2D vs 3D in a touch-free hand gesture based interface

An exploration of how 2D and 3D visual aids affect a user’s ability to learn a new interface

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Abstract

3D is a popular topic as an increasing amount of media and technology begin to support 3D interaction. With the rise of interest in 3D interaction, the question of why there is a demand and desire for 3D over 2D interaction becomes relevant. This thesis compares the differences between a 3D heads up display and a 2D heads up display for a touch free gesture based virtual keyboard. The gesture interface used in the tests is a way of communicating with a system using gestures of the hands tracked by a motion sensor. This thesis tested 16 users where half of the users used a 2D version of a heads up display and the other half used a 3D version of a heads up display. Both user groups were tested with identical conditions and in an identical environment. Raw statistical data was gathered from a logging mechanism in the interface and qualitative data was gathered from questionnaires and observation notes. The results from the experiment showed that the 2D and 3D heads up display gave very similar results. However, results also showed slightly better qualitative results from the 3D heads up display observation and questionnaire data. The conclusion indicated no clear advantage for the 2D version or the 3D version. The discussion shows that many other factors in the design process and selection of users, play a large role in the comparison of 2D vs 3D visualizations. Factors such as age and familiarity with different levels of technology are indicated to be contributing factors when comparing 2D vs 3D. The results and discussion hope to provide a starting point for future comparison research in the field of 2D compared to 3D visualization.

Keywords

Gestures, 2D, 3D, Interfaces, Virtual Keyboards, Heads Up Display, HUD, Touch-Free
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1. Introduction

This introduction provides a brief background of virtual keyboards and identifies the goal of this thesis. The research limitations are discussed and a short disposition provides an overview of the thesis.

Virtual keyboards (VK) and other gesture based interfaces are a challenging field of study. Specifically, the development of Vks at the turn of the 21st century have shown that there a variety of different approaches to designing Vks, each with different challenges (Yousaf & Habib, 2014). The majority of Vks display an actual projected keyboard on a surface or simulate one on a screen. In the case of projected Vks, this approach makes sense as the VK is a projection of an existing interface object. For other touch-based approaches to Vks such as Vks on a smart phone, the keyboard is shown as a heads up display (HUD) which shows a set of keys that are available to press.

In the case of touch-free gesturing for a VK, the choice of how to design what users see is difficult. The VK in this context is no longer a set of available keys but instead bound to specific gestures or in the case of a hand, its fingers. The VK is essentially the user’s hands, much like examples of Vks that use gloves or sensors attached to user’s hands. The traditional view of a keyboard used, even in projected Vks needs to be redesigned. The challenge lies in how to give sufficient visual feedback to both novice and experienced users who intend to use and learn a touch free gesture based VK.

Much of the focus of study on Vks have been in mapping the location of keys to improve efficiency. Experienced users have motor memory of where the keys are, which reduces the need to see the keys on a keyboard where as new users rely much more on visual cues (O’Brien et al., 2008). Although factors such as mapping and shape of Vks are of great importance to their use, their graphic interface or HUDs if they have one may also influence a Vks use. Usability of an interface can have large impacts on how users interact with a system (Nielsen, 2012).

To explore this challenge this thesis compared an existing Vks HUD in an experiment where two groups of users performed set tasks with a VK and the two group’s results were compared. Two visually different HUDs were used to visualize the same mapping of a touch free gesture based VK. One HUD in 2D and one HUD in 3D were used for the experiment. ErghisTech offered their collaboration and support throughout the process of this thesis.

The Erghis is a gesture based touch-free VK (TFVK), designed by ErghisTech, that was used to compare the design of a HUD for a touch free TFK. The mappings and functionality of the VK were identical in both HUDs. In both the 3D and 2D groups of users the TFK was used in the exact same way. The only difference between the two groups was that of the visual aspect of the HUD.

Users were asked to use the TFK to enter text or commands in a series of tasks. The experiment was conducted to determine how large a role a 3D or 2D variant of a TFK’s HUD played in the user’s experience of a TFK. This experience was measured in several terms. Because the main purpose of any keyboard is to input text, the time in seconds in which users completed a task and how many mistakes they made during this task was measured. Also the improvement between a first attempt and second attempt of the tasks was measured. Furthermore these results were complimented with a user questionnaire and observations in an attempt to measure the user’s enjoyment and willingness to use the TFK.

1.1. Goal

The aim of this thesis is to explore the differences between a 2D HUD, such as one might see on a smart phone or smart tablet, and a much less explored 3D HUD that is a 3D representation of the users own hands being seen on screen. This thesis specifically explores the comparison in the context of a gesture based TFK. The exploration will discuss the differences between the two HUDs as they are introduced to new users and measure, among other data such things as time in between keystrokes and mistakes made. Qualitative information such as questionnaires, user feedback and user observation will also be used to compare the two.
The goal of this exploration is to develop a conclusion, based on data from experiments, user feedback and observations, about the effectiveness of each HUD. As well as provide insight into whether 3D visuals can be more effective than 2D visuals in the context of the discussed TFVK and, if so, in what way.

1.2. Research Question
Considering the background and goal, this thesis will answer the following research question:

RQ. What is the difference, in terms of performance and user experience, between a 2D and a 3D representation (shown as a head-up display) of the same interface for a touch-free virtual keyboard?

1.3. Limitations
The Erghis (ErghisTechs TFVK) is one of the few TFVKs currently in development. Ractiv, a small California based company, launched and succeeded in funding their Kickstarter campaign in 2013 (Haptic Touch, 2013). They are in the process of developing a similar technology although their touch-free gesture-based interface is directly linked to the motion sensor they are developing; The Haptix (ractiv.com 2014). The Erghis is not tied to one motion sensor and Haptix does not currently (2014) provide support for touch free typing. The Haptix does not, as of 2014, provide access to any HUDs or associated visualizations for their proposed interface. As such, the Erghis’ TFVK will be the only TFVK tested on as developing a 3D HUD for multiple TFVKs would require a larger effort and most likely more manpower.

This thesis explores the difference between a 2D HUD and 3D HUD on the same TFVK in the mentioned context. It is important to note that the way in which the Erghis (the chosen TFVK) is implemented will not be explored. The Erghis TFVK was mapped and developed in house by ErghisTech. The mapping choices, such as what finger each letter or key is assigned to is not the focus of this thesis. Whether the actual gestures used are effective or well thought through, are also not in discussed in this thesis. Instead the thesis focuses on comparing two visually different HUDs on a single TFVK (The Erghis). The visual comparison focuses on the difference between the Erghis’ current 2D HUD, which is designed by ErghisTech and a 3D variation designed for this thesis.

3D development can be time consuming and its software development is complex. As such the experiment will be limited to an iterated development of one 3D HUD and the Erghis’s existing 2D HUD.

It is also noteworthy to discuss the context of gestures in this thesis. As gestures imply a wide range of movement that the human body can make, it is important to state the limitation of gestures. The TFVK deals specifically with hands, as these are the central and only means of communicating with the interface. Although other gestures, for example the use of arms and legs, are used in different systems, the focus of this thesis deals with the TFVK using only hands.

1.4. Hypotheses
Although little is known in terms of 3D HUDs for gesture interfaces, 3D interfaces are relatively more researched. 3D interaction can be complex as users often require an already existing knowledge base in order to be comfortable using a 3D UI (Hatchet et al., 2013, p.80). Hatchet’s research (2013, p.83) also points out that users in an interactive 3D touch based experiment in a museum were eager to use a 3D interface, were highly engaged and even enjoyed using it. However, others claim that 2D is a better alternative. Nielsen (1998) writes that humans have a genetic bias towards more 2D friendly perceptions as we have two eyes that look straight out. Nielsen (1998) further strengthens his assertions by arguing that the common devices we use for human computer interaction are designed for a 2D context such as the mouse or keyboard. Nielsen (1998) also states “Users need to pay attention to the navigation of the 3D view in addition to the navigation of the underlying model: the extra controls for flying, zooming, etc. get in the way of the user’s primary task.”
This research suggests that the 2D HUD will produce better results. However, in this case the method of communication to the system is neither common nor designed for use in a 2D space. Nielsen (1998) mentions that 3D should only be implemented when visualizing physical objects. The ball that users are asked to imagine is, in a sense, a physical object. A MindLab study commissioned by Blue-ray Disc Association (Tribbey, 2011) reported that the mind was more attentive and focused while watching 3D blue rays compared to their 2D counterparts. In addition to Tribbey’s (2011) findings, an experiment in building design which compared 2D models to 3D models concluded that those with a low understanding of spatial skills had an increased rate in understanding the designs. Those who had spatial skills did not seem to differ between the 2D and 3D models (Carvajal et al., 2005, p.4).

