that some of the participants' flying experience was affected because there was also discomfort in some of the sitting experience such as sliding, which might be caused by the complexity of learning to use the Limbic Chair. We also noticed that the turning mechanism design and the flying speed design were two important factors that effected the participant's VR flying experience.

This thesis contributed to knowledge space in the exploration of the possibility for a new VR flying interface: a "floating" Limbic Chair that could provide the user with a "flexible perching" stance. We found that this stance can provide a greater feeling of flying to the user in VR flying than the existing sitting stance and the standing stance.

This thesis also identified the strength and weakness of the Limbic Chair's application to VR flying, and suggested design of the VR flying interface with the Limbic Chair.

We identify four possible future directions to further investigate the Limbic Chair flying interface for VR application:

1) Using the Limbic Chair as an input device. In the study we used the chair to form a new posture between standing and sitting. However, the Limbic Chair could also work as a sensor. It could detect the pitch, yaw and roll date of the two shell seats, and send the signal to the system. This orientation sensor of the Limbic Chair could be used to detect leg gestures to control the flying. For example, when we detect "one leg raising, one leg pressing", we conduct the rotation movement. The Limbic Chair input could also be combined with the HMD positional and rotational input or other input resources to recognize the user's behavior and map to the flying control. In this way, the Limbic Chair becomes an input device, instead of merely a stance support, which could possibly enhance the control, and make it more easy, sensitive and intuitive;

2) Training the participants for a greater duration. As noticed in the experiments, some discomfort about the Limbic Chair flying experience might be reduced if the participants sat in a correct way. For example, for some participants, if he/she sits more backwards, he/she may not encounter the buttock stuck issue. But due to the novelty and the complexity of the Limbic Chair, and the limited experiment time, although we already considered the training of the participants for the Limbic Chair sitting, the training duration may not have been long enough for the participants to master the chair movements. It would be ideal if following experiments explored the effect of longer training sessions including separate days of training session before the experimental session, in order for the participants to better adapt to the novel chair movement.

3) Customizing the control parameters to the user's physiology and background condition. In our experiment, we observed that participants' individual difference might influenced the evaluations of the flying interfaces. For example, we found that the shorter participants had a higher chance to choose the Limbic Chair as their favorite flying interface than the taller participants. And the participants who has more VR experience tended to have a higher chance to dislike the Limbic Chair than the participants who have less VR experience. Having noticed this, we might optimise the flying experience of the Limbic Chair interface to fit the personal height, moving habit, and gaming experience, in order to gain better control.

4) Speed adapting to the virtual environment. We observed in the experiment, that the flying speed has a large influence to the participants' satisfaction of the flying experience. For example, in the virtual environment of experiment, because there were no much objects in the sky to provide references, the participants felt they moved much slower when they were high in the sky than when they were closer to the ground, although their actual flying speeds of the two conditions kept the same. This informed us that considering the environment-camera relationship might help with the flying experience. In fact, there have already been studies that looked at general locomotion speed adaption to the virtual environment (e.g. Ware and Fleet, 1997). They proposed a method to scale flying speed changes in relation to the user's distance to the VE's and found user preferred sampling processes. But to our best knowledge, no studies had applied speed adaption in embodied VR flying interface design. How to design speed adaptation in embodied VR flying interface design could be a further direction to explore.

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Appendix A.

Study 1 Interview Questions

Participant ID: ____________

Participant's Height: ____________

Part 1: Participants' opinions towards the quality of the Limbic Chair

1. How long time have you used the chair?

____

2. How long time have you been working with VR research/development/gameplay?

____

3. To what degree (0-10) do you think the limbic chair is:

Comfortable? And Why?

____

Easy to learn? And Why?

____

Easy to control? And Why?

____

Safe? And Why?

____

Enjoyable? And Why?

