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3.1 Introduction

Passive haptics is a term that has been used to describe a variety of technologies or techniques to provide the sense of touch to a user of a virtual environment. It is often defined by its distinction from active haptics, which simulate the sense of touch with energy exchange, typically electromechanical. A common active haptic technology used in immersive virtual environments is a haptic glove, often utilizing small motors at the fingertips. In contrast, passive haptics often utilize proxy objects placed in the physical world to co-incide with the virtual environment experience. The proxy objects can be simple or complex. They can be colocated and accurate with the virtual world or purposefully designed to trick the user. In our paper, we utilize a simple colocated passive haptic device and measure its effect on the presence and performance of subjects using a 2D panel in a 3D immersive virtual environment.

The advantages to using a simple passive haptic can be easily understood: less cost and complexity compared to most active haptic solutions. However, the disadvantage comes with its inflexibility. Due to their nature, passive haptics often have to be purpose built for a single or limited experience. While past research has aimed to address this, by either actively positioning a proxy object or simplifying the proxy object to fool the user, our application does not suffer from this limitation. The motivation for our research comes from the application of designing aerospace cockpits, complex human-machine interfaces where the user is stationed at their workspace. For the purpose of evaluating a cockpit design, the user does not need a dynamic tactile environment. Furthermore, many cockpit design processes already create a physical mockup which can provide the passive haptics for this evaluation.

We present our findings in testing passive haptics versus no haptics in an immersive virtual reality environment. Using a head-mounted display and a hand tracker, the subjects performed the same Fitts' Law style task under these two haptic conditions. The passive haptics was a flat surface placed at an angle on a desk in front of their seating area. Their performance on the Fitts' task was recorded as well as their responses to a presence survey, a self reported arm fatigue score and a general questionnaire.

3.2 Background

3.2.1 Haptics

Passive haptics has been a topic of research since the early immersive virtual environments. Robotic passive haptics were used to ameloriate the inflexibility of a proxy object by utilizing a robotic arm to position the proxy object in the virtual environment where the user was reaching[17, 13]. Insko[9] found increased presence using passive haptics for a maze, and also found that subjects trained with the passive haptics performed better after they were removed than the group that never used them. Another track of work combined active haptics with passive haptics, using a haptic glove with a physical panel to create mixed haptics [2]. Again, performance was increased with the haptics, but minimal differences were found between using the mixed haptics and the passive haptics alone. Similar to our motivation and work, Schiefele et al.[15] replaced a cockpit panel with a flat panel in an immersive head-mounted virtual environment, and found that users could activate buttons and switches in less time with the panel present than without. While much of the research involving passive haptics indicates an increase in the presence of the user, some have questioned whether active haptics provides benefits. Pontonnier et al.[14] discovered that subjects had decreased presence ratings in a virtual assembly task when using a haptic glove, versus both a real environment and a virtual environment without haptics. We build on this previous work by investigating the effects of passive haptics with the lastest virtual enviroment technology, as well as performing a complete Fitts' Law characterization between no haptics and passive haptics.

3.2.2 Fitts' Law

Fitts' originally devised a relationship between movement time and the distance and size of targets for a human performing rapid aimed movements[6]. This has since become known as Fitts' Law, and later work has refined the index of difficulty (ID) as:

$$ID = \log_2 \left(\frac{D}{W} + 1 \right) \tag{3.1}$$

where D is the distance to the target from the starting location and W is the width of the target. This formula for index of difficulty is known as the Shannons' formulation[12].

Commonly, the index of difficulty is related to movement time (MT) through a linear regression. However, in this work we are concerned with the measurement known as throughput (TP). Throughput has been recommended as the dependent measures for comparisons between experimental conditions[16]. As the name suggests, it can be thought of as the rate of information the human can input with the particular experimental setup or input device. It is defined as the index of difficulty over the movement time, and has the units of "bits per second."

$$TP = \frac{ID}{MT} \tag{3.2}$$

The use of Fitts' Law as a tool for human-computer interface research began with the research of Card et al.[4] for the evaluation of different input devices for text entry. In 2000, The ISO 9241-9 standard was published with guidance on using Fitts' Law as an evaluation of pointing devices[10]. Along with the ISO standard, there have been calls to standardize the use of Fitts' Law so that results can be compared across literature[16]. For a 2-dimensional task (where all the buttons exist on a single plane), it is reccomended to use the circle layout as shown in Figure 3.1. This layout is referred to as the "Fitts' circle" within this article.

In this work, we use the effective width for the targets, which is defined as:

$$W_e = 4.133\sigma \tag{3.3}$$

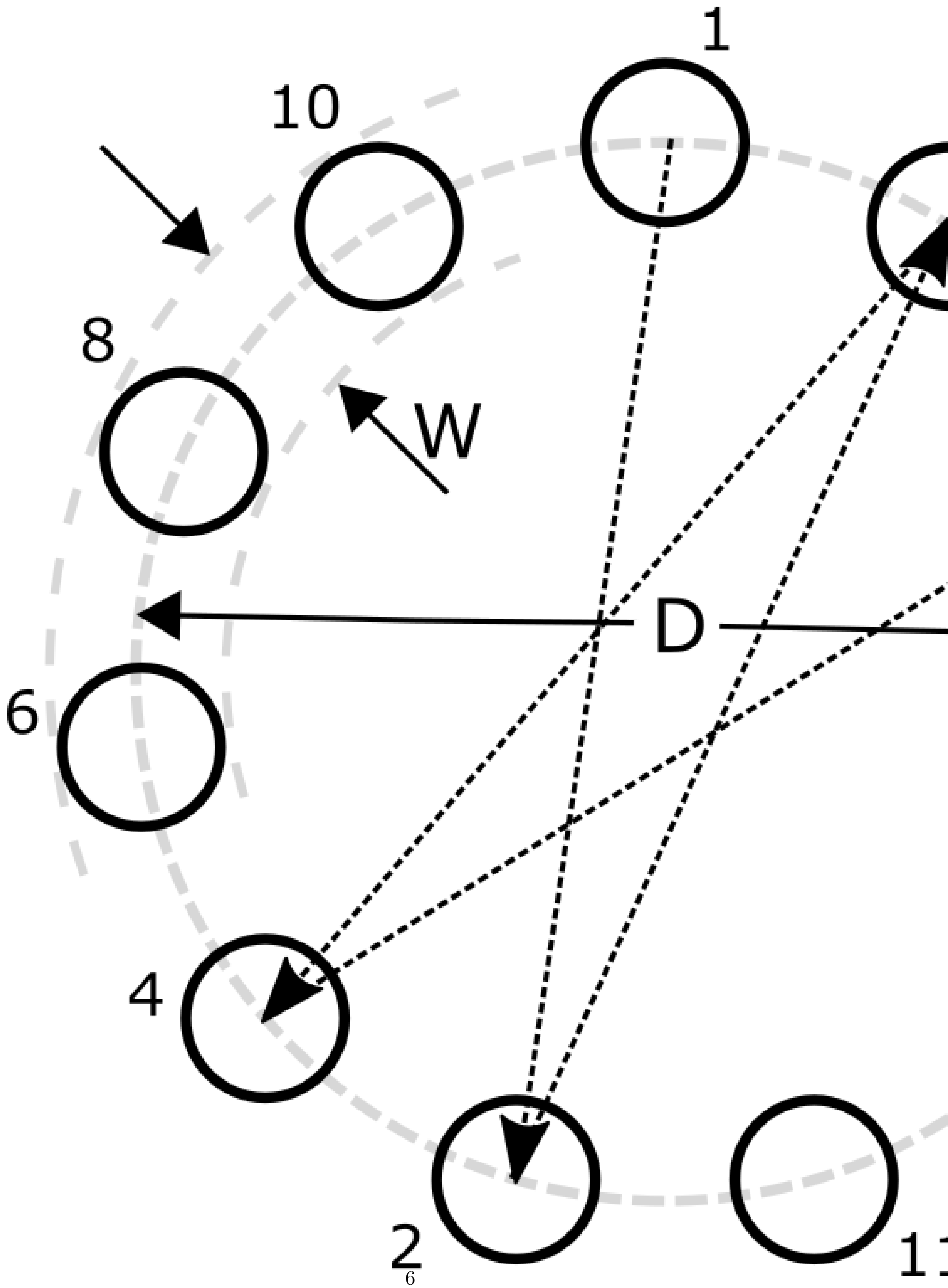


Figure 3.1: Fitts' Circle diagram. D is the distance between targets and W is the width of the targets.

where σ is the standard deviation of the end point positions. This is known as the adjustment for accuracy[18]. This correction accounts for the performance of the subject, especially on lower index of difficulty conditions where they may aim for the inside edge of a target. Hence, the use of the effective width provides the index of difficulty for the task that the subject performed, not the task presented to them. The effective width is calculated per subject per distance and width configuration, and subsequently used in the index of difficulty equation.

$$ID_e = \log_2\left(\frac{D}{W_e} + 1\right) \tag{3.4}$$

Fitts' Law has been used in evaluating virtual environments and their input devices. Most of the work has been focused on 3D stereo displays[11] or . Chun et al. (2004) evaluated a set of 3D stereo displays with a single haptic-enabled stylus using a Fitts tapping task. They did not have well-fit regressions, but this could have been due to a small range of ID values used (2-3), targets being placed in 3D space (a 3D task with 3D movement) with random order, and averaging across subjects before completing the regression. One condition performed a mid-air 2D planar task with 3D movement, and no significant difference in throughput was found compared to the same task with constrained 2D motion. The trajectories were analyzed to determine where the extra movement time was spent, which is discussed in a later section (Trajectories in Virtual Environments).

The use of Fitts' Law with haptics has mostly focused on active haptics[5].

- fitts law with haptics
- collect references

3.2.3 Presence

The feeling of presence is often specified as a goal of a virtual environment. A definition from Witmer and Singer[19] reads:

> "*Presence* is defined as the subjective experience of being in one place or environment, even when one is physically situated in another."

Increased presence can lead to increased performance in a virtual environment task[21].

3.2.4 Arm Fatigue

Despite the concern of arm fatigue in virtual environments[3], it was surprising that most results in literature were anecdotal or for mitigations without quantification of the fatigue. Since fatigue is a subjective quantity, it can be hard to measure it between subjects, and sometimes even within. The negative impact of arm fatigue on using virtual environments makes it worth investigating. The arm fatigue scale used within this experiment is a Borg Rating of Perceived Exertion (RPE) scale that ranges from 6-20[1]. Hincapie-Ramos et al.[8] proposed a model for quantifying and predicting the amount of arm fatigue that correlated well with a Borg scale.

3.3 Methods

The purpose of the experiment described within this paper is to answer the following research questions:

1. Will the throughput be higher with passive haptics?
2. Do subjects learn the task quicker with passive haptics?
3. What are the differences between the formation of reaching motion trajectories with passive haptics?
4. Does the use of passive haptics lower arm fatigue?
5. Does the use of passive haptics cause greater presence?

3.3.1 Experimental Setup

For the experimental setup, subjects were seated at a desk with a blank panel mounted on an angle in front of them. The plywood panel (45cm x 45cm) was used to provide only the backstop of the virtual buttons for the "Passive Haptics" condition. The button selection is registered by the subject moving their index finger into a hover zone (cylinder for the circle buttons) in front of the button that extends outward 0.5in. Their entrance into the hover zone is indicated to them by the button changing color. A successful button press is registered after 150ms, and is indicated by the color turning off and a button click noise being played over speakers.

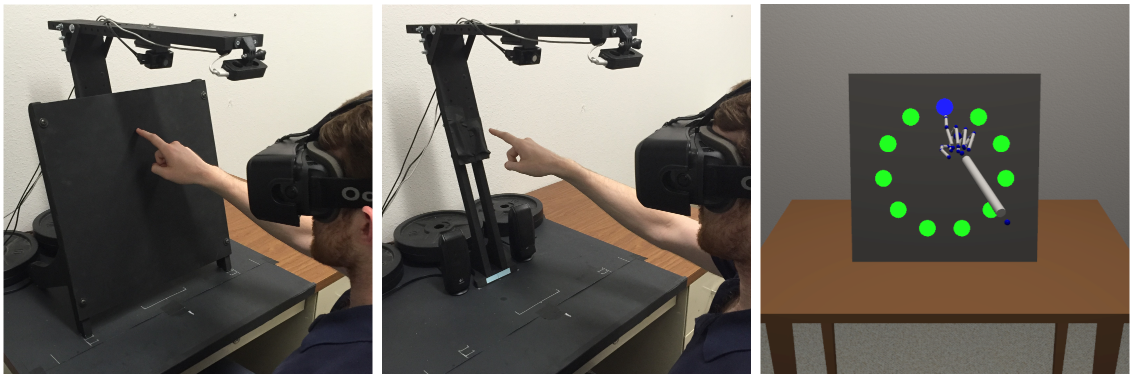
The equipment used consists of an Oculus Rift DK2 (Development Kit 2) head-mounted display (HMD) and a LeapMotion hand tracker. The low-persistence OLED display has a resolution of 1920x1080, with a referesh rate of 75Hz. The field of view is approximately 100°. It utilizes internal trackers and an external infrared camera for head tracking.