Based on the above research and experiments, results for the experiment of this thesis are expected to show a preference towards the 3D version of the HUD tested. This thesis therefore makes the following hypotheses (H1 and H2):

**H1.** It is expected that the 3D HUD will allow users to perform the tasks better, compared to the 2D HUD, in particular:

**H1a.** It is expected that the participants who used the 3D HUD will complete the tasks faster, compared to those who used the 2D HUD.

**H1b.** It is expected that the participants who used the 3D HUD will make less mistakes during the tasks, compared to those who used the 2D HUD.

**H1c.** It is expected that the participants who used the 3D HUD will complete the tasks faster and make less mistakes during their second session than during their first session, therefore showing a better learning rate compared to those who used the 2D HUD.

**H2.** It is expected that the 3D HUD will be perceived to be a more positive experience by the users, compared to the 2D HUD, in particular:

**H2a.** It is expected that the participants who used the 3D HUD will give more positive written feedback in the post-session and post-study questionnaires, compared to the participants who used the 2D HUD.

**H2b.** It is expected that the participants who used the 3D HUD will give more positive oral feedback during the study, compared to the participants who used the 2D HUD.

1.5. Disposition

The next section of this thesis will cover the background of virtual keyboards, motion sensors, heads up displays and the Erghis system in more detail. Section three discusses the design choices and process of the 2D and 3D HUD in detail. In the fourth section of the thesis a description of the experiment is detailed and the methods used. The fifth section presents the data collected and results from the experiment and the sixth section analyses the collected data and discusses the results. Finally the seventh section provides a reflection on the work of this thesis.

2. Background

*This section describes the important terms and ideas for this thesis as well as further study into the field of 2D and 3D development regarding HUDs.*

2.1. Virtual Keyboards

Currently, in 2014, VKs are a popular topic. Most consumers are no stranger to VKs. VKs are used every day by millions of people around the world on devices such as smart phones and tablets as it is estimated that one in
five people across the world own and use a smart device (Heggestuen, 2014). The term virtual keyboard can be somewhat ambiguous to many people. A VK is defined by Kölsch & Turk (2002) as “a touch-type device that does not have a physical manifestation of the sensing areas. That is, the sensing area which acts as a button is not per se a button but instead is programmed to act as one.”

With the exception of experimental types of VKs, such as those that use face recognition for input (Gizatdinova, 2012) the majority of VKs deal with hand gestures. The TFVK in this thesis is no different and deals exclusively with hand gestures.

The expanding use of smart phones, tablets and other devices, such as Google Glass, has created a demand for alternative methods of input in comparison to the traditional physical keyboards and mice. Devices that are unlikely to include a separate physical input device, such as a keyboard, require an alternative method of input (Virtual Keyboard, 2014). Smart phones for example, include the display of a keyboard on the phone itself that responds to touch (Figure 2). This VK is a response to the demand of evolving devices that require a higher degree of mobility. All virtual keyboards function on the premises of a way of signaling input, a visual interface, and an input device (Figure 1).

![Figure 1: The Components of a VK](image)

Virtual Keyboards are implemented in a broad variety of ways. Kölsch & Turk (2002) define a taxonomy of VKs, however the list is somewhat outdated. Below is a summarization of Kölsch & Turk’s (2002) taxonomy updated to better represent the current state of VKs.

### 2.1.1. Multi-touch VKs

Multi touch VKs allows reporting of multiple surface contacts and their pressure forces independently and simultaneously (Kölsch & Turk, 2002, p.6). The majority of the multi-touch VKs use the traditional QWERTY keyboard layout as a HUD on the device (Figure 2). The VK on the touch surface responds to pressure forces on the specific location of the force applied. This allows a keyboard layout to be displayed and used in a similar fashion that users would use a physical keyboard.
2.1.2. Wearable Sensor VKs

Wearable sensor VKs cover a wider variation of VK implementation. The wearable sensor VK makes use of one or more sensors attached to user’s hands. This could include a series of rings with accelerometers on each finger of a user’s hand (Figure 3) that registers the impact against a surface as a means of signaling input (Kösch & Turk, 2002, p.7). Wearable sensor VKs could also include bands or components that are worn on the hand by the user that sense movement or force as a means of input (Figure 4).

![Figure 3: Accelerometer Sensors on a user’s Hand](image1)

![Figure 4: Hand worn Components for a VK](image2)

2.1.3. Glove VKs

Glove VKs are similar to wearable sensor VKs in that they include one or a set of sensors that are worn by the user to facilitate input. Glove VKs however require wearing a material that houses the sensors. The material can be a common woolen glove that has pressure pads or sensors sewn into it or a more complicated material with fiber-optic detection built in to the glove (Figure 5). The users can either type on their own hand using the pressure pads or use the sensors to create a gesture or applied force against a separate surface to signal input.
2.1.4. Projection VKs

Projection VKs use a form of motion detection to read input from the user. With a projection VK a visualization of a keyboard is projected in one way or another onto a surface (Figure 6). The user can then type on the projected image on a surface to signal input to a system. The location relative to the mapped letter of the projected keyboard is detected by the motion detector or sensor accompanied by the projector. This sensing often done using infrared light (Kölsch & Turk, 2002, p.6).

2.1.5. Touch Free VKs

Touch free VKs require no surface to signal input to a system with. A sensor is required to read the users hands and the motion or gesturing of users hands is used to signal input to the system. The sensor is therefore required to recognize in one way or another the layout of a user’s hands. This VK requires a higher level of
fidelity in motion sensing technology and as such has not been commercially available until recently (2014). A TFVK is the chosen VK for the experiments of this thesis.

![Figure 7: Touch free typing using hand gestures](image)

### 2.2. Motion Sensors

Over the past decade (2004 – 2014) motion sensors have developed and entered the main stream. Products, such as the Kinect and Leap Motion, offer over 200 applications today (2014) in their online stores (123Kinect.com, (2014) Leapmotion.com, (2014)). Leap Motion was highly hyped and generated a 26000 developer interest before its release (Fogel, 2012). Business Wire (2014) claimed that “the growing demand for smartphones and tablets has accelerated the growth of the Global Consumer Motion Sensor market. In recent years, interactive TV has emerged as one of the most promising application trends in the Global Consumer Motion Sensor market.”

High accuracy motion detection affords the possibility for TFVKs to be used with a higher degree of accuracy and competency. In order to facilitate the use of a TFVK for this thesis a motion sensor is necessary to sense the user’s hands. The Leap motion is the current motion sensor used by the Erghis (The TFVK used for the experiment) and as such is the motion sensor used in this thesis.

### 2.3. The Erghis

The Erghis is the chosen TFVK for this research. The VK is designed to function cross device and any motion sensing device is intended to function with the Erghis. The Erghis itself is software that conveys a concept into an interface. The software interprets all information about a hand provided by a sensor. This information is then processed to carry out commands to a system, depending on what the software sees as a command. In the case of the Erghis, the concept of holding an imaginary ball in the air is used as the basis of the interface (Figure 8b).
The user can rotate this ball and "close" or "open" their thumbs to gain access to different characters and commands that one would normally find on a keyboard. When the user decides to carry out a command or input a character to a system they tap their fingers the way one would tap a smart phone to type a letter.

The imaginary Erghis ball (IEB) functions as a navigational principle to access a wide array of commands and characters. The IEB is divided into two halves where each half has three sections (Figure 8a). The result is that the IEB has a total of six sections. Each half has a total of three states and these are accessed by having one hand in the position shown in Figure 8a, rotating the corresponding towards or away from oneself. By rotating the hand in and out of these positions, the IEB gives a total of nine possible states as there are three sections and two halves where order matters and two halves in the same state are not counted twice (Figure 9).

Therefore, each section can be combined with the opposite section once, giving nine possible states to navigate into.

While in any given state there are four sub-states. Therefore there a total of 36 sub-states as nine states with four sections each totals to 36. Each of these sub-states contains a different set of characters known as a
keyset. The keysets are accessed by holding ones thumbs in one of four possible combinations of positions. The positions are (Figure 10):

1. Both thumbs “open”
2. Both thumbs “closed”
3. Left thumb “closed” and right thumb “open”
4. Right thumb “closed” and left thumb “open”

Each keyset has eight characters assigned to each finger, as there are four fingers on each hand excluding the thumb. Each sub-state has four possible characters. There are therefore a total of 288 character slots available to map. Not all character slots are mapped on the Erghis (Appendix F.).

![Figure 10. The four thumb positions of the Erghis](image)

2.3.1. Hold

It is noteworthy to state that the Erghis uses a hold mode and this represents the holding of a macro key. If, for example, the user held down the control key on a standard keyboard and pressed the letter “a,” this would, in many applications activate the selection of all available text. To simulate this, when a user hits the ctrl character it activates “Hold,” which allows the user to navigate to a secondary or tertiary character to issue a command.