____

4. To what degree (0-10) do you think using the chair to "fly" in the virtual environment is intuitive?

5. Which part of the overall sitting experience did you like/dislike most? Why?

Part 2: Participants' overall opinions on the flying movement with the Limbic Chair, and comparison with other interfaces:

1. Which flying movement did you like/dislike most? Why?

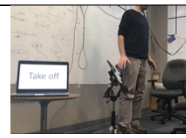
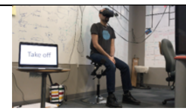
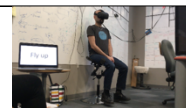
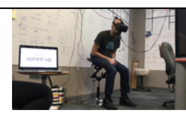
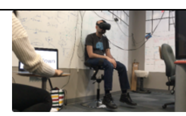
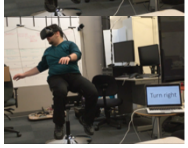
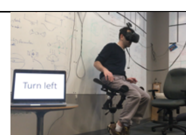
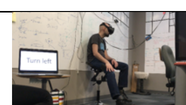
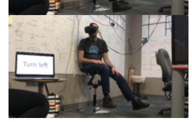
2. How do you think the limbic chair can be good/bad as interface for flying comparing to other chairs?

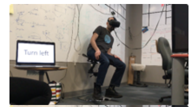
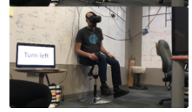
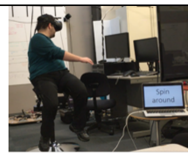
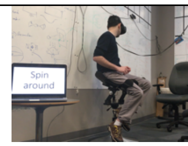
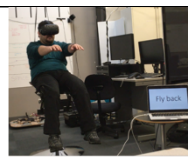
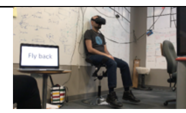
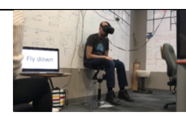
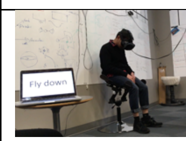
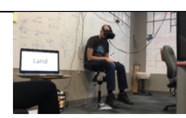
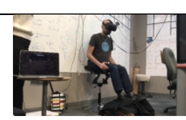
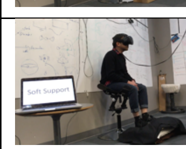
3. How do you think the limbic chair can be good/bad as interface for flying comparing to standing?

Appendix B.

Study 1 Participants' Movement Table

Study 1 Participants' movement table for data analysis (P02 did not authorize the publication use of video image)

	P01	P02	P03	P04	P05
Take off		-			
Fly up		-			 
Fly forward (speed up)		-			
Fly forward (speed down)		-			
Turn left/right	 	-	 	 	 

			 	 	
Stop and stay in the air		-			
Spin around		-			
Fly back		-	 		 
Fly down		-	 		
Land		-			
Additional setting 1 (hard support)		-			
Additional setting 2 (soft support)		-			

Appendix C.

Study 2 Pre-Experiment Questionnaire

Participant ID: ____________

PRE01 - Age: _____________

PRE02 - Gender:

O Male

O Female

PRE03 - Height:

O below 150cm/4.9ft

O 150cm - 160cm (4.9ft - 5.2ft)

O 160cm - 170cm (5.2ft - 5.6ft)

O 170cm - 180cm (5.3ft - 5.9ft)

O 180cm - 190cm (5.9ft - 6.2ft)

O above 190cm (6.2ft)

PRE04 - Vision:

O Normal

O Corrected (contact lenses)

O Corrected (glasses)

PRE05 - Which medium do you use most often to play video-games?

O game console of my own

O game console when I visit friends

O PC(online)

O PC(offline)

O mobile phone

O handheld console

O I don't play

PRE06 - How often do you play video games?

O Daily

O Weekly

O Once a month

O Once very 6 months

O Once a year or more rarely

PRE07 - How often have you used Head-Mounted-Displays (HMD) before?

O Never

O Sometimes

O Frequently

PRE08 - How often have you used the Limbic Chair before?

O Never

O Sometimes

O Frequently

PRE09 - (Please rate the items below:) How would you rate your everyday sense of direction? 0 = terrible to 10 = excellent.

____

PRE10 - (Please rate the items below:) How would you rate your level of fear of height? 0 = "no fear of height" to 10 = "very afraid of height".

____

TLX Source Rating

Source of workload comparison.

The definition of the source of workload:

Mental Demand (Low to Height)
How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?
Physical Demand (Low to Height)
How much physical activity was required? Was the task easy or demanding, slack or strenuous?
Temporal Demand (Low to Height)
How much time pressure did you feel due to the pace at which the tasks or task elements occurred? Was the pace slow or rapid?
Overall Performance (Good to Bad)
How successful were you in performing the task? How satisfied were you with your performance?
Effort (Low to Height)
How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level (Low to Height)
How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?