The LeapMotion is a markerless hand tracker which utilizes dual infrared cameras to provide a skelatal level position of hands and fingers in view. This position is used to provide an image of the hand position in the virtual environment, as well as for determining when a button is pressed. Instead of using the LeapMotion in its original face-up configuration, it was mounted above the working area and pointed down. Our pilot studies indicated that hand tracking from the LeapMotion was improved utilizing this face-down setup with the software using the head mounted configuration. However, the hand tracker could not be mounted on the head mounted display as it required a fixed position relative to the passive haptics to maintain appropriate registration between the virtual world and the passive haptics.

A custom calibration scheme was developed for the hand tracker as the initial registration between physical and virtual worlds was not very accurate. Despite the inaccuracy, the LeapMotion software was very precise, so after performing the calibration the registration was kept stable. The calibration performed a least squares claculation to solve for a transformation matrix between known real world locations and the reported location from the LeapMotion.

3.3.2 Experimental Task

The experimental task was a Fitts' circle in the virtual environment, performed by subjects in two haptic conditions. The subjects were seated at a desk for the experimental task, and the circle was located on a panel mounted on the desk. The two haptic conditions were "No Haptics (NH)" and "Passive Haptics (PH)." These conditions are pictured in Figure 3.2. For the "Passive Haptics" condition a physical panel was co-located with the



(a) Passive Haptics condition **(b)** No Haptics condition **(c)** View of virtual world

Figure 3.2: Experimental conditions and view of virtual environment.

panel in the virtual world, which was removed for the "No Haptics" condition.

There were no differences to the task itself or the method of button activation. The only difference between the conditions was the removal of the physical panel. The hand tracker remained in the same location, preserving the location of the buttons in the virtual environment. The dimensions of the virtual world were no different for either condition. In fact, there was no change to the software between the conditions.

Subjects performed the Fitts' circle for three different distances (20cm, 30cm, 40cm) and five different button widths (5mm, 10mm, 15mm, 20mm, and 25mm). These configurations were chosen to span a wide range of indices of difficulty (3.2—6.4). For each configuration of distance and width, subjects had to complete the full pattern of 11 buttons three times consecutively. This set of 33 movements for a single configuration is referred to as a single trial for a subject. The distance was kept constant for the consecutive trial until all five button widths were complete. The distances were presented in either smallest to largest or vice versa, which was counterbalanced among subjects.

This set of 15 trials was repeated for each haptics condition and the order was kept the same within subjects. The sequence that the two conditions were presented to each subject was also counterbalanced.

3.3.3 Experimental Design

As described in the previous section, the experiment was performed with a within-subjects design. Subjects were asked to complete the same experimental task for both conditions of haptics: Passive Haptics (PH) and No Haptics (NH). The two different haptic conditions are the main independent variables.

It was expected we would find a large amount of skill transfer between the two conditions, so the order in which subjects performed the two conditions was counterbalanced. This created a second independent variable that is between subjects. The subjects who performed the conditions with the PH being their first condition were one group, and the subjects who performed NH as their first condition were a second group. We call this grouping "sequence" and refer to the two groups as "PH First" and "NH First".

For a Fitts' Law evaluation, it is often recommended that the data collection only begins when the subject is fully trained on the task. However, one of the goals of the experiment is to investigate the learning rate of the subjects. For that reason, the subjects were given no seperate training time for the task or virtual environment.

In lieu of collecting the data from fully trained subjects, the throughput analysis will be carried out on movements that are determined to be composed of mostly ballistic motion. The filtering parameters were determined post-hoc from the trajectory recordings. Their development and parameter selection are discussed in the Results section.

3.3.4 Dependent Measures

The main dependent measure is the Fitts' throughput, measured through the movement time between button presses. Additionally, the trajectory of each movement is recorded from the hand tracker for analysis. To determine the arm fatigue, subjects were asked to rate their arm fatigue on the Borg scale from 6 to 20. The scale was presented with anchors as shown in Table A.10. The arm fatigue rating was collected at the beginning of each condition, and then after every other configuration of distance and width combination (and after the final trial, due to an odd number of trials). At the completion of each condition the subject was given a presence questionnaire. At the end of the experiment, an additional condition comparison survey was given to ask for opinions on the two haptic conditions.

3.3.5 Trajectory Phases

Human reaching movements have long been known to consist of two distinct phases[20]. To seperate the trajectories into the various phases, a simple algorithm was developed. First, the local minima are found throughout the velocity profile of the movement to seperate the movement into various submovements. The “ballistic phase” is then classified as the submovement which contains the peak velocity of the entire movement. The various submovements after the ballistic phase are classified as the “corrective phase”. Any movement before the ballistic phase is classified as a “reaction time”. An example of the results of this classification is shown in Figure 3.3. This mathematical definition does break down for certain cases where a subject might have two submovements in the ballistic phase due to a mid-course correction or similar, however one of the main purposes of this classification was to find movements which are appropriate to use for the Fitts’ Law calculations.

3.3.6 Trajectory Filtering

We used a low-pass filter on the trajectory recordings to reduce the amount of noise. The LeapMotion processes data at a variable frequency, thus creating a variable rate for recording. The frequency typically varies from about 100Hz to 120Hz. To perform the filtering, the data was first resampled to a fixed rate of 100Hz. The filter used is a fourth-order Butterworth filter with a cut-off frequency of 5Hz. The cut-off frequency was chosen as voluntary hand movements have been shown to be below such a rate.

3.3.7 Statistical Methods

The throughput, arm fatigue rating and presence score were all statistically tested using a two-way ANOVA with one within-subjects factor (Haptics) and one between subjects factor (Sequence). When the ANOVA showed an interaction effect, the two Sequence groups

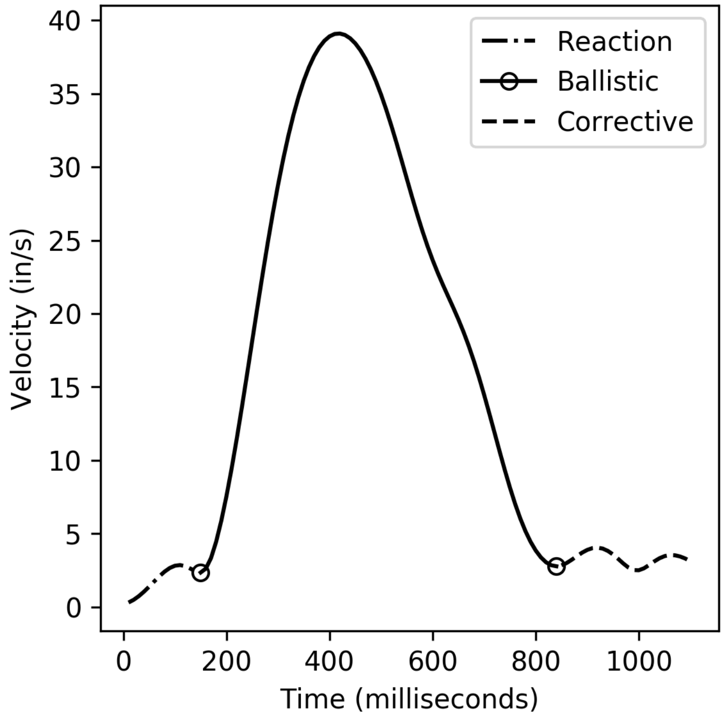


Figure 3.3: Example trajectory with three phases indicated.

were seperated and a repeated measures t-test was performed for the Haptics factor with each group. The statisitical significance level was corrected using the Bonferroni correction given the three dependent measures being tested. This leads to effects being considered statistically significant at the 0.0167 level ($\alpha = 0.05/3 = 0.167$). Effects between $0.05 < p < 0.0167$ are noted as marginally significant. Additionally, the presence questionnaire was tested using Cronbach's alpha for internal consistency.

3.4 Results

3.4.1 Participants

Twenty (20) subjects were recruited from the UC Davis engineering student population, both undergraduate and graduate students. The age range was 19—29 ($M = 22.95, \sigma = 3.0$) with 16 males and 4 females. The genders were balanced amongst the counterbalanced groups. All subjects indicated either less than one hour or no prior experience with virtual reality.

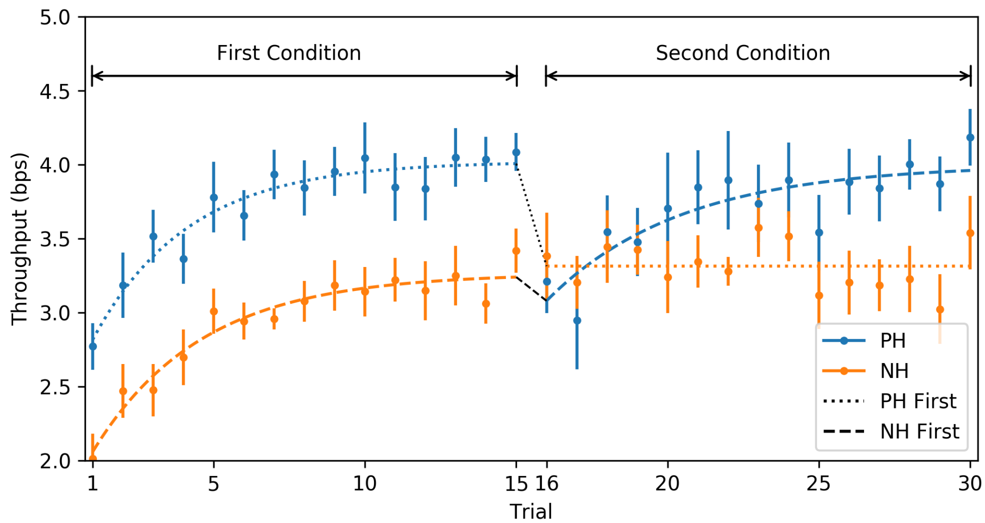


Figure 3.4: Throughput per trial. The learning curve exponential fit is given by Eqn. 3.5 with parameters from Table 3.1.

3.4.2 Throughput

The throughput is calculated per movement using Equation 3.2 and meaned per trial before being meaned per subject and condition. Throughput is used to investigate the first two research questions: do the subjects learn quicker and does their throughput performance improve with passive haptics.

Rate of Learning

The average throughput for each trial, seperated by haptics condition, is shown in Figure 3.4. An exponential rise to a learned state can be fit to each haptics condition to model the learning curve of the subjects. The equation used is given as:

$$\mathrm{TP}(T) = \mathrm{TP}_\infty - (\mathrm{TP}_\infty - \mathrm{TP}_0)e^{(-T/\tau)} \tag{3.5}$$

where T is the trial number, TP_∞ is the asymptotic learned value of throughput, TP_0 is the initial value at $T = 0$ and τ is the time constant. The time constant is the amount of trials for the throughput to rise 36% of the difference between the fully learned throughput (TP_∞) and the initial throughput (TP_0). The parameters of the fit for each condition is shown in Table 3.1, as well as the standard error of the estimate (SEE). The value of

Sequence	Condition	Haptics	TP_∞	TP_0	τ	SEE
PH First	First	PH	4.0	2.4	3.2	0.58
PH First	Second	NH	3.3	3.3	0.0	0.65
NH First	First	NH	3.3	1.7	3.6	0.49
NH First	Second	PH	4.0	2.8	4.5	0.78

Table 3.1: Exponential fit parameters of Eqn. 3.5. Curves are shown in Figure 3.4.

throughput from the regression fit as a percentage of TP_∞ for certain trials are listed in Table 3.2.

The rate of learning is very similar amongst both groups in the first condition. For the first condition it can appear that the subjects performing NH learned quicker than their counterparts performing PH by looking at the time constants. However, as the values in Table 3.2 show, the NH First group started their first trial at a lower percentage of their learned state. The shape of the learning curves are very similar and both groups reached approximately 90% of their fully learned state by the 5^{th} trial.

The learning curves are quite different for the second condition. The NH condition does not have a learning curve, with a straight line being a better fit than the exponential function. This indicates the transfer of training from the PH condition allowed the group who did PH first to immediately perform in NH at the same level as the fully learned state of the subjects who learned NH in their first condition. This transfer of training to the second condition did not occur as strongly for the group who did NH first. Their initial performance of PH did start out at a slightly higher level than the subjects who did PH first (2.8 bps vs 2.4 bps), but after 5 trials this difference had converged (3.6 bps vs 3.7 bps).