The hold mode can also be activated independently of a macro key and can be filled with a number of characters. When released, the held characters are implemented in the order they were entered. All held keys can also be dismissed by toggling off “Hold.” This command has its own character slot.
2.4. Heads Up Display

The term used for displaying information on a screen that informs a user how they are interacting with a program is called a heads up display (HUD). The HUD was initially designed for military aircrafts (Figure 11) as a means of displaying information to the user, so the user would not have to move his or her focus away from the overall screen (Design Library, 2014). “Dividing attention across multiple tasks or sources of information is thought to be enabled by a working memory system” (Design Library, 2014). Working memory is a concept introduced in the 1960’s as a term that to describe an intermediary between the short term memory and the long term memory. This allows the user to bridge existing long term memory of a system, such as certain functions or controls they may already know with information they are receiving in the present, such as feedback, video and audio.

![Figure 11: An Aircraft HUD](image)

HUDs are by far most seen in ground and air vehicles. A large body of research exists on optimizing and studying HUDs for vehicular purposes. The HUD for this thesis however refers to a digital application HUD. HUDs for applications are most common in video and computer gaming (Figure 12). The Geelix HUD, for example “is an in game HUD for sharing gaming experiences with friends and others” (Holthe et al. 2008). The HUD uses the same principles as that of the automobile HUD, where information relevant to the needs of the user are shown overlaid upon the current focal point. The same principle of the HUD for game information and automobile information can be used for a TFVK.
Using a HUD for a keyboard is not new. Certain companies such as My-T-Touch (My-t-touch.com, 2014) use a HUD for their touch screen keyboards. The keyboard display on the touch screen is a multi-touch VK and allows users to keep their focus in one place by including a visualization that gives information and feedback to a user where the visualization lies within their current focal viewpoint.

The HUDs used for the experiment in this thesis uses the same concept as those in vehicles and games. The purpose of the TFVK HUDs are to provide information to the user while they are focused on other applications. For example, users may type and be aware of what they are typing much like a person types on a keyboard without actually looking down at the keyboard and losing their focus. For the purpose of this study, the HUD refers to the visual aids displayed on the screen simultaneous to any other program the user is using (Figure 13). The HUDs also have the possibility of having their transparency changed so that they may lie in any area of the screen while a user is typing. For the experiment in this thesis however the HUDs transparency were kept at 100%.
3. Erghis HUD Designs

This section provides a description of the existing design of the 2D HUD and a detailed explanation of the process of design and the final design of the 3D HUD.

3.1. The Erghis 2D HUD

The Erghis First is the current 2D HUD. It displays two 2D hand representations and blocks that display each character in a keyset. The states are displayed as two columns of three rows of blue squares in between the hands that represent the location of the current state. On the right hand side is a legend displaying all keysets available for the current state and a small diagram of how a user might hold their thumbs to access the active state’s keysets. If the hands of the user are not recognized by the sensor, the thumbs character slots and navigation blocks become red (Figure 14). The 2D HUD displays the keys that are held in memory in the upper in the left hand side of the HUD (Figure 14).

It is important to note that the 2D HUD might visually suggest that a user hold their hands in a different way. This is not true as the HUDs visual layout does not change the way in which the Erghis TFVK is used. The exact same gestures, movements and mapping are used with both the 2D and the 3D HUD. The only difference between them is their visual appearance.

![Figure 14. The Erghis’ in house 2D HUD](image)

3.2. The Erghis 3D HUD

The 3D HUD is the 3D designed prototype and will be compared against the Erghis 2D HUD. The 3D HUD was based on the principles of “naturalism” (Mann, 1998) in interfaces as well as by drawing on traditional heuristic design guidelines (Nielsen, 1995). The 3D HUD, as a type of interface, was built from interface guidelines and research to support a fair and valid attempt at comparing the differences between two functional HUDs.

3.2.1. Naturalism in the Erghis Prototype

The Erghis follows naturalism in its core design principle as it makes use of hand gestures. Bowman et al. (2012) discusses how naturalism in interfaces is useful when dealing with six degrees of freedom (6-DOF), which the hands of the Erghis are designed to use.

Naturalism is “reusing and reproducing interactions from the real world so that users can take advantage of their existing skills, knowing what to do and how to do it.” (Bowman, 2103).
It is logical, then, that applying the principles of naturalism in the design of the Erghis prototype would be a good course of action. The other alternative would have been to take what is known as “magic techniques.” This technique implies that an interaction be “intentionally less natural, or they might enhance natural interactions to make them more powerful” (Bowman et al., 2012, p.80). In the context of the 3D HUD an example of a magic technique would have the fingers glow or highlight with a different colour when the users tap a character. This is considered a magic technique because people’s hands do not glow or change colour when they type on the keyboard in real life. Magic techniques are used to simplify tasks that would otherwise be cumbersome or unpractical in a user interface, as they resemble real world interaction too much (Bowman, 2013). Since the design was intended to simulate as much real world interaction as possible, a more natural approach was used. The object of the 3D HUD was to teach the user to make real world gestures that allowed them to effectively use the interface.

The way in which the Erghis interface is designed follows a natural form by using the human hands in a way that lets the fingers rest naturally as if they would if they were they idle. This allows interaction and movement of the hands and fingers with a high degree of fidelity and, as such, fits Bowmans (2014, p.87) criteria for when naturalism may benefit a design. In Bowman’s (2014, p.86-87) experiments, the instances in which users were required to mimic an action or movement in the application which they saw, tended to have much better results with a natural interface in comparison to a magic technique interface. This strengthens the choice to use a natural approach to the Erghis’s prototype design as magic techniques could have resulted in the user getting confused or misinterpreting the way in which to use the interface with a hyper-natural or non-natural design. The natural approach was the best fit for the desired functionality of the 3D Erghis HUD.

### 3.2.2. Heuristic Design

Simply mimicking hand gestures as a design choice might not have be sufficient. Therefore, the design was further reinforced by a number of heuristic design guidelines (Nielsen, 1995) in order to develop a stronger 3D HUD. Nielsen (1995) details several heuristic guidelines (HG) for good design. The following guidelines were chosen to help design the 3D HUD:

HG.1. **Visibility of system status**: The system should always keep users informed about what is going on, through appropriate feedback within reasonable time.

HG.2. **Match between system and the real world**: The system should speak the users’ language, with words, phrases and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order.

HG.3. **Consistency and standards**: Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform conventions.

Nielsen (1995) details more guidelines some of which are more applicable to web-type applications and some of which were not included in the design of the 3D-HUD due to time restrictions. These guidelines are not included in this thesis however.

Using the listed guidelines, the basic draw up of the first Erghis prototype followed the specifications identified below:

1. The Erghis prototype will display and show a human-like 3D-representation of two hands, giving the user an awareness of their own hands and creating a likeness of the interface in terms of the user’s world as detailed in HG2.
2. The Erghis prototype will display a sphere. This also follows HG2’s concepts. The sphere represents the imaginary ball and as such should look like a ball.
3. The fingers and thumbs will animate in a natural way to reflect the users hand movements. By following HG1, this will allow the user to receive important feedback on what is happening when they make actions with their fingers and or thumbs.
4. Each keystate will be displayed at the fingertips of the animated hands to show the user what letters or commands are available in that subsection. This follows HG3 that users should not be confused with different behaviour or actions that give different results.
5. The ball will represent which state or sub state the user is currently active in. This way the user is again given good feedback about what state they are in as stated in HG3.

3.2.3. Prototyping
A prototyping process (Benyon, 2010, p.184) was applied to develop a functional. A combination of both Lo-fi and Hi-fi prototypes were used (Benyon, 2010, p. 185-187):

- **Lo-fi prototypes** are meant to be developed quickly and focus on the main and underlying ideas. They intent to capture early design ideas and aid the overall process of generating more solutions (Benyon, 2010, p.187).
- **Hi-fi prototypes** are a much closer to the final version and look and feel similar to what the end result may look like (Benyon, 2010, p.185).

In the early process of development several lo-fi sketched prototypes were developed using the specifications listed above. The initial sketch designs had the 3D representations of the hands directed away from the user, as if the user was looking down at their own hands (Figure 15).

![Figure 15: Lo-Fi 3D HUD Prototype Sketches](image)

This made it hard to follow HG1 as there was no apparent way to display what keys were available to a user as well as it may have been hard for the user to see a finger move due to the perspective of the hands. This was resolved by mirroring the user’s hands so that the 3D hands appeared as though one might see if they held their hands up in front of a mirror. This way the user would have clear access to see their fingers move and allow the text to be connected to the fingers without blocking any of the other important parts of the display (Figure 16).
After the sketch was considered satisfactory a mock example case was tested on a paper prototype of the Erghis 3D with the Erghis team. Using several different coloured sticky notes and a mirror, a simulation of how the 3D HUD might behave was conducted. The test subject imagined that their hands, which they saw on the mirror were that of the 3D HUDs graphical hands and as they moved their hands and fingers to interact with the prototype, the coloured sticky notes were changed by someone else to represent what would happen on screen. When the test subject typed a letter, a helper wrote it on another paper tapped to the mirror.