Please compare in pairs the following source of workload by your perceived importance:

Effort or *Performance*

Temporal Demand or *Frustration*

Temporal Demand or *Effort*

Physical Demand or *Frustration*

Performance or *Frustration*

Physical Demand or *Temporal Demand*

Physical Demand or *Performance*

Temporal Demand or *Mental Demand*

Frustration or *Effort*

Performance or *Mental Demand*

Performance or *Temporal Demand*

Mental Demand or *Effort*

Mental Demand or *Physical Demand*

Effort or *Physical Demand*

Frustration or *Mental Demand*

Simulator Sickness Questionnaire

Please rate your feeling of the symptoms below:

General Discomfort:

O none; O slight; O moderate; O severe

Fatigue:

O none; O slight; O moderate; O severe

Headache:

O none; O slight; O moderate; O severe

Eye Strain:

O none; O slight; O moderate; O severe

Difficulty Focusing (Eye Focusing):

O none; O slight; O moderate; O severe

Salivation Increasing:

O none; O slight; O moderate; O severe

Sweating:

O none; O slight; O moderate; O severe

Nausea:

O none; O slight; O moderate; O severe

Difficulty Concentration:

O none; O slight; O moderate; O severe

Fullness of the Head:

O none; O slight; O moderate; O severe

Blurred Vision:

O none; O slight; O moderate; O severe

Dizziness (with Eyes Open):

O none; O slight; O moderate; O severe

Dizziness (with Eyes Closed):

O none; O slight; O moderate; O severe

Vertigo (Can't tell whether an object is vertical):

O none; O slight; O moderate; O severe

Stomach Awareness:

O none; O slight; O moderate; O severe

Burping:

O none; O slight; O moderate; O severe

Appendix D.

Study 2 Experiment Questionnaire

(In every section, the participant answered the Experiment Questionnaire once for the corresponding flying interface)

Participant ID: ____________

Section:

O One;

O Two;

O Three

Interface Type:

O Limbic Chair;

O Normal Chair;

O Standing

Presence (IPQ)

(Please indicate your level of agreement for the interface on a rating scale from 0 = “fully disagree” to 10 = “fully agree”.)

IPQ01 - In the computer generated world I had a sense of "being there"

IPQ02 - Somehow I felt that the virtual world surrounded me.

IPQ03 - I felt like I was just perceiving pictures.

IPQ04 - I did not feel present in the virtual space.

IPQ05 - I had a sense of acting in the virtual space, rather than operating something from outside.

IPQ06 - I felt present in the virtual space.

IPQ07 - How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?

IPQ08 - I was not aware of my real environment.

IPQ09 - I still paid attention to the real environment.

IPQ10 - I was completely captivated by the virtual world.

IPQ11 - How real did the virtual world seem to you?

IPQ12 - How much did your experience in the virtual environment seem consistent with your real world experience?

IPQ13 - The virtual world seemed more realistic than the real world.

Other

(Please indicate your level of agreement for the interface on a rating scale from 0 = “fully disagree” to 10 = “fully agree”.)

OTR01 - Task difficulty of locating the chest (to find where it is) was high.

OTR02 - Task difficulty of opening the chest (to move close to the chest) was high.

OTR03 - I had a strong sensation of self-motion through the space with the interface.

OTR04 - The interface was easy to learn

OTR05 - The interface was easy to use

OTR06 - I feel safe using this interface to fly.

OTR07 - My position (posture) was comfortable.

OTR08 - Flying with this interface is close to the way I would imagine to fly.

OTR09 - I could imagine using the interface for longer time periods.

OTR10 - I enjoyed exploring the whole scene using this interface.

OTR11 - I enjoyed the flying experience using this interface.

OTR12 - I feel fresh/excited/delighted/relaxed during the flying experience using this interface.

OTR13 - I have the freedom to move (physically using this position).

OTR14 - I have the freedom to move (in the virtual environment).