These results indicate that subjects did not learn faster with Passive Haptics. The only differences between learning rates is the positive transfer of training from performing Passive Haptics first and No Haptics second. The answer to the research question *Do subjects learn the task quicker with passive haptics?* appears to be that the passive haptics

Sequence	Condition	Haptics	TP_1	TP_5	TP_{10}	TP_{15}
PH First	First	PH	70.0%	91.5%	98.3%	99.6%
PH First	Second	NH	100.0%	100.0%	100.0%	100.0%
NH First	First	NH	63.0%	87.8%	97.0%	99.2%
NH First	Second	PH	77.0%	90.6%	97.0%	99.0%

Table 3.2: Percentage of fully learned state for various trials for each group and condition. TP_i is $TP(i)/TP_\infty$ using Eqn. 3.5.

does not make subjects learn faster, but they are able to learn the task quicker without passive haptics afterward. It does appear that the fully learned state is different between the haptic conditions, which is investigated further in the next sections.

Ballistic Movement Filtering

Before they could be used for the Fitts' Law analysis the trajectories were filtered so that only movements which were direct to target were included. A well-learned movement appropriate for Fitts' Law is one which moves directly towards the target and does not have much extranous movement or idle time beyond what is required to complete the task. A number of deviations from these well learned movements were observed in the dataset which we aimed to filter out for the final throughput calculations. We describe in this section the three metrics developed that were used to determine whether a movement was direct to target.

The first metric was the ratio of path distance travelled in the ballistic phase to the distance between the targets for that movement (i.e. 20cm, 30cm or 40cm). Ideally, the ballistic portion would cover the majority of the distance between the targets. A movement which covered too little of the target distance could mean the subject slowed or stopped in the middle of movement, and one that covered more could mean the subject overshot or had an indirect trajectory. A sample movement that gets flagged by this filter is shown in Figure 3.5, which has a ratio of 1.49. This is an example of a movement that does seemingly

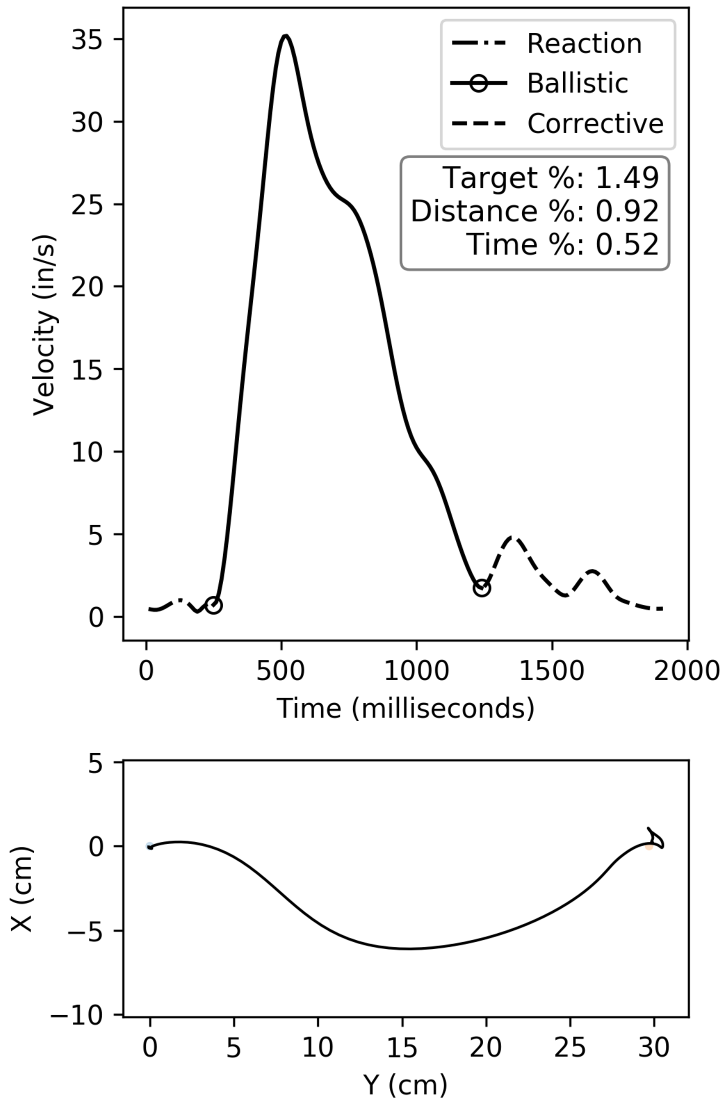


Figure 3.5: An example of a movement with a large ballistic distance to target distance ratio. The bottom plot shows the projection of the trajectory on the plane of the Fitts' circle.

have a direct movement toward the target, but includes a large deviation perpindicular to the movement axis. This deviation could mean the subject initially aimed their ballistic portion in the wrong direction but performed a correction during the movement. The limits for this filter were chosen as having a ratio between 0.90 and 1.10, i.e. within 10% of the target distance. This filtered out 4577 of the 17970 movements.

The second filtering metric was also based on the ballistic phase path distance. For this metric it was compared to the total path distance the subject travelled for their entire movement. This filter targetted movements where after the ballistic phase the subject moved away from the target, or had a smaller but significant movement before the main ballistic movement. An example is shown in Figure 3.6 which shows a movement which passed the first metric (the ballistic phase distance ratio to the target distance was 1.03), but the ballistic phase was only 56% of the total distance travelled during that movement. This was a common problem where a subject would have a false start and move towards the next target before their button press was activated. The threshold was set at 0.80 which has 4264 movements lower than the threshold, though only 1675 were unique from the target distance filter.

The last filter took a time based approach, and looked a the ratio of the time spent in the ballistic phase over the total movement time. This filter removed movements where the subject spent an inordinate amount of time either before or after the ballistic phase. If they were not moving during the non-ballistic phases, it would not have been caught by the distance-based filters either. The threshold of 0.40 meant that 4496 movements were filtered, however only 873 of those are unique of the other two filters. Figure 3.7 illustrates a movement where the subject waited before initiating the ballistic movement. Since the subject did not move during this idle time, the other two filters did not flag this movement.

The combination of these three filters led to 7125 of 18000 movements being filtered out, leaving 60% of the movements. For each of the metrics, the threshold was determined by investigating the distribution and looking at sample movements on either end of the threshold to determine if it was an approriate value.

The final check before performing the Fitts' calculation was to ensure that each trial had enough data for the adjustment for accuracy calculation. The adjustment for accuracy is based on the distribution of endpoint data from a single trial (which is one distance and width configuration). One trial consists of 30 consecutive movements, but the ballistic filtering could diminish the amount remaining in each, so a trial was only included if at least half (15 of 30) movements were considered to be good movements by the ballistic filters. This means that movements from a trial that did not have enough good movements were also filtered out from the Fitts' calculation. Not only is this important to make sure the adjusted width is valid, it also removes trials where the subject likely did not reach a fully

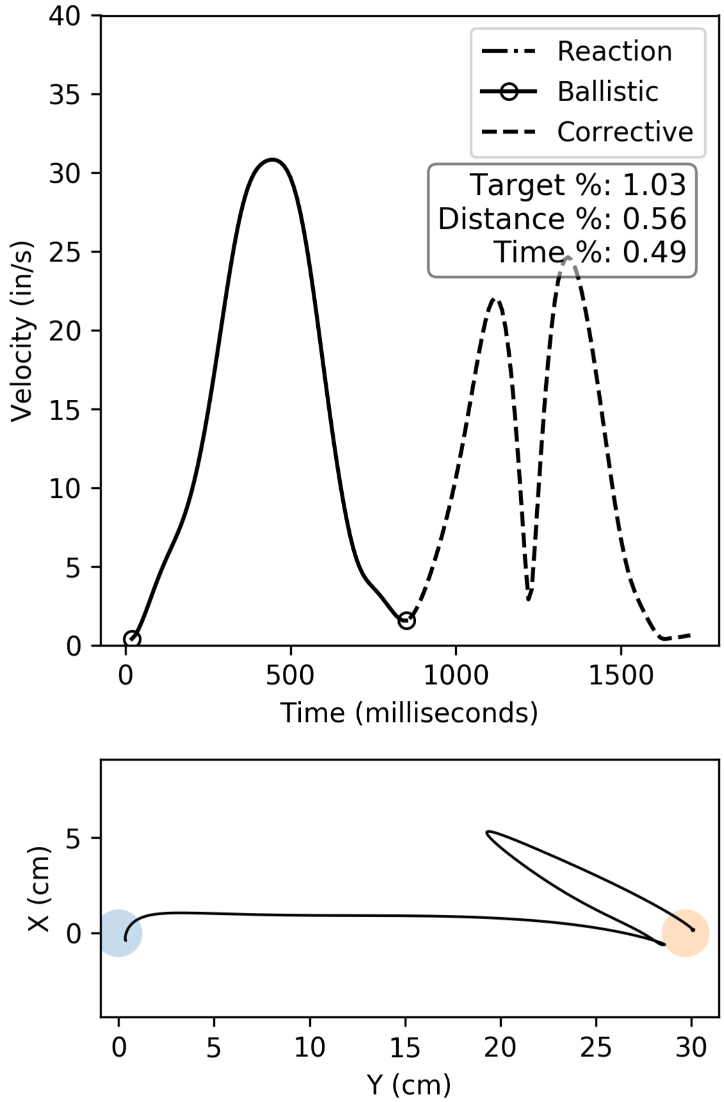


Figure 3.6: An example of a movement with a small ballistic distance to total path distance ratio. The bottom plot shows the projection of the trajectory on the plane of the Fitts' circle.

learned state, as most of their movements were not primarily ballistic movements direct to target. On average, 11 of 15 trials per condition from each subject ($M = 10.98, \sigma = 3.25$) had enough good movements to be included. This left 9218 movements for the Fitts' calculation, just over half of the total movements (51.3%). Slightly more movements were filtered from the No Haptics condition, with 47.1% of NH movements left after the filtering, compared to 55.5% of the PH movements.

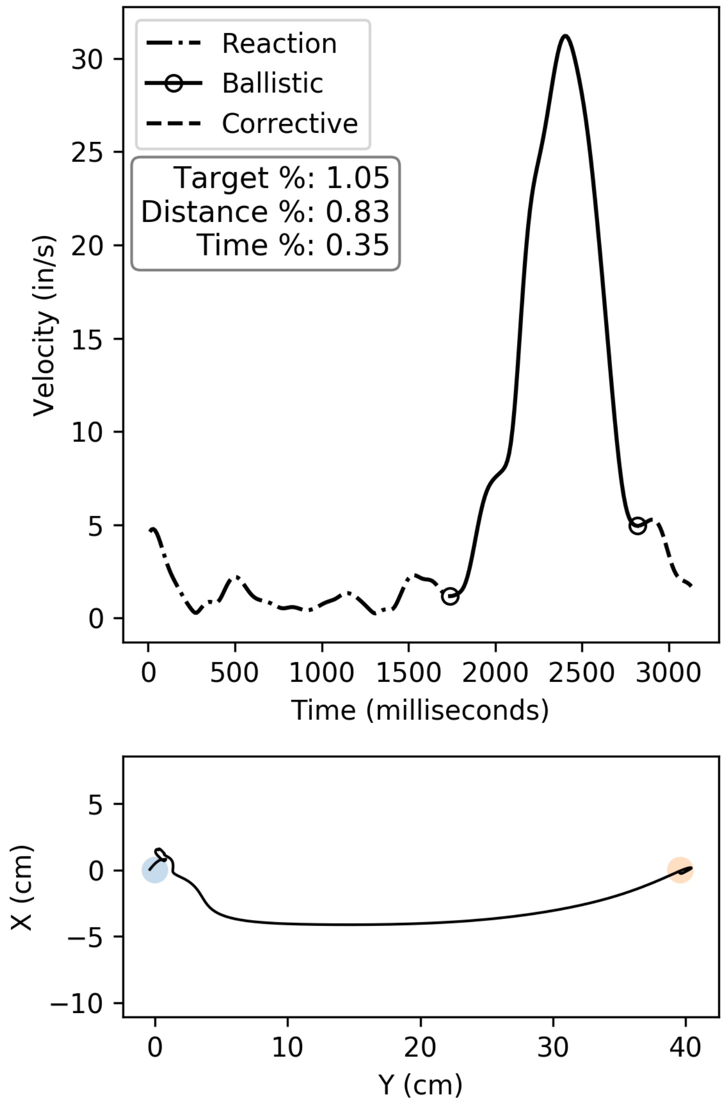


Figure 3.7: An example of a movement with a small ballistic time to total time ratio. The bottom plot shows the projection of the trajectory on the plane of the Fitts' circle.