Figure 16 shows some of the early concepts of having the letters displayed on part of the sphere. Under the paper prototype test it became apparent that there was confusion and the test subject found it hard to read when trying to find certain letters and commands. To resolve this issue, an iteration of the paper prototype was carried out again with the letters floating in front of the sphere. An additional sticky note with the letters separate from the coloured sticky notes that represented the ball were used and led to more satisfactory responses.

With a successful paper prototype concept, an early 3D model was built. This hi-fi prototype had minor functionality, showing rotation animation and a small finger animation (Figure 16).

Also added as a feature in the 3D prototype was the flashing and colour change of the hands when they were not recognized from the sensor. The hands shown in Figure 17 blink and turn red when not seen by the sensor. This is important to note as it deviates from the design guideline of naturalism. A natural approach to this feedback problem would have the hands simply disappear. However, this might have caused the user to be confused or believe the sensor was not working. As such the decision was made to mirror the red colour from the 2D HUD and cause the hands to blink when the hands were not recognized by the sensor. With this choice, the design still integrated a level of naturalistic principles in that the hands disappeared from sight in short blinks.

The final hi-fi 3D HUD prototype used in the experiments was very similar to the initial modelling and was fully automated using the ErghisTech API (Figure 17).
4. Methodology
This section discusses the details of the experiment, how it was conducted and its process.

4.1. The Experiment
The main chosen method of the experiment was the A/B testing method. A/B testing is appropriate in this situation as it allows the direct comparison of the two different HUDs in question. Martin & Hanington (2012, p.10) state that “A/B testing is an optimization technique that allows you to compare two different versions of a design to see which one gets you closer to a business objective.”

![Figure 17: The final 3d HUD prototype design](image)

In this case the objective is the RQ and as such 2 groups of users were asked to perform an identical set of four tasks on one of the HUDs (Figure 18a).

As Martin & Hanington (2012, p.10) discuss, A/B methods do not reveal why the users may or may not perform better on one instance when compared to the other. To gain some understanding about the users’ experience, usability testing was also employed. Each user was observed (Figure 18b) under the performance of the tasks and notes were recorded depending on user actions and/or comments (Martin & Hanington, 2012, p.432). Finally, to complement the qualitative and quantitative data collection, a survey was used to gather further
insight from the user’s perspective (Figure 18b). Martin & Hanington (2012, p. 386) indicate that surveys should include other complementary methods such as the observation method. The chosen form of survey is a questionnaire and not an interview mainly as a means to help overcome the challenge of collecting such data in a short amount of time (Martin & Hanington, 2012, p.386).

4.2. Participants
The Erghis is a novel interface and, as such may have been more difficult for those who already have a low comfort level with commonly used technology, such as laptops, smart phones and tablets, to grasp. Texting and gesture interaction with systems are a common aspect of daily life for younger users. For example, the demographics of users of the Kinect tends to be in the range of the 15 to 40 years old (Microsoft Advertising, 2011, p.3). The Leap Motion is mostly used for gaming as more than 50% of Leap Motion apps are games (Airspace.leapmotion.com, 2014). As gamers on average also tend to fall into this age demographic (Moltenbrey, 2012) we can assume that a high percentage of Leap Motion users fall within the 15 to 40 year old demographic as well. Situating the experiment within this demographic helped ensure that users had some familiarity with 3D and motion sensing technology.

The users selected for the experiment were a mixed group of 16 male and female users between 20 and 30 years old. They came from mixed occupations and or programs of study and had varied levels of experience with gestures and gesture interface experience.

4.3. Materials
In order to conduct the experiment the following materials were required and used:

- Personal Desk
- PC
- Leap Motion Sensor
- Installed versions of the 2D and 3D HUD
- Task tracking software installed and active
- User dossier with questionnaire, user info sheet and note sheets for the observer to take notes on
- Instruction sheet for the user
- Task Sheet with tasks listed for the user

4.4. Tasks
As mentioned in section 4.1 the users were required to complete a set of 4 tasks for the experiment before they filled in the questionnaire. These tasks were designed to derive data to attempt to answer the RQ of this thesis. The tasks were designed specifically to address H1a, H1b, and H1c.

As with the design of the 3 HUD discussed in section 3.2.3, an iterative process was used to establish a set of 4 tasks which would provide useful data. The tasks performed by the users under the experiment are as follows:

1. Type “The quick brown fox”
2. Erase everything you just wrote by using the common ctrl-a select everything method:
   - Find and tap Ctrl
   - Then find and tap a
   - Then find and tap Backspace
3. Type HELLO WORLD!
4. Type User@gmail.com

Typically when measuring speed and learning to type certain sentences that contain a wide variety of letters and finger positions are used. One sentence common in many typing applications and commonly seen in programs such as Microsoft Word for font display is “The quick brown fox jumps over the lazy dog”
(support.microsoft.com, 2014). This original sentence was pilot tested with several people and found to be too long of a sentence. As such it was shortened to the form seen in Task 1.

Keyboard typing does not involve only letters and as such it was deemed important to include a task that requires a short-cut command. The short-cut command in task 2 is among several common commands used often, such as but not limited to the control f (Find) command, the control s (Save) command and the control b (Bold) command. This task seemed to take less than 2 – 3 minutes in the pilot tests and as such was left as is.

Among the commonality of short-cut commands when typing is the need for upper case letters. The 3rd task was originally developed to have the user type their own name in upper case letters. This displayed a problem early on as those pilot testing the tasks had a varying length of names and when measuring speed would create unfair results. The task was therefore changed to its current form which uses a common phrase used when learning to program.

The final task also was originally intended to have users write their own email however this ran into the same problems as the original task 3 did as well as potentially making some users feel uncomfortable giving out information they may or may not have wanted to give out. The generic email was therefore formulated to avoid this. The email as a choice itself for a task was meant to combine all 3 tasks in that the user would have to make use of symbols, letters and upper case and lower case letters.

4.5. Conditions
Half of the users were randomly assigned one of the two HUDS and the other half the other HUD. Each was asked to perform a series of tasks (Appendix A.) and then complete a questionnaire at the end (Appendix B.). All users were then invited back within a one to three day period (depending on their available schedule) to perform the tasks a second time. Great care was taken to prevent the users from being aware of the other HUD until they had completed all tasks and the questionnaire the second time.

4.6. Procedure
Each user was seated at the home computer and provided with an introductory sheet (Appendix C.) that explained the Erghis and how it functioned. The users were instructed to read through the guide and indicate when they were finished. Once finished, they were given roughly five minutes to freely explore the Erghis. All users were informed that, if they had any difficulty with technical aspects not related to the experiment, help would be offered. Otherwise, the users were encouraged to try and figure out and solve the problems on their own. In some cases, the users were verbally offered brief bits of advice if they began to take an unreasonable amount of time to complete a task (>20 minutes). For example, a user after reading the introduction sheet several times, waved and moved his/her hands much faster than the sensor was able to keep up with. He/she continued this for over 20 minutes before advice on the control speed of their hands was provided. This seemed to resolve this user’s difficulties. This brief advice was provided to prevent the user from becoming overly frustrated and giving up.

Once the user had five minutes to play around with the assigned HUD, they were provided with a hand-out with a set of four tasks on them (Appendix A.). The user was asked to solve each task. A logging mechanism was activated before the user began each test and when the user noted that they were done, the logging mechanism was stopped and started for the next task (Figure 19).
The users were invited back a second time and provided with the same tasks to repeat. In this second session, the users were not given the five minute warm up period, although they could look at the introduction guide at any time. At the end of the final task they were given the same questionnaire (Appendix B.) to fill out, without access to the questionnaire they had filled out in their first session. They were also given a final sheet to comment or give any further thoughts or impressions on the Erghis (Appendix D.).

During all of the tasks, users were observed and notes recorded to interpret the actions and decisions by the user (Figure 19). The users were not asked to talk aloud, although many did anyways. In several situations, the users would comment on how difficult it was to get the sensor to read their little finger movement. Several other users would speak aloud to themselves saying such things as “Now where was that other letter?” or “I don’t understand where the letter l is.” Users often had comments such as “What?” or “How did that happen?” which gave useful insights into some of the difficulties they experienced. For example, the comment “How did that happen?” was often verbalized when the states changed unexpectedly when users held their hands in a position that was difficult for the sensor to read.

5. Result

This thesis makes an empirical and qualitative comparison of two different HUDs for a TFVK. This section explains the results of the experiment and provides insights into the range of results from the experiment.