Simulator Sickness Questionnaire

(Please indicate your level of having the below symptom on a rating scale from 0 = “none”, 1 = “slight”, 2 = “moderate”, 3 = “severe”)

SSQ01 - General discomfort

SSQ02 - Fatigue

SSQ03 - Headache

SSQ04 - Eye strain

SSQ05 - Difficulty focusing

SSQ06 - Salivation increasing

SSQ07 - Sweating

SSQ08 - Nausea

SSQ09 - Difficulty concentrating

SSQ10 - « Fullness of the Head »

SSQ11 - Blurred vision

SSQ12 - Dizziness with eyes open

SSQ13 - Dizziness with eyes closed

SSQ14 - Vertigo

SSQ15 - Stomach awareness

SSQ16 - Burping

NASA TLX

(Please rate from 0 to 10)

TLX01 - Mental Demand (0 as "low" - 10 as "high")

TLX02 - Physical Demand (0 as "low" - 10 as "high")

TLX03 - Temporal Demand (0 as "low" - 10 as "high")

TLX04 - Performance (0 as "good" - 10 as "bad")

TLX05 - Effort (0 as "low" - 10 as "high")

TLX06 - Frustration (0 as "low" - 10 as "high")

Control (CF from PQ)

(Please rate from 0 - 10)

PQ01 - How much were you able to control events?

PQ02 - How responsive was the environment to actions that you initiated (or performed)?

PQ03 - How natural did your interactions with the environment seem?

PQ04 - How natural was the mechanism which controlled movement through the environment?

PQ05 - How much did your experiences in the virtual environment seem consistent with your real-world experiences?

PQ06 - Were you able to anticipate what would happen next in response to the actions that you performed?

PQ07 - How completely were you able to actively survey or search the environment using vision?

PQ08 - How much delay did you experience between your actions and expected outcomes?

PQ09 - How quickly did you adjust to the virtual environment experience?

PQ10 - How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

PQ11 - How much did the control devices interfere with the performance of assigned tasks or with other activities?

O Limbic Chair;

O Normal Chair;

O Standing

Appendix E.

Study 2 Post-Experiment Interview Questions

Participant ID: ____________

POST01 - Which interface do you like most?

O Limbic Chair;

O Normal Chair;

O Standing

POST02 - Why you like this interface most?

____

POST03 - Which interface do you dislike most?

O Limbic Chair;

O Normal Chair;

O Standing

POST04 - Why do you dislike this interface most?

____

POST05 - Which one do you think is closest to your imagined way of flying?

O Limbic Chair;

O Normal Chair;

O Standing

POST06 - Why do you think this interface is closest to your imagined way of flying?

____

POST07 - What do you think is the difference (good part and bad part) of the Limbic Chair comparing to the standing position and the normal chair? Why?

____

POST08 - What part in the experience did you enjoy most? Why?

____

POST09 - What part in the experience did you dislike most? Why?

____

POST10 - Which scene do you like most?

O Snow Mountain;

O Lake;

O Desert

POST11 - Why do you like the scene most?

____

POST12 - Any other suggestions, comments?

____

POST13 - Other notes.

____

POST14 – The participant found the S1 chest in ______ seconds?

POST15 - The participant found the S2 chest in ______ seconds?

POST16 - The participant found the S3 chest in ______ seconds?

Appendix F.

Publication Lists

Malmstrom, C., Zhang, Y., Pasquier, P., Schiphorst, T., and Bartram, L. (2016). MoComp: A Tool for Comparative Visualization between Takes of Motion Capture Data. In Proceedings of the 3rd International Symposium on Movement and Computing (MOCO '16). ACM, New York, NY, USA, Article 11, 8 pages. DOI: https://doi-org.proxy.lib.sfu.ca/10.1145/2948910.2948932.

Bakała, E., Zhang, Y., and Pasquier, P. (2018). MAVi: Movement Aesthetic Visualization Tool and its use for dance video making and prototyping. In Proceedings of the 5th International Conference on Movement and Computing (MOCO '18). ACM, New York, NY, USA, Article 11, 5 pages. DOI: https://doi-org.proxy.lib.sfu.ca/10.1145/3212721.3212838

Zhang, Y., Riecke, B., Schiphorst, T., Neustaedter, C. (2019). Perch to Fly: Embodied Virtual Reality Flying Locomotion with a Flexible Perching Stance. Submitted for the 2019 CHI Conference on Human Factors in Computing Systems. ACM.