Throughput

The throughput was found to be higher in the PH condition, at 4.25 bps compared to the 3.76 bps of the NH condition. A two-way mixed ANOVA was performed to determine the effect of haptics condition. Since we already expected order effects and have seen them with the transfer of training seen in the Rate of Learning section, the sequence the subjects performed the haptic conditions was a between subjects factor. The effect of haptics was found to have a significant effect on the throughput ($F(1, 18) = 35.59, p < 0.001$) between

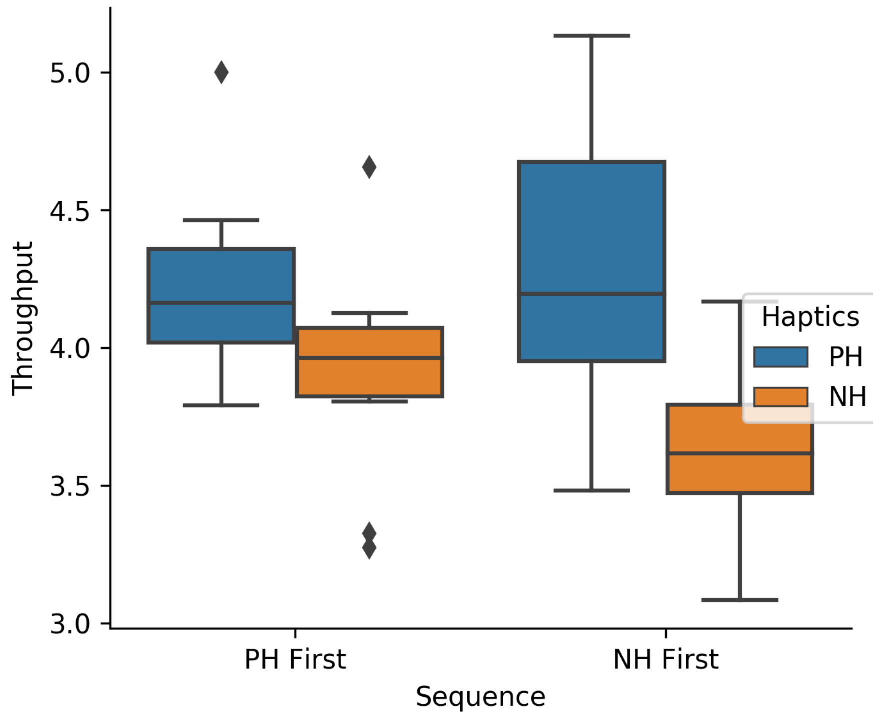


Figure 3.8: Throughput boxplot by haptics and sequence.

the PH condition ($M = 4.25, \sigma = 0.44$) and the NH condition ($M = 3.76, \sigma = 0.38$). There was no effect on throughput based solely on sequence group ($F(1,18) = 0.53, p = 0.47$), but there was a marginally significant interaction effect between the sequence and haptics ($F = (1,18) = 4.48, p = 0.048$).

As can be seen in Figure 3.8, this marginal interaction effect appears to indicate that both groups had improved performance but the PH First group performed better at the NH condition. The post-hoc repeated measures ttest between haptic conditions for the subjects who performed PH First was significant ($t(9) = 4.62, p < 0.001$), with the PH condition ($M = 4.23, \sigma = 0.34$) outperforming the NH condition ($M = 3.91, \sigma = 0.40$). The mean of the differences between subjects was 0.32 bps. The group of subjects who performed NH first also had a significant effect ($t(9) = 3.96, p < 0.001$) the PH condition ($M = 4.28, \sigma = 0.54$) and the NH condition ($M = 3.62, \sigma = 0.32$), with a higher mean of differences of 0.66 bps. These post-hoc tests confirm that both groups had a significant effect of haptics, though the NH First group had a larger difference between the conditions.

It is worth noting that without using the ballistic filter, the major conclusions

	Filtered		Unfiltered	
Haptics	Mean	SD	Mean	SD
PH	4.25	0.44	3.86	0.50
NH	3.76	0.38	3.25	0.37

Table 3.3: Throughput scores by haptics condition.

found do not change. The only major difference is the magnitude of the throughput and size of the differences. The statistical tests have the same results as well. The results by haptics for both filtered and unfiltered are shown in Table 3.3. These results indicate that subjects do have higher throughput with passive haptics, answering our first research question.

3.4.3 Trajectory Phases

As described in Section 3.3.5, each movement of the subjects can be dissected into three distinct phases: reaction time, ballistic phase, and corrective phase. We have already seen that, overall, the subjects took more time to complete a movement without the passive haptics in place with the results of throughput. In this section we investigate the differences in time spent in the three phases. We report here the means of time spent in each of the three phases. Times reported are all milliseconds. The results also include the filtered and unfiltered results, where the filtered results only include movements that were deemed purely ballistic by the filtering methods in Section 3.4.2. The unfiltered results include all movements. The phases were meaned per subject first, and then by condition. The time spent in each phase is listed in Table 3.4. Each phase was tested for the effect of haptics and sequence through a mixed two-way ANOVA.

The reaction time had no effect by haptics ($F(1, 18) = 0.32, p = 0.58$) or sequence ($F(1, 18) = 0.001, p = 0.98$). However, for the interaction between the two a significant effect was found ($F(1, 18) = 18.56, p < 0.001$). The interpretation of this interaction effect without main effect significance is that the first and second condition had a different reaction time, without dependence on the haptics condition or group. The mean reaction time in the first condition was 130.9 milliseconds ($\sigma = 41.0$), but in the second condition it was just over 20 milliseconds faster, with an average of 109.1 milliseconds ($\sigma = 36.6$). The reaction time for both conditions was lower than generally accepted values for reaction time to a visual or aural stimulus. This is not surprising, as the task was a serial task which the subjects would likely learn the pacing of throughout the experiment. They would learn to anticipate the activation of a button (which was also the start of the next movement) as it would activate 160 msec after the subject entered the zone of the previous button. In fact, this interaction effect tells us that subjects did learn how to anticipate the activation event independent of the haptics or the order they performed the seqeunces.

The ballistic phase time had a significant effect of haptics ($F(1, 18) = 24.14, p < 0.001$) between PH ($M = 772.6, \sigma = 67.7$) and NH ($M = 719.5, \sigma = 60.0$). There was no effect of sequence or the interaction effect between haptics and sequence. Since the ballistic phase should be mostly independent of the use of passive haptics, it was not expected to see the ballistic phase have an effect of haptics. It is unclear the exact mechanism that led to this, but it could likely be an artifact of the passive haptics causing the subjects to learn the movement, and thus allowing them to move quicker. There is little difference between the filtered movements and unfiltered movements results, the difference of the means were within a few milliseconds.

The corrective phase time also had a significant effect of haptics ($F(1, 18) = 22.46, p < 0.001$) between NH ($M = 256.6, \sigma = 42.1$) and PH ($M = 199.1, \sigma = 48.1$). There was no effect of sequence or the interaction effect between haptics and sequence. This result was expected as one of the main benefits of the passive haptics is that the subject does not have to 'find' the target along one dimension. There was a more noticeable difference between the results of the unfiltered and filtered movements for the corrective phase. The corrective phase time was much higher in both conditions, with PH having a mean of 564.7 ($\sigma = 253.6$) and NH having a mean of 837.2 ($\sigma = 293.2$).

		Filtered			Unfiltered		
		Mean	SD	p	Mean	SD	p
Reaction Time	PH	118.58	45.32	0.57	241.57	205.39	0.33
	NH	121.44	34.80		291.97	169.19	
Ballistic Phase	PH	719.54	59.99	< 0.001	679.48	44.79	< 0.001
	NH	772.57	67.62		727.53	60.01	
Corrective Phase	PH	199.13	48.10	< 0.001	564.73	253.56	< 0.001
	NH	256.58	42.08		837.22	293.15	

Table 3.4: Time in each movement phase by haptics conditions.

3.4.4 Arm Fatigue

The subjects were asked for a rating of their arm fatigue every other trial, as well as before the first trial and after the last trial of each condition. One trial lasted for 30 movements and consisted of a single distance and width configuration. The scale ranged from 6 to 20, and subjects were allowed to record decimal ratings. The full scale with anchors are shown in Appendix **??**. The average rating at each trial, seperated by haptics condition, is shown in Figure 3.9.

There is an evident difference between the two haptic conditions for the first condition performed, with the NH condition subjects accumulating more fatigue throughout the trials. At the end of the first condition, the subjects who performed the PH condition rated their arm fatigue 3.25 points lower on average than the NH condition subjects. Both groups have a similar rate of recovery, but the second condition quickly converges and shows no apparent difference between the two haptics conditions.

A within-subjects repeated measure (haptics) with two between-subjects measures (sequence and trial) ANOVA was performed to test the significance of haptics and the interaction effect of haptics and sequence. The interaction effect of haptics of sequence was found to be significant ($F(1, 18) = 22.6, p < 0.001$) as well as the main effect of haptics

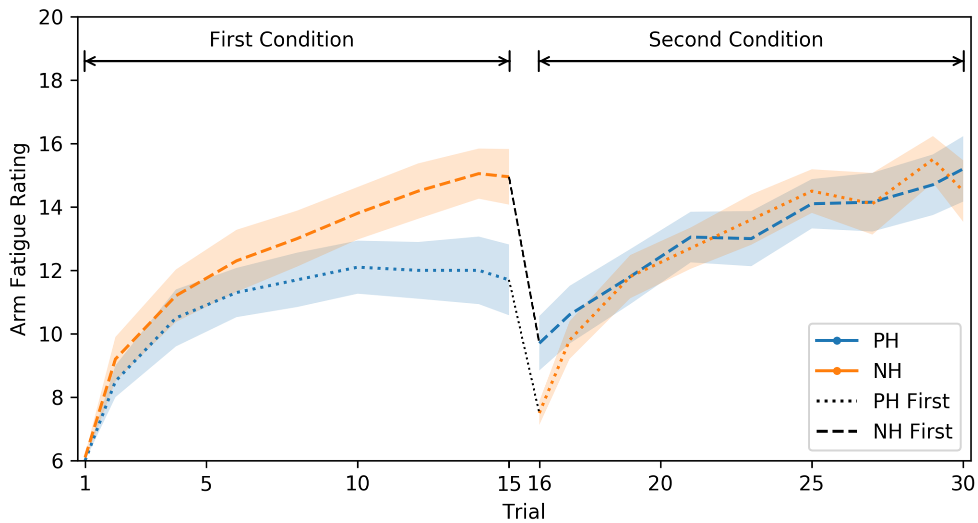


Figure 3.9: Arm Fatigue by Trial.

($F(1,18) = 5.47, p = 0.03$). As a result of the significant interaction effect, a post-hoc ANOVA with Haptics and trial as the two within subjects repeated measures was run on both sequence groups. The NH First group had no effect due to haptics ($F(1,9) = 2.08, p = 0.18$), consistent with the observations from Figure 3.9. The subjects rated the same trial between conditions an average of only 0.69 ($\sigma = 2.1$) points higher for the PH condition, which was their second condition. The PH First group did have a significant effect due to haptics ($F(1,9) = 42.37, p < 0.001$). This group rated the PH condition an average of 2.0 ($\sigma = 2.0$) points lower within trials. As expected, the effect of trial number was significant for all of these tests ($p < 0.0001$).

These results show that the subjects only had reduced arm fatigue using the passive haptics for the first condition. For all other conditions the arm fatigue ratings reached the same level by the end of the condition.

3.4.5 Presence

The presence survey was adminsistered after each haptics condition. The questions had a 7-point Likert scale response with anchors at either end and the middle. The score given in this section is a sum of the responses, on a scale of 1 to 7, where a higher score indicates higher presence. A few questions were asked with an inverted scale (i.e. a score of

Haptics	Score	Std. Dev	Cronbach's alpha
PH	77.7	9.56	0.718
NH	71.0	9.70	0.711

Table 3.5: Presence Score Summary

1 indicated higher presence) and were reversed before the score was calculated. The internal consistency of the presence questionnaire was tested per condition using Cronbachs' alpha, and was found to be consistent in both conditions ($\alpha = 0.72$ and $\alpha = 0.71$ for PH and NH, respectively). The full survey questions and average responses per condition are listed in Table 3.6. The item total correlation (the correlation between the questions' score and the total score) is also listed for each question.

The average scores per condition are given in Table 3.5. The presence scores were tested with a mixed within subjects repeated measures (haptics) and between subjects measures (sequence) ANOVA. The score had a marginally significant effect between Haptics conditions ($F(1, 18) = 6.08, p = 0.024$), with Passive Haptics having a slightly higher mean ($M = 77.7, \sigma = 9.56$) than No Haptics ($M = 71.0, \sigma = 9.70$). There was no significant effect of Sequence ($F(1, 18) = 4.01, p = 0.58$) nor for the interaction effect between Sequence and Haptics ($F(1, 18) = 0.71, p = 0.41$).