5.1. Terminology

The experiment was divided into two distinct sessions. Each user came back after a period of 24 hours or more and completed the same tasks as they did in the first session.

Each user was assigned with a prefix, an identifying number and a suffix. The prefix noted the type of HUD (2D or 3D), and the suffix the session (A for the first and B for the second session).
5.2. Data Collection

The experiments provided an extensive collection of data. The tasks for each user and attempt produced a character separated value file (CSV), a file of values separated by commas. Each CSV file contained several hundred lines of information compiled from every movement and action a user completed during a task. These CSV files contained: a time stamp that identified time in milliseconds beginning from 0 when the task was started; the current state the IEB was in; which thumbs were up or down; and a string for any output characters in that action.

The data was parsed into a self-made database using C# and the .NET framework library. The data was used to construct an Excel table that was organized around columns for each user and included information such as, but not limited to:

1. Time in between keystrokes (H1a)
2. Total strokes made (H1b)
3. Total time of task (H1c)

This master Excel table was used to synthesise and analyse the observations and conclusions that follow. In addition to the master Excel table, each user test produced a small dossier from each user and attempt. The dossiers contained details for the user, a questionnaire and a comment section for each task (Appendix D.). The questionnaire data was entered manually into the master Excel table and the comments were extracted into a point-form list of positive and negative comments for each user group and attempt.

5.3. HUD Comparison

The RQ posed by this thesis was “How does the experience and effectiveness of a 2D HUD and a 3D HUD compare in the context of using a touch free gesture based interface?”

The experiment collected several types of data, including empirical data and user feedback from questionnaires and comments. It was difficult while observing the experiments to come to any early conclusions. Users did not generally demonstrate clear preference in speed or enjoyment through observable behaviours.

An early scan of the data also failed to identify any clear differences. An initial review of the qualitative and quantitative data indicated that usage patterns of the HUDS were relatively similar. The questionnaires offered a strikingly similar result. Users provided similar or identical responses when asked if they believed the two HUDs represented their gestures or whether they experienced ease or difficulty understanding what was going on.

These results raised questions for future study about whether ease of use, accessibility and enjoyment of visualizations are determined by the technology (3D vs 2D), or are more strongly influenced by a user’s previous experiences with, and attitudes toward, similar technologies.

The following observations explore these results and provide an in-depth comparison of specific aspects of each task of the experiment.

5.3.1. Average Time to Complete Task

The 2D and 3D HUD appear to have a very similar mean completion rate in terms of seconds (Figure 20). The standard deviation (SD) for 3D_A, 3D_B and 2D_A all report a high variance from the mean. Over the first attempt, 3D and 2D were very similar, diverging mostly on Tasks 1 and 4. However, the 3D users had a slightly better overall average time when completing Task 2 in both the first attempt and the second attempt.

2D8_B’s total task 4 completion time (682 seconds) was much higher than the standard deviation range of 148 – 252 seconds where the SD is +/-52 seconds from the task 4 mean 200 seconds. Because of this outlier the 2D_B users for task 4 seem to have taken longer than 2D_A for task 4. Without the outlier this is not the case.
Task 1 also shows a slightly higher task completion time for 3D_A. This indicates, as Task 1 was the first task introduced to the user, that the learning curve for a 3D visualization may be higher than a 2D visualization when encountered for the first time. However due to the high variance for 3D_A task 1 (SD = 431, M = 552) it is difficult to make any significant conclusions.

Figure 20 shows that both 3D and 2D had similar results in A yet the 2D users in B showed a noticeable difference in speed compared to the 3D users in B. Also shown in Figure 20 is a clear improvement rate from A to B in both the 2D and 3D users. The high level of SD also suggests that users experienced the TFVKs very differently from one another.

Figure 20 shows that both 3D and 2D had similar results in A yet the 2D users in B showed a noticeable difference in speed compared to the 3D users in B. Also shown in Figure 20 is a clear improvement rate from A to B in both the 2D and 3D users. The high level of SD also suggests that users experienced the TFVKs very differently from one another.

![Average Time per User Group per Task per Attempt](image_url)

**Figure 20** Average time taken per task per user per attempt with SD error bars for each task based upon the mean of each tasks total user times

### 5.3.2. Average Mistakes per Task

Each task used a specific number of strokes that were required to complete the task (Table 1). Each user demonstrated errors when they completed these tasks. The average mistakes per task were measured by subtracting the specific strokes required to complete the task from each user’s total strokes per task.

3D users had a larger number of mistakes in A, yet used an equal amount of mistakes or less in the following three tasks. Noticeably, in B, 2D users made on average a higher number of mistakes than 3D (Figure 21) with the exception of task 1. On a whole the SDs of each task are close too if not larger than the mean of each task. As with Figure 21’s results this reinforces the suggestion that users had a wide range of different experience when using their respective TFVKs.

2D8_B’s results of 202 total strokes was far above other users total strokes (SD = 59, M = 36). The results for 2D_B in Task 4 is otherwise lower than 2D_A and does not accurately represent the data population otherwise.

From the observation notes of Task 4 of 2D8_B, it was noted that this user made a mistake and decided to search for the left arrow key to move back, as one would with a left arrow key on the keyboard, instead of simply using backspace twice to delete a character. This explained why the user had an abnormally high time completion and mistake rate for Task 4 B. This raises interesting observations about how users view and interact with a TFVK and is further explored in the discussion.
### Table 1. Amount of Strokes Needed Per Task

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Strokes Needed to Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
</tr>
</tbody>
</table>

#### Figure 21

**Users average mistakes per task per attempt with SD error bars for each task based upon the mean of each tasks total user mistakes**

#### 5.3.3. Average Delay in Between Key Strokes

3D users and 2D users experienced a similar average delay between key strokes. In Task 1, 3D users had a lower delay than 2D users. When 3D_A mistakes were cross referenced from Figure 22, there were indications that 3D_A users experienced a lower delay between key strokes but made more mistakes. This was reinforced by the results of the key stroke delays for all users and is illustrated in the result of both attempts of Task 2 indicated in Figure 22, compared to the resulting mistakes indicated in Figure 21.

Task 1 3D_A users had lower delays between key strokes compared to their second attempt for that task. This occurred again in Task 3 and suggests that users were using the visual of the HUD to find the characters they are looking for. 2D users had a lower delay between keys strokes from A to B in all tasks and suggests, in contrast to the 3D HUD, that users had an easier time remembering and accessing the different characters. Overall the SD for the average keystrokes do not have as wide a variance than the average mistakes or task completion time. However the SD are still significantly large. For example 3D_A task 2 users performed very differently from one another (SD = 4, M = 8). 2D_A Task 2 users also displayed a wide variety of results (SD = 4,
M = 8). The remaining tasks follow this trend with the exception of 3D_A task 3 where users performed much more similarly to each other (SD = 1, M = 5).

In contrast to mistakes made and task completion time, 2D8_Bs task 4 results (3.37 seconds between stoke) were nearer the mean of 2D_B task 4 (SD = 1, M = 5) and in this case 2D8_Bs outlying results did not affect the SD as highly as with mistakes made and task completion time.

**Figure 22** Average delay between keystrokes per user group per task per attempt with SD error bars for each task based upon the mean of each tasks total user keystroke delay.

5.3.4. Improvement from Attempts in Time

As the experiment required each user to return and repeat the tasks for a second attempt, the improvement rate from one HUD to the next in terms of speed and mistakes was also measured.

Table 2 shows the overall improvement between users A and B in task speed. 2D users had a higher improvement rate in Task 1, increasing their speed by an average of 314 seconds. 2D users also demonstrated a great improvement rate in speed for Task 3. However, an increased improvement rate for 3D users was also experienced in Tasks 3 and 2. This increased improvement rate provides interesting information on how users experienced the 3D vs the 2D HUD and is explored further in the discussion of this thesis.

2D8_B abnormal data gives a negative result in improvement between A and B. See sections 5.3.2 and 5.3.1. Without this, the results otherwise show an improvement.
### 5.3.5. Improvement from Attempts in Mistakes

Although 2D users showed a clear improvement in time in their second attempts, the data in Table 3 demonstrates that 3D users actually experienced a greater improvement result with mistakes made. 2D users made fewer mistakes in their second attempt, demonstrating an overall improvement that exceeded 3D users. For example, 2D users made 44 fewer mistakes on average in Task 2 in their second attempt compared to the 37 fewer mistakes made by the 2D users in the same task.

Task 3 also shows a more significant improvement for the 3D users compared to the 2D users. Task 4, however, diverges from the trend of higher improvement results for 3D users as 2D users, had 18.75 less mistakes on average than five of the 3D users. Task 4 required users to combine each of the different methods and navigation used in the previous three tasks. This suggests that the 2D HUD is easier to use when using its range in a broader context.

#### Table 2 Overall difference in task completion rate per user group between attempt 1 and 2.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>3D</th>
<th>3D</th>
<th>Diff</th>
<th>2D</th>
<th>2D</th>
<th>Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Time Taken Task 1 (sec)</td>
<td>552.89</td>
<td>356.23</td>
<td>196.66</td>
<td>494.44</td>
<td>178.98</td>
<td>315.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Time Taken Task 2 (sec)</td>
<td>147.78</td>
<td>65.75</td>
<td>82.03</td>
<td>170.26</td>
<td>85.09</td>
<td>85.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Time Taken Task 3 (sec)</td>
<td>396.56</td>
<td>255.26</td>
<td>141.29</td>
<td>395.68</td>
<td>186.04</td>
<td>209.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Time Taken Task 4 (sec)</td>
<td>232.16</td>
<td>161.25</td>
<td>70.91</td>
<td>173.43</td>
<td>200.27</td>
<td>-26.84</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 3. Overall difference in mistakes made per task per user group between attempt 1 and 2

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>3D</th>
<th>3D</th>
<th>Diff</th>
<th>2D</th>
<th>2D</th>
<th>Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Strokes Task 1</td>
<td>77.875</td>
<td>33.75</td>
<td>44.12</td>
<td>55</td>
<td>17.375</td>
<td>37.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Strokes Task 2</td>
<td>15.875</td>
<td>6.25</td>
<td>9.62</td>
<td>16.125</td>
<td>11.75</td>
<td>4.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Strokes Task 3</td>
<td>61.125</td>
<td>23.875</td>
<td>37.25</td>
<td>58.5</td>
<td>33.875</td>
<td>24.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Strokes Task 4</td>
<td>23.875</td>
<td>18.875</td>
<td>5</td>
<td>32.75</td>
<td>35.75</td>
<td>-3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 5.3.6. User Questionnaire Response

All users filled in a questionnaire after they completed each session. The user marked one of five squares to respond to a statement or question.

Users were asked to answer four questions to indicate how easy certain parts of the HUD were to understand and were given a range of five options, with 1 indicating “very easy” and 5 indicating “very difficult”.

Responses provided by 3D users were on average almost identical to 2D users, with a small difference between their memory of where each individual character was and whether or not they understood how their hands were being recognized by the sensor (Table 4).
How difficult did you find the following tasks?

<table>
<thead>
<tr>
<th>Task</th>
<th>3D_A</th>
<th>3D_B</th>
<th>2D_A</th>
<th>2D_B</th>
</tr>
</thead>
<tbody>
<tr>
<td>QA. Switching between the different key sets:</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>QB. Remembering where each character was:</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>QC. Remembering all the different key sets:</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>QD. Knowing whether your hands were recognized by the sensor or not:</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

TABLE 4. AVERAGE USER RESPONSE TO TASK DIFFICULTY QUESTIONNAIRE.

All users were also asked to state whether or not they agreed with a set of statements by checking one of five different boxes, where 1 was “agree strongly” and 5 was “disagree strongly” (Table 5). Both 3D and 2D users groups answered, on average, almost identically.

How accurate do you find the following statements?

<table>
<thead>
<tr>
<th>Statement</th>
<th>3D_A</th>
<th>3D_B</th>
<th>2D_A</th>
<th>2D_B</th>
</tr>
</thead>
<tbody>
<tr>
<td>QA. The visual aid represented how I was using and moving my hands and fingers</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>QB. With practice I would be able to type comfortably using the Erghis</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>QC. The visual aid for the Erghis was very easy to understand</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>QD. The visual aid for the Erghis was very to use</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

TABLE 5. AVERAGE USER RESPONSE TO HUD EXPERIENCE

5.3.7. User Gesture Technology Experience

Users were asked to rate themselves on their gesture experience. They were asked to rate themselves on a scale of 1 to 5, where 1 was “no experience” and 5 was “lots of experience”.

Table 6 show the user results for gesture experience. 75% of the 2D users rated themselves as a 4 or higher whereas only one of the 3D users rated themselves higher than 3.
5.4. Outlying User
An outlier was identified in the data (Appendix H.), as user 2D8 choose, during Task 4, to explore the interface for a specific key. This user spent a large amount of time doing this. Users were not informed that they were being measured on speed of task completion and were not made to feel any time pressure. Most users, regardless of this, attempted to find the quickest way to complete each task. Some users would get distracted by a key or character they hadn’t seen before, but would then return to the task at hand. User 2D8 did not follow the average user behaviour and instead displayed a more explorative based approach rather than having the goal of completing the task as fast as they could in mind.

5.5. Trends
Patterns in the data highlight a number of contrasts and comparisons between each HUD. Several significant trends stand out.

The SD for most of the task data sets are significantly large (Figure 20, Figure 21 and Figure 22). This indicates that each user experienced a wide variety of difficulty or ease for each task in terms of speed, mistakes and keystroke delay.

The 2D and 3D users had very similar overall completion times per task (+/- 35 seconds for A and +/- 76 seconds for B) and an overall similar rate of mistakes per task (+/- 8 for A and +/- 8 for B). The 2D overall average delay between key strokes was almost identical to those of 3D, with exception of Task 1 where 3D_A users had a distinctly higher average delay between key strokes.

The data collected from the experiment is extensive. The presented data sets and charts are those deemed most relevant for this topic. However, more data can be easily retrieved from the collection over time, depending on the purpose of inspection.

6. Discussion
This section discusses the results of the experiment in the context of the RQ posed by this thesis:

What is the comparison, in terms of performance and user experience, between a 2D and a 3D representation (shown as a head-up display) of the same interface for a touch-free virtual keyboard?
6.1. Comparing the two HUDs
The data and results indicate that the 2D HUD and 3D HUD performed very similarly to each other in terms of task completion speed, mistakes made and keystroke delay. While the 2D HUD performed slightly better in certain tasks such as a faster Task 1 completion time in both sessions (Figure 20) the 3D HUD was slightly better in others such as Task 2, 3 and 4 mistakes made in B (Figure 21).

Average time between task completions differed by no more than 76 seconds between user groups (Table 2 Overall difference in task completion rate per user group between attempt 1 and 2.). The number of mistakes between each user group differed on average by only 8 key strokes or less (Table 3).

Despite the similar HGDs statistical results, there was a higher positive feedback from users with the 3D HUD. User 2D6 desired a 3D HUD commenting “[that] the interface should be in 3D somehow” without knowing there was a 3D interface being tested on other users.

The 3D users also made a number of comments that indicated their second attempts were easier than their first. One user remarked, “Amazed how quickly it is to get info and how fast I could gain speed from just a short period”. Another user wrote, “I understood where to find capital letters this time and this made it a lot easier.” Only one 2D user observed that the task became easier the second time, commenting, “A lot easier to find the different combinations the second time.”

The 2D users were more critical of their interface, sharing a total of 19 comments that indicated difficulties or suggestions for improvement compared to nine critical comments from the 3D users. These are difficult statistics to interpret, as some users may or may not have chosen to comment. However, the users who completed tasks with the 3D HUD tended to be more enthusiastic about using it.

3D users’ average response, when asked how hard it was to remember where each character was, was greater than that of 2D users. On the other hand, when asked if the users knew whether their hands were recognized by the sensor, the 2D users responded with preference to the 2D HUD. The 3D users found it easier to remember where the individual characters were, yet had a harder time understanding that their hands were seen or not seen by the sensor.

This analysis suggests that while statistically the 2D HUD users performed better, the experience of using the TFK was enjoyed more by the 3D HUD users in this specific experiment.

6.2. False Hypothesis
H1 hypothesized an overall superiority for the three statistical hypotheses H1a, H1b and H1c. The null hypotheses, being that there was no significant differences between the results of the 2D and 3D HUD, in this case cannot be rejected.

No significant difference can be ascertained with any degree of certainty that H1a, H1b or H1c are proven. A two tailed t-test on 3D_A vs 2D_A in all 4 tasks for time completion, with the null hypothesis being no significant difference in time to complete the task, yielded these results by order of ascending task number:

1. Two-sample(7) = 2.36, p = 0.79
2. Two-sample(7) = 2.14, p = 0.79
3. Two-sample(7) = 2.14, p = 0.99
4. Two-sample(7) = 2.18, p = 0.46

The results show a significantly large p values (p>0.05) which suggests the null hypothesis is likely (csic.com, 2014). T-tests across the other tasks and measurements yield the same results. This thesis therefore concludes that for the population tested there was no significant difference between the 2 HUDs tested in terms of that hypothesised by H1a, H1b and H1c.
H1 was proven false by the statistical outcome. Yet, the results indicate H2a and H2b to be true. Section 6.1 shows many of the positive comments from the 3D users further comments and notes on the questionnaires. The 3D users appear to have had a more positive experience than the 2D users. The observation-notes also show that 3D users tended to have a more positive responses and were overall more curious about the HUD and the experiment than the 2D users. What may have caused this divergence in predictions?