3.4.6 Condition Comparison

The condition comparison survey asked the subjects five questions directly comparing the two conditions. A summary of their answers are shown in Table 3.7. The subjects overwhelmingly responded that they preferred the Passive Haptics (PH) condition (Q5), with all but two subjects choosing it. In fact, no subject preferred the No Haptics (NH) condition, the two subjects who did not choose PH responded that neither was more preferred.

The other questions had responses similar to the results from the other sections. The majority of subjects responded that they were more accurate and faster in the PH condition (Q1 and Q2), which agrees with the throughput results. The subjects who chose

Question	NH		PH	
	Score	ITCorr	Score	ITCorr
1. How much were you able to control events?	4.8	0.59	5.3	0.74*
2. How natural did your interactions with the environment seem?	4.3	0.45	5.0	0.81*
3. How much did the visual aspects of the environment engage you?	5.4	0.36	5.3	0.65
4. How much did the auditory aspects of the environment engage you?	6.2	0.32	6.0	0.19
5. How much did the tactile (sense of touch) aspects of the environment engage you?	2.6	0.31	5.6	0.53
6. To what extent did you associate the computer generated arm and hand with being "your body" while in the virtual environment?	4.5	0.35	5.0	0.65
7. How natural was the mechanism which controlled movement through the environment?	4.0	0.48	4.5	0.72*
8. How much did your experiences in the virtual environment seem consistent with your real-world experiences?	4.0	0.49	4.5	0.66
9. How involved were you in the virtual environment experience and the task you were performing?	5.8	0.50	5.8	0.22
10. How distracting was the control mechanism?†	4.0	0.52	4.7	0.29
11. How much delay did you experience between your actions and expected outcomes?†	4.7	0.38	4.9	0.04
12. How quickly did you adjust to the virtual environment experience?†	2.9	-0.08	2.1	-0.31
13. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	4.9	0.65	5.2	0.25
14. How much did the control devices interfere with the performance of assigned tasks?	4.0	-0.40	4.0	-0.45

Question	NH	Neither	PH
Q1. In which condition did you feel you performed faster?	1	1	18
Q2. In which condition did you feel you performed more accurately?	3	2	15
Q3. Did you feel that your arm fatigued more or quicker in one condition over the other?	13	3	4
Q4. Did you feel that you were actually in the virtual room more in one condition over the other?	3	4	13
Q5. Which condition did you prefer?	0	2	18

Table 3.7: Condition comparison survey summary of results.

Neither or NH were usually not actually faster or more accurate in the NH condition. In fact, only two subjects had a throughput that was higher in the NH condition, and neither subject chose NH as the condition they performed faster in, though one did say they performed more accurately in the NH condition.

Question 4 asked subjects directly about their feeling of presence, and 13 subjects chose PH, with the remaining split between 4 saying neither and 3 saying NH. The results of the presence questionnaire suggested that subjects felt more present with the passive haptics, which this agrees with. The arm fatigue question (Q3) was worded to ask which condition they felt provided more or quicker arm fatigue, and 13 subjects felt this was the case with the NH condition. The remaining were split between neither (3) and PH (4). The results of the arm fatigue questionnaire during the experiment found a similar result as the condition comparison survey.

3.5 Discussion

- time of each button press
- trajectory information for filtering
- arm fatigue rating every other circle
- presence questionnaire after each condition
- condition comparison questionnaire at end of experiment
- naive button registration
- arm fatigue not validated

3.6 Conclusion

Chapter 4

Design Evaluation Experiment

4.1 Introduction

The final experiment combines the lessons of the previous experiment to investigate the use of the Rapidly Reconfigurable Research Cockpit (R3C) in a design evaluation study. The goal of this experiment is to determine if the R3C system can be used in the place of a more traditional evaluation tool. As previous chapters have discussed, there are a number of self-evident advantages to using the R3C system. However, there remain some technical limitations to the technology that could hinder adoption. We found that a button targetting task took more time in our virtual environment than in the real world (Chapter **??**). The following experiment (Chapter 3) found that a Fitts' Law task produced a higher throughput using a passive haptics layer, mitigating some of the time increase of targeting buttons in a cirtual environment. In the experiment described in this chapter, we used the R3C system as the simulation tool for a design evaluation study of a cockpit instrument. The purpose in undergoing this evaluation study is to understand if these limitations would interfere with the metrics that might be used in evaluating a new cockpit design.

We designed an experiment which asks for feedback from subjects who take the role of design evaluators for a cockpit instrument. The subjects were divided into two groups: one group used an R3C setup to operate the instrument, while the other used a more traditional setup: a touchscreen simulator of the instrument. This seperation of groups will allow a comparison of the feedback from subjects between groups. Both groups

Figure 4.1: Simulator Workstation

evaluated the same two instrument designs, and subjects were asked to provide feedback using the same questionnaires. We hypothesize that the R3C system could be used in place of a traditional simulator if the two groups provide similar responses to the designs. Additionally, we utilized common quantitative metrics to evaluate performance to determine if the conclusions that would be drawn from these change between groups.

4.2 Methods

4.2.1 Simulator Setup

The simulator workstation as configured for each group is shown and annotated in Figure 4.1. It was designed to have as much as possible to be the same between the two configurations. The joystick and instrument were positioned in the same location for each group. Neither group had out the window visuals, relying only on the attitude indicator on the instrument. For the Virtual Reality (VR) group, the visuals showed a plain interior of a cockpit, but the out-the-window view was black. Both groups had an aural indication (a click noise of a button being pressed) when a button was activated on the instrument, using the speakers mounted behind the instrument panel.

Beyond the VR group using a virtual reality headset for the visuals, the main difference between the two groups was the method for pressing the buttons on the instruments. The VR group used the hand tracker activated system previously described in Chapter chapter 2. For this experiment, the buttons were configured to highlight a blue color when the hand tracker registered a finger within the zone. The zones were extended 0.1in around the border of the button, raised a height of 0.5in above the surface of the button. When the button was activated after the 150 millisecond delay, the highlight would disappear and the button in the virtual world would move inwards as if it were being pushed in[1], the press sound would play, and the behavior on the instrument associated with pressing that button would occur. A separate release sound would play when the finger left the zone after a

[1]Of course, the physical button could not and did not move.

successful press, and for the VR group the button would move back to its starting position.

The Touchscreen (TS) group used a 10.1 inch capacitive touch screen with resolution of 1024x600. The active area of the screen was 8.8in by 5.1in, with outside dimensions of 10.4in by 6.7in. The two instruments were rendered in a web browser using standard HTML elements. Javascript press and release events were used to simulate the same behavior as described for the VR group, except for the highlighting before a button press. The visuals of the tracker were rendered on top of the browser window with the same OpenGL rendering code used for the VR group.

4.2.2 Task Design

Based on the technology available for the simulator base, a number of requirements were laid out that would guide the design of an appropriate task and instrument designs. The instrument and task required:

- Flight task using a standard joystick
- Additional task that requires use of multiple buttons on the instrument
- Able to develop simulator for both touchscreen and R3C setup
- Able to design two different layouts with one design having distinct flaws
- Simple design, yet complex enough task to have sufficient workload
- Operationally relevant tasks analogous to those required in a cockpit

Ultimately, we designed a task that required number and letter inputs using the buttons, while simultaneously flying a pitch disturbance profile.

Tracking Task

The tracking task display was a standard attitude indicator display, shown in Figure 4.2. Each tick corresponds to 1 degree in the dynamics simulation, with major ticks at intervals of 5 degrees. The attitude indicator was rendered to the size of 3.4 inches

Figure 4.2: Attitude Indicator Display

square on the instrument. Subjects controlled the one-dimensional (pitch only) task using a joystick with their left hand. The joystick is pictured in Figure 4.1.

The flight dynamics model of the simulator was a stability derivative based model for a Boeing 747 in low altitude flight. The block diagram of the dynamics is shown in Figure 4.3. The dynamics model was updated and recorded at a rate of 125Hz. The output of the joystick, r_{js}, varies from -1.0 to 1.0, and the gain of $10°$ was chosen to ensure the pilot had enough control authority to complete the task. The flight condition is listed as "Flight Condition 2" in NASA CR-2144[7]. This dynamics model was chosen due to availability. The specifics of the dynamical model were not important other than providing a response similar to an aircraft in flight. The model was linearized from sea-level flight at an airspeed of 335 ft/s. The configuration of the airplane had the gear up, no flaps, total weight of 654,000 lbs, and an angle of attack of $7.3°$. The transfer function of the aircraft dynamics is given as:

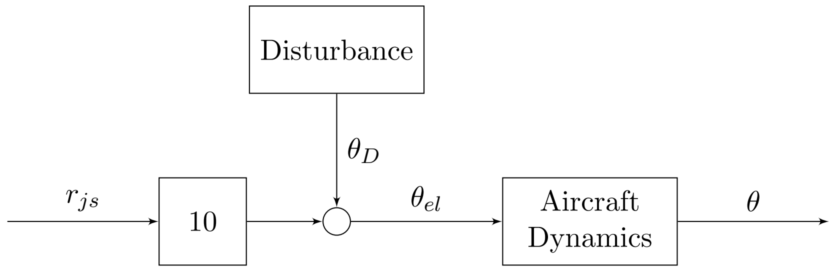


Figure 4.3: Tracking Task Dynamics Block Diagram

$$\frac{\theta}{\theta_{el}} = \frac{-0.572(s+0.553)(s+0.0396)}{(s^2+2\zeta_1\omega_1+\omega_1{}^2)(s^2+2\zeta_2\omega_2+\omega_2{}^2)} \tag{4.1}$$

$$\omega_1 = 0.0578 \qquad \zeta_1 = 0.0160$$

$$\omega_2 = 1.12 \qquad \zeta_2 = 0.798$$

The disturbance model is based off the model developed in SweetRef[**?**]. It is designed to provide a broad spectrum of frequencies that the human controller needs to respond to. The disturbance is a sum of sines described by:

$$\theta_D = K\sum_{i=1}^{12}\left[a_i\left(\frac{2\pi k_i}{240}\right)\sin\left(\frac{2\pi k_i}{240}t+\phi_i\right)\right] \tag{4.2}$$

The k_i terms are given as,

$$k_1 = 7, \qquad k_2 = 11, \qquad k_3 = 16$$

$$k_4 = 25, \qquad k_5 = 38, \qquad k_6 = 61$$

$$k_7 = 103, \qquad k_8 = 131, \qquad k_9 = 151$$

$$k_{10} = 181, \qquad k_{11} = 313, \qquad k_{12} = 523$$

The amplitude terms are $a_i = 0.5$ for $i <= 6$ and $a_i = 0.05$ otherwise. The phase terms, ϕ_i, were randomly selected on the $(-\pi, \pi)$ interval ensuring a uniform distribution. This random selection was pre-calculated for each trial, however the order was repeated for each subject so there was no between subject variance in the disturbance signal. Furthermore, each subject received the same sequence of disturbance signals for each instrument design. The disturbance amplitude, K, was chosen such that the root-mean square (RMS) of the signal was 3.5 degrees. The value of the was chosen through pilot studies to ensure the task was challenging but not overwhelming.

Prompting Task

The prompting task was designed to be both a realistic task for a cockpit as well as a demanding task when done in addition with the tracking task. The task developed required the subjects to read and memorize a short string of characters and enter it back using the buttons on the instrument. To limit the task physically (by number of buttons) and mentally, the characters used were the number 1 through 6 and the letters A through F. The prompts were 4 characters long and once the subject started entry the prompt would disappear, forcing them to hold it in short term memory.

The sequence of the prompts was separated into 10 second "windows". The prompt would appear randomly between 2 and 3 seconds of the start of the window. From the time of appearance, subjects were given seven seconds until timeout. When the subject pressed the first button of the prompt, the prompt itself was cleared and asterisk symbols ($*$) were shown in place of the prompt for each button entry by the subject. If the subject ran out of time, the text in entry area would return to black. Although subjects were briefed on the timeout and given practice to learn the pace, no warning or indication of time left was shown during the trials. Whether they completed the prompt within the time limit, or they timed-out, this process was repeated every 10 seconds. This meant that subjects had at least 3 seconds of time with no prompt.

The prompts themselves were always composed of three numbers followed by a letter or three letters followed by a number. This structure was decided upon to provide a consistent pattern, yet still utilize both letters and numbers in every prompt. The prompts were randomly chosen but were not allowed to have repeat numbers or letters. The selection of letters or numbers as the first three characters was randomly chosen as well, with an equal weight to each.

4.2.3 Instrument Designs

The two different designs used were developed to be both realistic as a cockpit instrument design that would be under consideration, yet still have one design with flaws that would be found in a design evaluation. We developed a ‘Keypad’ design with the prompting task button keys on the right side and the tracking task on the left, and an ‘Edgekey’ design with the prompt buttons split on either side of the tracking task display. The tracking task display was the same size on the display for both designs. The prompting task text was placed below the tracking task display, and the same font, size and color was used for both designs. The prompting task text font was approximately 0.62in tall. These were kept consistent to limit the number of possible variables between the two designs. The prominent difference is the placement and behavior of the buttons which is described in this section.

The Keypad design is pictured in Figure 4.4. The buttons are 1in by 0.75in, with about 0.26in between buttons horizontally and 0.38in vertically. Each button has the label directly on the top of the button. The 3D-printed instrument used for the VR group had the buttons raised a height of 0.31in from the surface of the instrument. The button labels were also raised to provide a tactile feedback. The font was approximately 0.36in tall, and the labels were embossed above the button surface 0.05in.

The Edgekey design is pictured in Figure 4.5. In this design, there is not a single button for every number and letter. Instead, the bottom button on either side would switch the behavior (and labels) of the remaining six buttons from being 1 through 6 to A through F. In other words, the bottom “switching” buttons would change the rest of the buttons from the numbers to the letters, and vice-versa. The labels were placed offset from the button on the “screen” portion of the instrument, allowing them to change dynamically. The fonts were approximately 0.32in tall, and were blue on the screen. The buttons are slightly smaller in this design, at 0.76in by 0.55in. A smaller button size was needed to fit the labels and the buttons side by side. The spacing between buttons vertically is the same as the Keypad design at 0.38in. The center to center distance between the two sides of the button rows is 7.3in. The 3D-printed instrument version had raised nubs on each

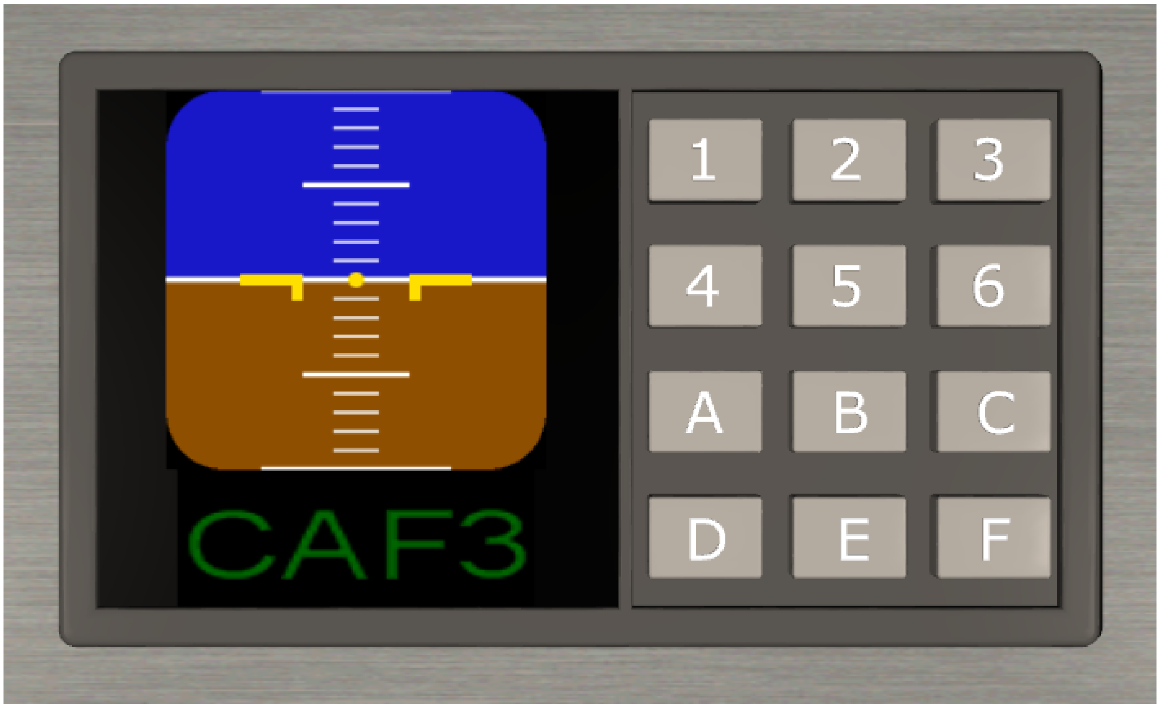


Figure 4.4: Keypad Design

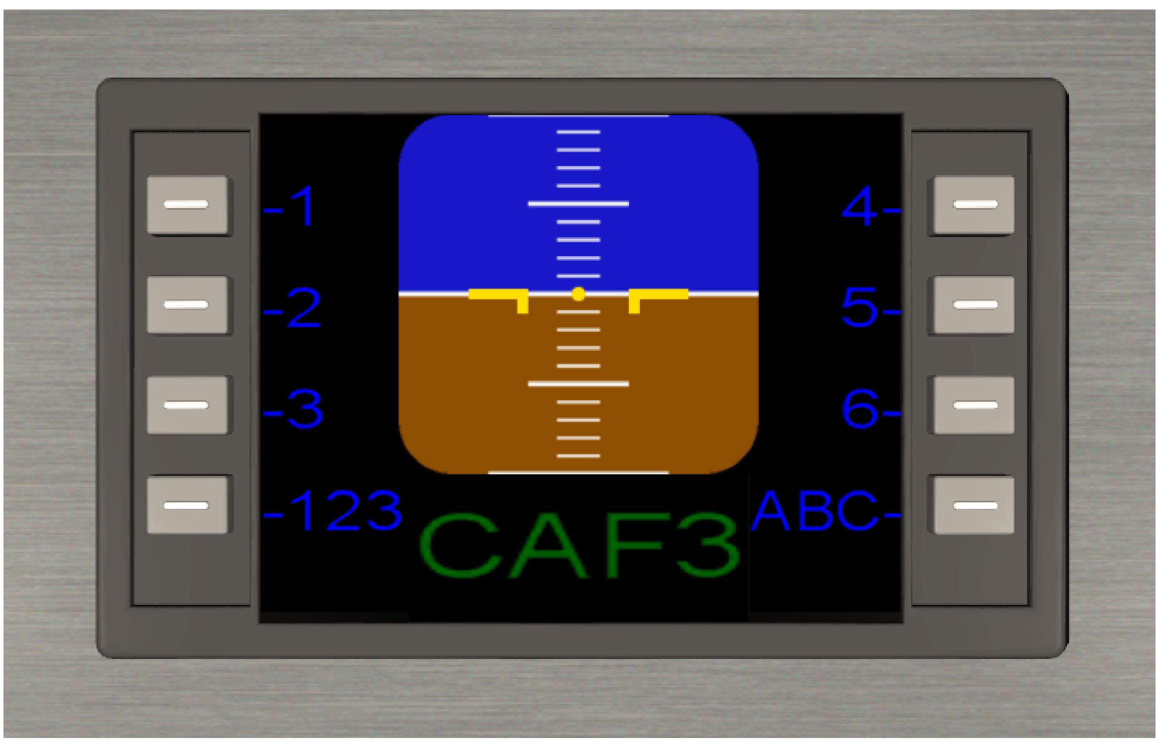


Figure 4.5: Edgekey Design

button covering half the width, 0.08in tall and raised 0.05in. As with the Keypad design, the buttons had the same height of 0.31in from the surface.

While some of the more subtle differences were expected to be noted by the evaluation study (e.g. having smaller buttons, different position of the flight task), the major flaw designed into the Edgekey design was the switching key to change from letters to numbers and back. This additional action fundamentally changed the demands of the task, as the subjects now had to press this additional button to change labels at least once per prompt. The cognitive workflow of the subject is diagrammed in Figure 4.6. The additional mental effort of the Edgekey design is shown in the dashed box, where the subject has to verify the state of the instrument and possibly press the switch button before they press the buttons of the prompt. Since the prompts were kept as a consistent format of three of the same type and fourth of the other, this extra work was easily skipped for most buttons, and anticipated between the third and fourth button. There was no guarantee that the next prompt would start with the instrument in the correct state for the new prompt, so there was always an additional cognitive load in determining whether a switch was necessary at the beginning of the prompting window, which would be accompanied with the physical effort if the switch was needed.

4.2.4 Experiment Design

Subjects were divided into the two groups, Touchscreen (TS) and Virtual Reality (VR). The overall sequence of the experiment started with a training session on the simulator and the task, followed by an evaluation session for each of the two designs, finishing with questionnaires asking subjects to evaluate the two designs. The timeline of the experiment was the same for each subject, except for counterbalancing the order that the designs were evaluated. The training portion started with a slide deck explaining the tasks, the simulator that the subject was using (depending on which group they were in), and the functionality of the two designs they were to evaluate. Next, they performed practice trials with just the tracking task and then just the prompting task. The practice trials of the tracking task were 60 seconds long and repeated until the subjects' performance had flatlined. This took between three to six trials for each subject.

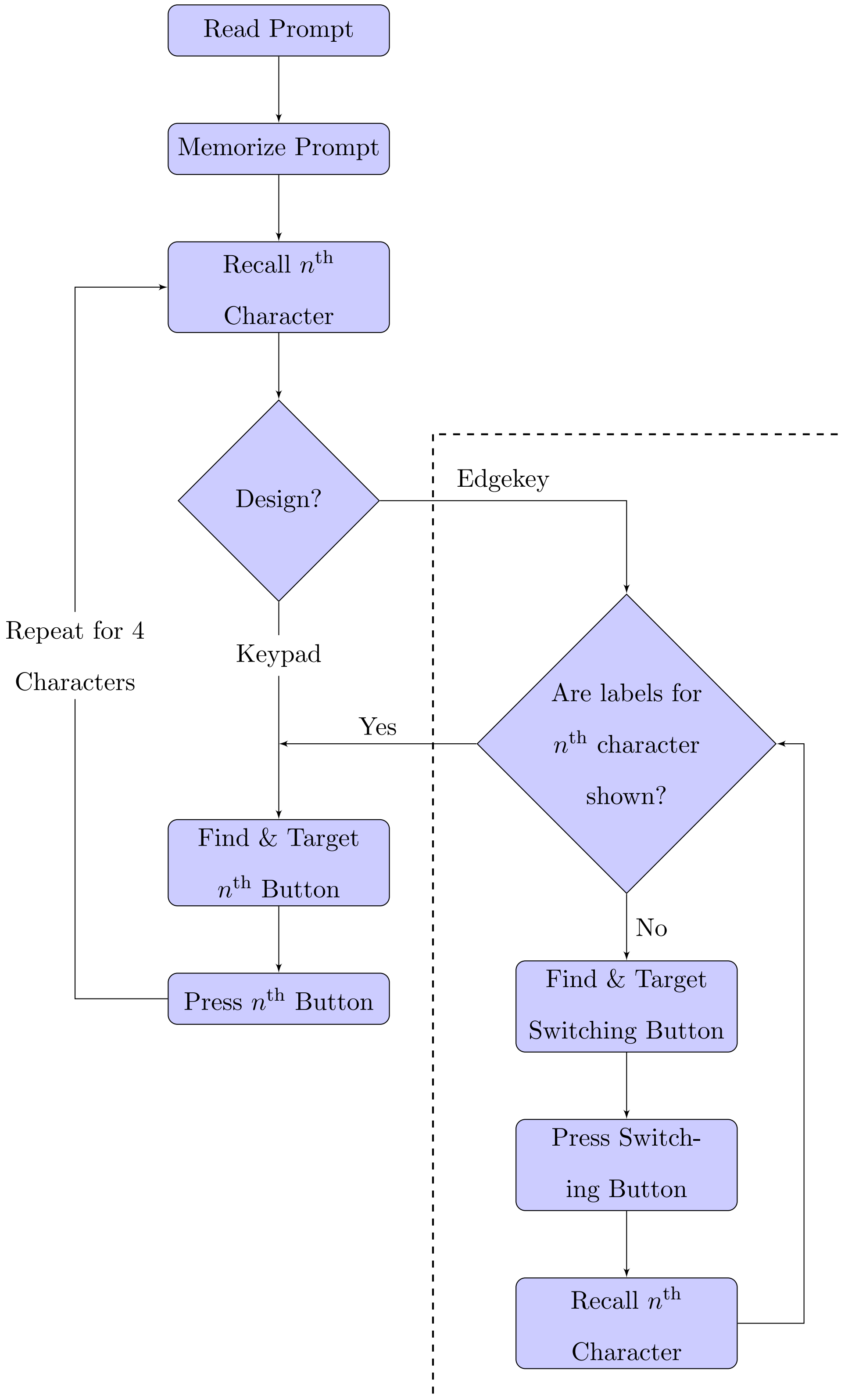


Figure 4.6: Prompting Task Flowchart of Cognitive Work for Each Design. Extra work of Edgekey design encolsed in dashed line box.