The data is complex and extensive. There are a variety of possible reasons for the results. First, the statistics of the user group’s self-rated experience with gesture technology are very interesting. The results show that at least 75 % of the 2D HUD users rated themselves as having a high or a very high level of gesture technology experience, whereas only one user rated themselves higher than some level of gesture technology experience, from the 2D user group. The questionnaire asks the users gesture experience regarding smart phone and tablet use, which while they are VEs are perhaps not entirely relevant to a TFVK. The difference between user groups based on this is interesting to note but not reliable. In hindsight an improvement to the experiment would have been to change the experience question to relate to more TF gesture based devices such as the Kinect or Wii.

In the hypothesis for this thesis (Section 1.4), it was noted that users often require some existing knowledge with 3D interfaces in order to be comfortable using one (Hatchet et al. 2013, p.80). The demographic (15-40 yrs. old) for the user test was selected with this in mind. Users with existing 3D experience were not expected to experience a sensory overload when introduced to a 3D HUD. This allowed the user groups to test both HUDs without the disadvantage of being unfamiliar with 3D user interfaces. This factor implies that, because the 3D users were already used to 3D technology, the HUDs graphical presentation played a small role in their ability to use the TFVK.

Bowman’s (2014, p.86-87) experiment suggested that users who mimic what they see on an interface tend to experience better performance. This result was one of the key principles in the choice of how the 3D HUD was designed. Two of the 3D users commented that they had trouble typing the letters with the 3D HUD by moving their fingers like the animation did. The actual movement that users used to type more accurately was more of a tapping motion compared to the curled poking motion that the animation displayed. Additionally problems were also caused when users held their hands too close together. The 3D HUD animation may have illustrated the hands grasping the ball too close together, and more users who used the 3D HUD were observed making this mistake. This can indicate that the 3D HUD does indeed support mimicry in the tested users, as Bowman (2014, p.86-87) suggests in his research. The similar results in the statistical data may also be influenced by these factors.

The 2D HUs design layout does not very well mirror the form in which a user should hold their hands. The mappings of letters to the fingers are also do not conform to standard VK layouts. It was expected that this divergence in design would give a higher chance of H1a, H1b and H1c to be more likely. Yet the results were similar between each HUD. This suggests that for the sample group that the visual aspects of the HUD (2D and 3D) did not have a huge effect on the user’s performance.

Other designs in the 3D HUD may also have influenced the results. For example, one user commented on the colour and lighting of the 3D HUD. 2D8 after completing all tasks and attempts was shown the 3D HUD. This user mentioned that, in comparison to the 2D HUD, the 3D HUD was very dark and heavy looking. This brings up possible question that was not previously considered. Although none of the 3D HUD users commented on the colour and lighting of the HUD, it is possible that colour and lighting can have an influence on a user’s performance.

The results also indicate that user group’s enjoyment of a HUD is not necessarily related to their performance. The 3D users, as previously indicated, were observed to have enjoyed the experience more than 2D HUD users as predicted in H2b. Many users also expressed frustration when using the 3D HUD by sighing or growling. These same users, however, expressed verbally after the tests that they really enjoyed the experience and were curious to know the results as predicted in H2ba. In contrast to this, 2D users often discussed ways in which the 2D version could be improved or inquired about how this technology would be practical or useful.
The 3D users’ higher level of enjoyment compared to 2D users indicates that this particular user group followed similar behaviours to those that Hatchet’s et al. (2013, p.83) users experienced in the museum experiment. Hatchet et al. (2013, p.84) concludes that users benefit from interactive experiences and are motivated to use them. This is demonstrates that, although the 3D HUD in this experiment produced a slightly less empirical advantage, it has potential to be beneficial to the users of this study regardless.

Finally, 3D’s higher rate of improvement in time from session A to session B, coupled with their level of enjoyment, suggests that the 3D users were more engaged in the tasks the second time.

6.3. Suggested Improvements

The conclusions from the experiment suggest many alternatives to future tests. With such a small sample group, it is difficult to make generalizable conclusions with any certainty.

There are many factors that could be changed and iterated that could provide a more accurate and improved experiment. The following paragraphs discuss some of these factors.

The user sample groups divergence in gesture experience may have been a small factor and the gesture experience was self-rated. This is a subjective judgment and could be measured differently to represent a more specific composite of user experience levels result. The experiments could be preceded with a small task based experiment in which the user is provided with a gesture based system or other similar VKs as well as small typing task similar to the tasks implemented in the experiments of this thesis. By using this information the sample group could be divided equally between the 2D and 3D HUDs with more specific knowledge of their gesture experience.

Aside from gesture experience, the sample group for this thesis was largely a homogenous group. The results provide insight into a very specific demographic in terms of age and geographic location. This is also a result of the limitations of a bachelor level thesis and the provided time. Be that as it may, a broader demographic in age and geographic location could provide a more fair and accurate result of 3D vs 2D with gesture interfaces. The sample group was also a small group of people. With a larger group of people more reliable and indicative statistical results could be drawn from the groups. This increase in population size of the experiment might lead to a smaller degree of error and give more reliable results.

In the design of the 3D HUD, a legend that is present on the 2D HUD (Figure 14) was omitted. Following Nielsen’s heuristic design guidelines (1995), the table was omitted from the 3D version as it was believed that this information was redundant as the user can see the imaginary ball they are asked to imagine. Nielsen also indicated that abstract information spaces do not work well in a 3D space (Nielsen, 1998). The 3D users responded in the survey that, on average, they found it harder to remember where each keyset was compared to where each individual character was. The 2D users, in contrast, found that it was slightly easier to remember where the keysets were than the individual characters. This suggests that the legend of the 2D HUD would, in fact, contrary to Nielsen’s guidelines, be beneficial to the 3D HUD and should be included in the design for similar experiments.

Age can also be an important factor, as while younger demographics tend to have more experience with 3D and intuitive design, older demographics may have a higher level of familiarity with instruction manuals and guidance in the form of text. For example, VCR guides and household appliances used to come with large manuals. Both groups in the experiment of this thesis were in a demographic familiar with 3D, and it was concluded that their correspondingly similar results were a cause of this. The 2D vs 3D experiment, enacted with an older demographic, could provide the same opportunity as this thesis in a different context. It would be of great interest to find out whether the two HUD test groups experience similar results with users who have a low level of 3D familiarity.

Because the 3D users seemed to mimic the 3D display, designing the finger animations in a more accurate way would benefit future test between the 2D and 3D HUDs. This design flaw was an oversight in design, based on the way the Erghis was planned to function. The Erghis implements the hand positioning as seen in the 3D
prototype. However, as the motion sensor technology is still limited, the actual positioning of the hands and ways in which the fingers move did not represent the optimal way that fingers should move to get the best readings.

6.4. Further Research
The experiment conducted in this thesis was limited to manpower, experience and time. The possibility of expanding these experiments offer exciting potential. Much remains unclear about the nature of 3D interfaces, especially while the field of touch free gestures grows and become more relevant. Does colour and lighting affect the user in a 3D interface environment? If so, in what ways and why?

Does different demographics experiences with 3D technology have a high level of influence on performance, suggested by this thesis? More research is needed to say with certainty on a larger scale.

Other TFGBIs are starting to emerge aside from the Erghis. Will the Haptix (ractiv.com, 2014) develop their HUD in a different way? Will they include a HUD at all? It would be highly interesting to perform the same tasks with the Haptix if their product includes a HUD. Perhaps the Erghis may function with the Haptix and, if so, does the motion sensor greatly affect the results of the 2D vs 3D test?

Virtual reality, not previously discussed in this thesis also has the potential to demand design choices and guidelines for development in a 3D environment. This is especially needed when more haptic options become available to virtual reality systems. Are there ways to implement a 2D HUD in a 3D virtual environment and if so how would it compare to 3D HUD in that environment?

The question of whether the benefits outweigh the costs of 3D development is still relevant and much more research in 2D vs 3D will be required to answer these questions.

6.4.1. Outlier behaviour
User 2D8 raised an interesting observation of how users might interact with TFVK’s. This user’s actions (See Section 5.4) deviated from the standard deviation and caused the averages to show unexpected results.

As mentioned in Section 5.4 the user took an exploratory approach to using the TFVK rather than trying to finish the task as fast as possible as the other users were observed to have done. This behaviour could suggest a different way of implementing the experiment. Users could instead be asked to explore the TFVK to find and use different macros and keys and perhaps be measured on their speed or mistakes afterwards.

It would be informative to have 2D8 return and perform the tasks again with the instructions to finish the tasks as fast as possible and with as little mistakes as possible.