For the evaluation sessions with each design, they performed six trials with both tasks. The first three were a minute long, and were considered practice trials, and not included in the data analysis, though this was not communicated to the subjects. The following three trials were two minutes each, and were used for the analysis. Each evaluation session concluded with a two minute trial of just the tracking task without the prompting task. This was included to investigate if the subject had improved or fatigued at the tracking task throughout the experiment.

The independent variables of the experiment are Group and Design. The Group is the simulator the subject used, a between subjects factor, and either TS or VR. The Design is a within subjects factor, the two instrument designs that every subject evaluated — Edgekey and Keypad.

4.2.5 Dependent Measures

The dependent measures were chosen to evaluate the performance of each task individually as well as the workload of the subject. For the tracking task, the root-mean square error (RMSE) was calculated for each trial. The error in this case is simply the pitch shown to the subject, the output of the flight model described in Section 4.2.2.

The prompting task has two dependent measures, for speed and accuracy. For speed we consider the *response time*, defined as the time between when the prompt is first shown to the subject and when they press the first button of their response entry. The accuracy is measured by how many prompts they complete correctly. Twelve prompts are shown to the subject within each trial. The response time was meaned per trial first and then per design for each subject, and the number of correct prompts is meaned per design for each subject.

A NASA Task Load Index (TLX) survey was administered after they completed each design to measure the workload of the subject. The TLX survey asks for a rating of their workload between 0-100 for the following subscales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. Our implementation allowed selection of the ratings within increments of 5, and included anchors of "Low" and "High" at the extrema of 0 and 100, respectively (except for Performance, which uses

"Good" and "Bad"). The midpoint was also visually indicated with a larger tick. The ranked pairs modification was used and completed for both times the subject took the survey. This modification asks the subject, for each of the pairwise combinations of subscales, which they felt contributed more to their workload. The number of times they select each subscale is used a weight to calculate a weighted mean for the total TLX score.

Finally, the subjects were given a questionnaire asking for their feedback on each instrument design. For each design, the subjects were asked the following questions:

- Please comment on any difficulties you had performing the prompting task with this design especially in contrast to the other design.
- Please comment on anything you liked in this design.
- Please comment on anything you did not like in this design.
- Any other comments?

Additionally, the following questions were asked:

- Which instrument design did you prefer? Why?
- Did you experience any physical fatigue during the experiment? Where?
- Any other comments?

An open form text box was used for the response field for each of these questions.

In a standard design evaluation study, the feedback received from the users in this questionnaire (and other debriefing interviews) would often be the main source for carrying out re-design. The purpose of this feedback in this experiment is to determine and document in which ways does this feedback differ. For example, if most subjects in one group noted issues with the size of a button, while no one in the other group found an issue with that button, this would indicate that using this VR system may not highlight the same issues regarding button sizes. The groups were purposely left ambiguous in the example, as it does not matter which group found the flaw and which group did not comment on it. Although we could postulate as to which group are "correct" in their evaluation of the instrument, it is not a useful exercise, as the only result is to document what potential differences could arise so that users of this system can be aware.

With that goal in mind, the analysis of the feedback questions seeks to find differences between the groups. The sentences from the open form responses were first separated into single feedback comments, and summarized using common language. If a single subject repeated the same comment in the answers to multiple questions, they were only counted once. Each of these simplified feedback comments were assigned to a category or overall summary of their feedback. This process was completed separately for each group. We aim to look for feedback that is unique to a certain group or feedback that receives a higher frequency of comments in one group. This will provide a summary of where the groups provide the same feedback and where they provide differing feedback.

4.2.6 Hypotheses

The main hypothesis of this experiment is that the use of a VR/R3C simulator will not affect the conclusions of a design evaluation study, compared to a traditional touchscreen simulator. We do expect that some of the dependent measures may have a significant difference in Group or a significant difference in Design. The more important measure for us, however, is the interaction effect. This will test if the change between Designs is similar for the two Groups. If this is the case, then it may indicate that an evaluation study using one of these simulators could draw differing conclusions of an evaluation study using the other. Statistically, we will test the hyptothesis that there exists no interaction effect between Group and Design for any of our dependent measures.

Additionally, the two tracking only trials performed at the end of each evaluation session, as well as the final tracking only training trial, will be used to investigate if the subjects were still learning the tracking task. The concern if subjects became more trained in the tracking task is that it could lower their attentual needs to that portion of the task, causing a change in performance on the prompting task that was not due to the design change. These hypotheses are enumerated here:

H1. The tracking task RMSE will have no interaction effect between Group and Design

H2. The prompt response time will have no interaction effect between Group and Design

H3. The number of correct prompts will have no interaction effect between Group and Design

H4. The NASA TLX scores will have no interaction effect between Group and Design

H5. The tracking task RMSE for the last training trial and the tracking only trials will not change throughout the experiment

4.2.7 Statistical Tests

The quantitative dependent measures are tested with a two-way ANOVA, with one within subjects factor (Design) and one between subjects factor (Group). The Design factor contains two levels, the two designs each subject tested, Edgekey and Keypad. The Group factor also contains two levels, the VR (Virtual Reality) group and the TS (Touchscreen) group. When the ANOVA showed significance in the interaction test, post-hoc repeated measured t-tests were undertaken to determine the significance of Design within each Group. Independent samples t-tests were used to test the significance of Group within each Design. The last hypothesis testing the effects of learning on the trials with only the tracking task will be tested with a two-way ANOVA, with the Group as a between subjects factor, and the trial number as a within subjects factor. The trial number is chronological in the order the subjects performed them. The first trial was the last tracking only training trial, and the next two were tracking only trials at the end of each design evaluation.

Statistical significance level was corrected using the Bonferroni correction considering the 5 hypotheses being tested. All effects were considered statistically significant at the 0.01 level ($\alpha = 0.05/5 = 0.01$). Effects which have a significance level between $0.05 < p < 0.01$ are considered to be marginally significant.

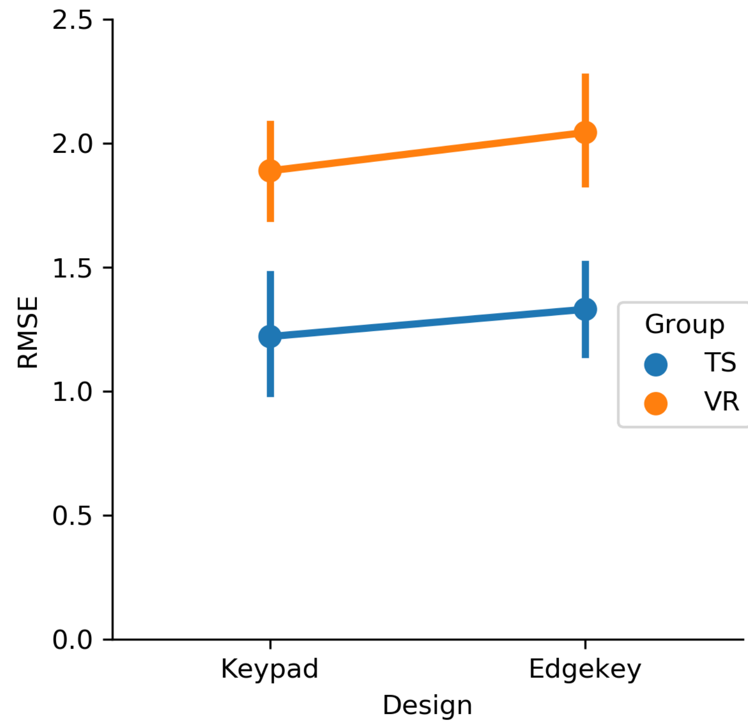


Figure 4.7: Factor Plot of RMSE

4.3 Results

4.3.1 Demographics

Twenty-three subjects were recruited from the UC Davis engineering undergraduate and graduate student population. Twelve subjects were placed in the VR group, and the remaining eleven in the TS group. The mean age was 21.0 ($\sigma = 3.14$), with 19 male and 4 female subjects. The genders were balanced between the two groups. Most subjects had no flight experience (two were student pilots), and all of the VR group subjects indicated that they had less than one hour of experience using virtual reality headsets. It should be noted that the subjects are not the beneficial population of the research. The task and experiment was designed with this in mind and mitigated through training and the simplicity of the task design.

4.3.2 Performance Measures

Tracking Task RMSE

The performance of the tracking task was measured using the root-mean square error (RMSE) of the pitch. The effect of Group yielded an F ratio of $F(1, 21) = 21.4, p < 0.001$ indicating a significant difference between VR ($M = 1.28\text{deg}, \sigma = 0.38\text{deg}$) and TS ($M = 1.97\text{deg}, \sigma = 0.38\text{deg}$). In both groups, subjects were performing the tracking task using the same joystick. The most direct factor that could contribute to the decreased performance in the tracking task for the VR group is the loss of visual acuity in the tracking task display due to the technical limitations of the VR head-mounted display. Indirectly, the additional workload of the prompting task could be taking attention away from the tracking task. The effect of Design indicated a marginally significant difference ($F(1, 21) = 5.94, p = 0.024$) for the tracking task RMSE between Keypad ($M = 1.57\text{deg}, \sigma = 0.51\text{deg}$) and Edgekey ($M = 1.70\text{deg}, \sigma = 0.52\text{deg}$). The only change in the tracking task display between the two instrument designs is a small change in position. It moves from being on the left side for the Keypad to the middle for the Edgekey. Since there was no change otherwise, this suggests that any difference on the tracking task performance between the designs would be related to additional workload from the prompting task. The interaction effect was not significant ($F(1, 21) = 0.17, p = 0.69$).

We can investigate the trials where the subjects were only doing the tracking task to further investigate the change in performance between the two groups. The subjects ran a single trial that was just the tracking task without the prompting task at the end of each evaluation session. These trials were included to be used as a test of the assumption that the subjects were no longer learning, but can also be used as a test of the Group factor on the tracking task performance. The effect of group on RMSE for the tracking-only trials yielded a marginally significant difference ($F(1, 21) = 4.81, p = 0.039$) between the VR Group ($M = 1.32, \sigma = 0.50$) and the TS Group ($M = 0.91, \sigma = 0.43$). There was no significant difference for the effect of design ($F(1, 21) = 0.068, p = 0.80$). The interaction effect between group and design was also not significant ($F(1, 21) = 3.21, p = 0.087$).

Although the tracking only trials found a marginally significant difference for the

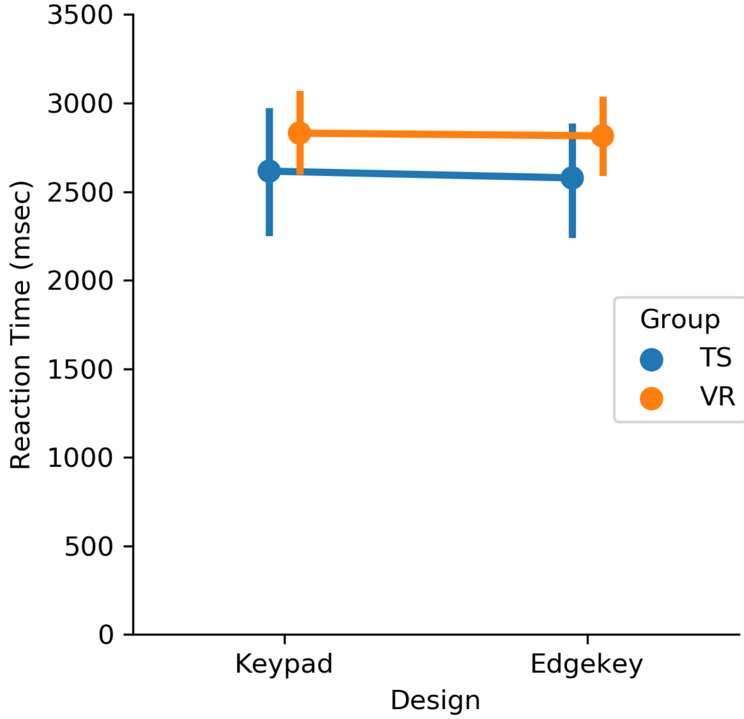


Figure 4.8: Factor Plot of Response Time

group, the difference was much more distinct for the trials with both tasks. This indicates that when the subjects were focused on the single task, they were able to mitigate most of the visual resolution differences between using a touchscreen and the virtual reality screen. Additionally, the marginally significant difference between the designs for the trials with both tasks was reduced to no significance when the additional prompting task was removed. This also points to the additional workload of the prompting task causing a performance drop on the tracking task. The factors leading to the added workload of the prompting task are investigated in the next performance measures discussed.