It is difficult to say more about 2D8s behaviour without further information. A new study with more participants that might have users test both the 3D HUD and 2D HUD would be useful to perform while looking for similar behaviour.

2D8 encourages some interesting questions. Would 2D8 have had a similar result had they tested the 3D HUD? With further iterations of the experiment would 2D8’s exploratory behaviour yield higher performance results?

7. Reflection
This thesis has provided insights on how users see visualizations that represent what is happening in real life. I have found the research extremely interesting and hope the data may be used in the future to further explore this subject. There are many other aspects and perspectives to be derived from the data. It remains an exciting area of research.

The work load was exceedingly challenging and it became very clear late in the research that the thesis was a very ambitious undertaking for a bachelor level thesis. There were many aspects to the research that, because they were not necessarily relevant to the thesis questions, were not discussed. The prototype itself was a 2 month undertaking of programming, modelling, designing, literature study, programming experience and an
depth collaboration with the creators of the Erghis. The data analysis was also a significant undertaking as the tests produced over 128 separate CSV files. As well as over 100 pages of user information, observation notes and questionnaire completed forms.

The CSV files required the programming of a standalone app to convert the data into values that were easy to analyse. Once these values were available, many hours were spent building a large data table with several hundred rows of information. This information was used to build the charts and tables that are presented in the thesis.

Finally each user test produced a dossier of 6 pages per user and totalled over 96 separate pages of information that were to be processed and tracked.

The user tests were a two week project that involved scheduling and implementation. Each user test took an average of about 40 to 45 minutes, including time for the user to read the introduction, warm up, perform the test, and fill in the questionnaire.

Overall, I am very satisfied with the results gained and the experience from the work, both in user testing and planning. I hope, in conclusion, that the work itself is of benefit and help to those further researching the exciting field of 2D and 3D visualization.
8. References


Oliveira, S., Jorge, J., & Gonzalez-Mejome, J. n.d. 2012. *Dynamic accommodative response to different visual stimuli (2D vs 3D) while watching television and while playing Nintendo 3DS Console*. Ophthalmic And Physiological Optics, 32, 5, pp. 383-389, Science Citation Index, EBSCOhost. [Accessed 14 May 2014].


9. Appendix

9.1. Appendix A.

**TASKS:**

1. Type the quick brown fox

2. Erase everything you just wrote by using the common ctrl-a select everything method:
   - Find and tap **Ctrl**
   - Then find and tap **a**
   - Then find and tap **Backspace**

3. Type **HELLO WORLD!**

4. Type **User@gmail.com**
### Questionnaire

1. **How difficult or easy did you find the following tasks?**

<table>
<thead>
<tr>
<th>Task</th>
<th>Very Easy</th>
<th>Very Difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching between the different key sets:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remembering where each character was:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remembering all the different key sets:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knowing whether your hands were recognized by the sensor or not:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. **Can you give any specific examples or discuss your answers above?**

3. **How accurate do you find the following statements?**

<table>
<thead>
<tr>
<th>Statement</th>
<th>Agree Strongly</th>
<th>Disagree Strongly</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Visual aid represented how I was using and moving my hands and fingers.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With practice I would be able to type comfortably using the Erghis.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The visual aid for the Erghis was very easy to understand.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The visual aid for the Erghis was very easy to use:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
9.3. Appendix C.

The Erghis

Thank you for taking the time to test out the Erghis! We greatly appreciate your time.

Introduction.

The Erghis is a new way to interact with the computer! Using the motion controller that is in front of you, you can communicate to the computer by using only your hands. Today we are testing the effectiveness of our visual aid. The visual aid is the program you have open in front of you and it is called the Erghis. Using the Erghis, we would like you to try and complete a series of tasks where you will type using the Erghis.

How to Use the Erghis

In order to facilitate good communication between the motion controller and your hands imagine that each of your hand is placed on either side of a ball. It is divided into two halves and depending on how each half is rotated, different output (letters, numbers, Enter key, etc.) are displayed. This is a similar motion to a rubrics cube. Except, imagine the rubrics cube is a ball.

Place your hands on each half of the ball and then make sure you are 20-30 cm above the motion controller. Balls do not have flat surfaces, so angle your hand slightly sideways and inwards, this will make it easier for your hands to be tracked. Always keep your hands clearly separated so they can be correctly identified by the motion controller. Your thumbs may be easily become blocked if your hands are too close together or if your fingers are closed.

On each hand you can use your thumbs to see different key sets. Each hand has 4 characters. Spread your thumbs out away from your hand. Maintain a natural hold with your hand, don’t stress and strain your fingers. Just hold the imaginary ball naturally and make sure your thumbs are pointing up towards the ceiling. When you close a thumb or both you will access different key sets. Don’t close your fingers though! They need to be recognized on their own.

The sphere as mentioned has 2 halves. You can rotate a half into 3 states. Therefore there are a possible 9 combinations of states. In each state there are a set of keys called key sets. For example you may have the left half rotated down and the right half in the middle or both halves rotated up. Imagine again the rubrics cube movement. Each state has 4 different key sets. These key sets are accessed by having your left thumb closed, or your right thumb closed, or both thumbs closed or finally by having both thumbs up or open.

When you have found the correct key set that contains a letter or command you wish to type simply tap your finger inwards to indicate you are selecting that letter. If you have trouble getting it to listen try slowing your tap down or speeding it up. The most effective way to tap is in a controlled easy tap with your finger. If you move to slowly it may not recognize your tap. If you jab too fast it may also miss your tap.

If you feel as though your hands are not being recognized pull them far out to the sides, wait a second and then slowly bring them back over the motion sensor as if you were squeezing a very large beach ball to a smaller football.
Before You Begin

That’s a lot of information! But please don’t be nervous. Today we are testing to see how well we have implemented this system. Not how well you use it. If you are having trouble or find it difficult remember that it is our fault and not yours! The whole reason we are doing these tests are to find out how well users can interact with this system. Before you begin the tasks, take 5 minutes and play around with the Erghis, try and get a feel for it and explore the different key sets and states by rotating the ball and opening and closing your thumbs.
9.4. Appendix D.

User______________________________ Attempt______________________________

NOTES:
## User:

<table>
<thead>
<tr>
<th>Age:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User #</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time Slot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tablet and Smart Phone Experience</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Time (min)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time Slot</th>
<th>Attempt 1</th>
<th>Attempt 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Experience</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lots of Experience</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Time (min)</th>
<th>Attempt 1</th>
<th>Attempt 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 9.6. Appendix F.

<table>
<thead>
<tr>
<th>Left Half (H&lt;sub&gt;left&lt;/sub&gt;)</th>
<th>Right Half (H&lt;sub&gt;right&lt;/sub&gt;)</th>
<th>Left Thumb</th>
<th>Right Thumb</th>
<th>Left Hand</th>
<th>Right Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>Up</td>
<td>Down</td>
<td>Up</td>
<td>F, E, D, C</td>
<td>G, H, I, J</td>
</tr>
<tr>
<td>Up</td>
<td>Up</td>
<td>Up</td>
<td>Down</td>
<td>N, M, L, K</td>
<td>O, P, Q, R</td>
</tr>
<tr>
<td>Up</td>
<td>Up</td>
<td>Down</td>
<td>Down</td>
<td>V, U, T, S</td>
<td>W, X, Y, Z</td>
</tr>
<tr>
<td>Up</td>
<td>Up</td>
<td>Up</td>
<td>Up</td>
<td>Enter, Space, Delete, Insert</td>
<td>On Top, HUD, A, B</td>
</tr>
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<td>Up</td>
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<td>Up</td>
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</tr>
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<td>“No mapped characters”</td>
</tr>
<tr>
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</tr>
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</tr>
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<td>6,7,8,9</td>
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<td>Up</td>
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<td>Up</td>
<td>Hold Mode, Reset Hold,</td>
<td>Alt, Alt Gr</td>
</tr>
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<td>Up</td>
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<td>“No mapped characters”</td>
<td>“No mapped characters”</td>
</tr>
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<td>Up</td>
<td>“No mapped characters”</td>
<td>“No mapped characters”</td>
</tr>
<tr>
<td>Down</td>
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</tr>
<tr>
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<td>Mid</td>
<td>Up</td>
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<tr>
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<td>“No mapped characters”</td>
</tr>
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<td>Down</td>
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<td>Up</td>
<td>Mute, HUD, Settings,</td>
<td>Transp., On Top, Handles,</td>
</tr>
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</tr>
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<td>Up</td>
<td>0. , , ! ?</td>
<td>_ : ;</td>
</tr>
<tr>
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<td>Up</td>
<td>Up</td>
<td>Down</td>
<td>^ &gt;</td>
<td>&lt;</td>
</tr>
<tr>
<td>Mid</td>
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### User data from attempt 1.

### Appendix H
User data from attempt 2.