Prompt Response Time

The first measure of the prompting task is the response time of the subject. The response time is defined as the time from the prompt is shown to each subject until they press the first button of the prompt. For the Edgekey design, it would be possible that the subject had to start with the switching button if the new prompt did not start with the same mode (letters or numbers) as the previous prompt (see Figure 4.6). Since this button would not clear the prompt when it was pressed, it is not considered the first button of their entry. However, this would still require an additional movement of the subject, adding additional time. For this reason, the prompts which required the subject to start with the switch key are filtered out of this analysis. After filtering, 885 of the total 1700 prompts recorded for the Edgekey design were kept.

The response time was unique among the dependent measures, as all tests were insignificant. The effect of group yielded an F ratio of $F(1, 21) = 1.19, p = 0.29$ indicating no significant difference between VR ($M = 2812\text{msec}, \sigma = 383\text{msec}$) and TS ($M = 2594\text{msec}, \sigma = 567\text{msec}$). One factor that could influence the response time between groups is the additional time to activate a button in the VR environment versus the touchscreen. The touchscreen subjects were using a familiar interface for activating the buttons, while the VR subjects needed to activate the button with the virtual hand. However, a large portion of the response time for the subject is their cognitive processing of the prompt – recognizing the new prompt has appeared, reading it, then memorizing it. Beyond potential differences in the visual environment, the cognitive portion should not take more time for one group or the other. A potential reason that there could be a lower than expected difference between the group means is that some VR subjects learned to keep their hand closer to the instrument so that the hand tracker could keep it in view. When the hand tracker lost view of the hand, the re-acquisition time could be significant, so holding it close to the instrument would prevent this from happening. This issue comes up again when looking at the subjects' response to questions about fatigue.

The effect of design was also insignificant ($F(1, 21) = 0.68, p = 0.42$) between Keypad ($M = 2728\text{msec}, \sigma = 512\text{msec}$) and Edgekey ($M = 2687, \sigma = 471\text{msec}$). The biggest difference between the two designs is the switching key on the Edgekey design. As described above, the need for an additional switch press before the first prompt button was filtered out, so we are only comparing prompts where the first button was available right away to the subject. Even though the physical requirements were filtered out, subjects still need to verify that the labels are in the correct state for starting entry. Since the Edgekey design had more time pressure due to the need for the switch key, subjects could have learned to respond quicker to adapt for this. However, these differences in the design did

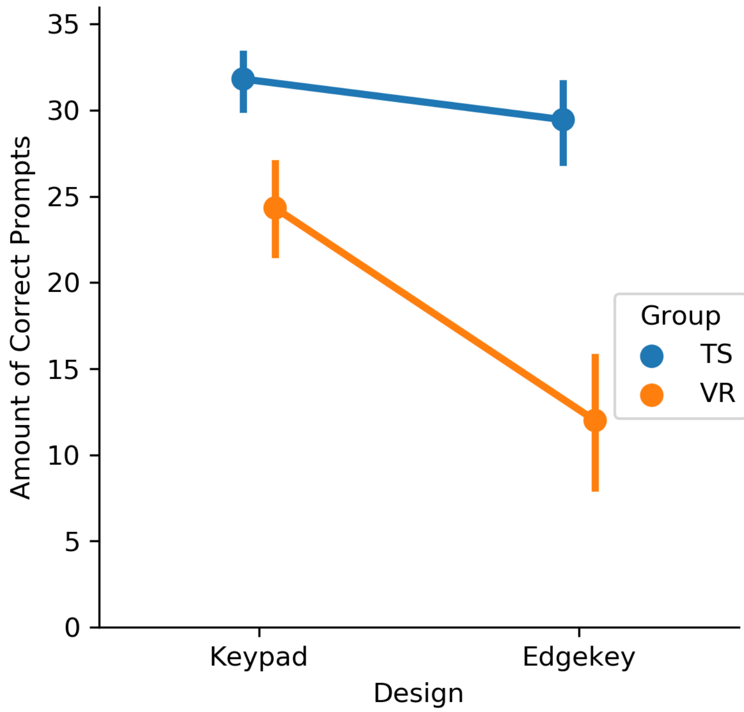


Figure 4.9: Factor Plot of Correct Prompts

not appear to have a significant effect on the response time. Finally, the interaction effect was not significant ($F(1, 21) = 0.001, p = 0.96$).

Prompts Correct

The second measure of the prompting task is the accuracy of the subjects in correctly completing the prompt. To get the prompt correct includes two important components for the subject. First, they must remember the prompt as they enter it, and second, they must be able to physically press the buttons within the seven second response window. For the statistical test, we are using the count of how many prompts each subject completed successfully per trial. Among the incorrect prompts, we can differentiate between whether the subject entered the prompt incorrectly (failure to remember the prompt) or whether the subject ran out of time (failure to physically press the buttons). These counts are reported to help analyze the results, but are not used in the statistical tests. There were 12 prompts per trial, and every subject completed three trials for each design.

The number of correct prompts had a significant interaction effect between group

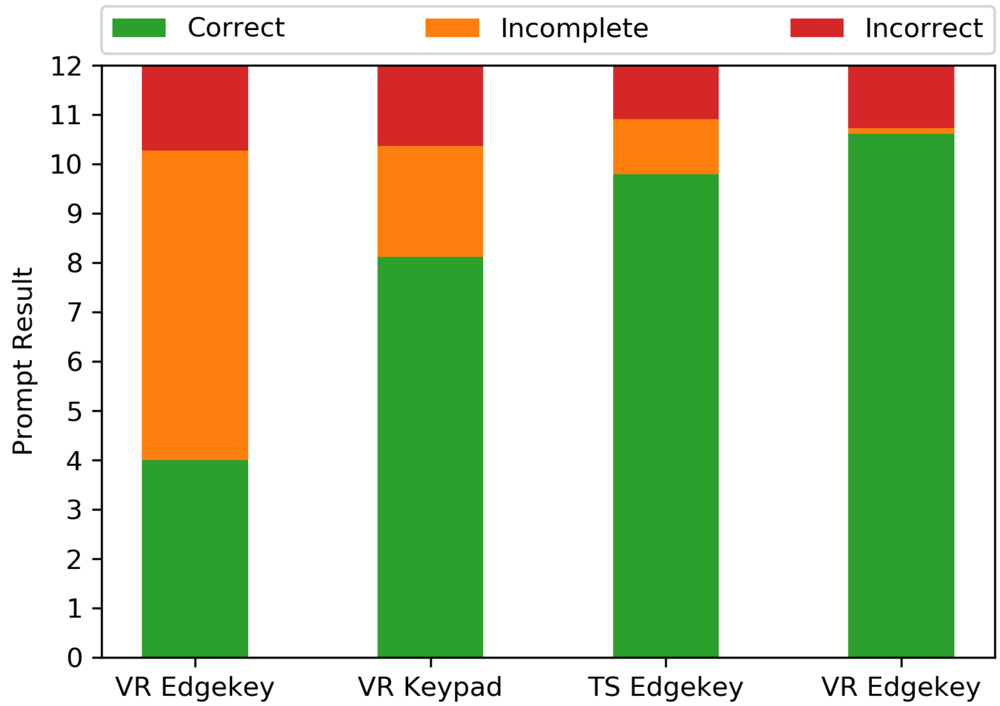


Figure 4.10: Result of prompts

and design ($F(1, 21) = 27.8, p < 0.001$), meaning the main effects must be interpreted with the post-hoc tests as well. Both main effects were significant, the effect of group yielded an F ratio of $F(1, 21) = 43.9, p < 0.001$ while the effect of design yielded an F ratio of $F(1, 21) = 64.1, p < 0.001$.

For the effect of design on the VR group, the repeated measured t-test indicated a significant difference ($t(11) = 8.0, p < 0.001$) between the Keypad ($M = 8.11, \sigma = 1.62$) and the Edgekey ($M = 4.00, \sigma = 2.37$) The TS group had a marginally significant difference ($t(10) = 2.28, p = 0.045$) between Keypad ($M = 10.6, \sigma = 0.96$) and the Edgekey ($M = 9.82, \sigma = 1.38$). These results indicate that both groups had trouble with the additional time pressure caused by the Edgekey design requiring the use of the switch key. The TS group performed a lot closer to their performance in the Keypad design, however, only getting approximately 1 fewer prompt correct. The VR group had much more difficulty in the Edgekey design, correctly completing about half as many as they completed in the Keypad design. However, they had more difficulty in both designs compared to the TS group.

This agrees with the post-hoc tests for differences between groups within each design. These tests had significant effects for both the Keypad design ($t(21) = 4.44, p < 0.001$) between the VR group and the TS group, and the Edgekey design ($t(21) = 7.05, p < 0.001$) between the VR group and the TS group. The main effect of group clearly has a meaningful effect, which found the VR group ($M = 6.05, \sigma = 2.88$) had significantly fewer correct prompts than the TS group ($M = 10.2, \sigma = 1.2$). This difference is largely due to subjects not being able to complete the prompt. Figure 4.10 shows the breakdown of the mean result of each trial for each group and design.

Across all groups and designs, very few prompts were completed that were incorrect, and most of the difference in number completed correctly is due to the incomplete prompts. A contributing factor for this would be the method of button activation used for the VR group combined with the time pressure. Another contribution would be the limitations of the hand tracker. When the hand tracker lost tracking or gave bad information, it became hard or impossible for the subject to activate a button until the hand tracker returned to normal. When this happened in the middle of a prompt, the amount of time it took to recover from the bad tracking would lead to a timeout on the prompt entry, causing an incomplete prompt. The variance of number correct was also much larger in in the VR group, which could be caused by some subjects adapting to the unfamiliar VR environment more rapidly.

NASA TLX

After the subject completed their trials for each design, they filled out a NASA TLX workload survey. Their scores, weighted means by the pairwise comparisons, are used here as a measure of their self-reported workload. The interaction effect between group and design was found to be significant ($F(1, 21) = 8.25, p < 0.001$). The main effects showed a significant difference in design ($F(1, 21) = 23.6, p < 0.001$), but not in group ($F(1, 21) = 1.69, p = 0.21$). This could mean that the group did not affect the TLX score, but in the presence of an interaction effect, the post-hoc tests guide the interpretation.

The repeated measures t-tests indicated significance between designs for the VR group ($t(11) = -4.20, p = 0.001$) between the Keypad design ($M = 54.4, \sigma = 20.4$) and the

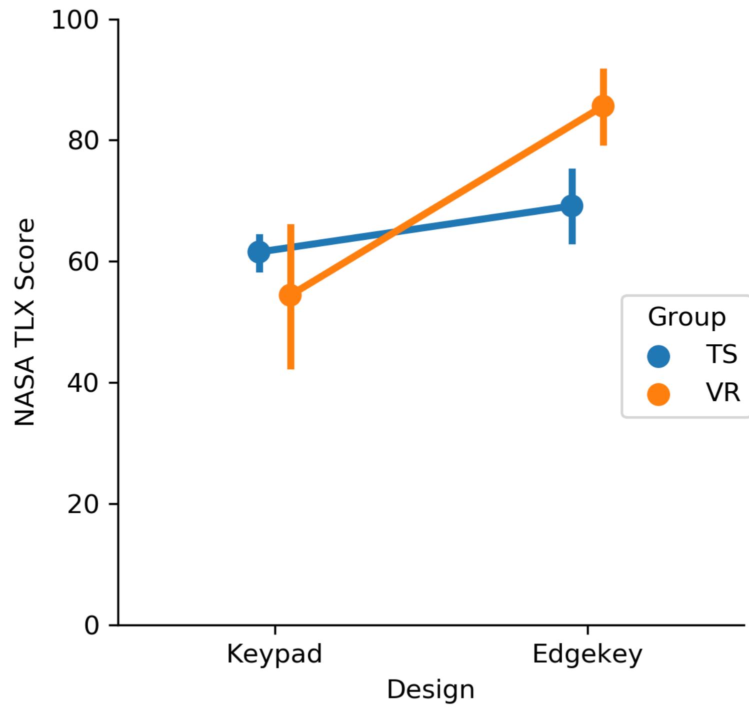


Figure 4.11: Factor Plot of NASA TLX

Edgekey ($M = 85.6, \sigma = 11.2$) There was a marginally significant difference between designs for the TS group ($t(10) = -2.72, p = 0.02$) between the Keypad design ($M = 61.5, \sigma = 4.46$) and the Edgekey ($M = 69.2, \sigma = 10.1$). The effect of design was much stronger in the VR group, but both groups indicated respectively higher workload on the TLX scores for the Edgekey design. This follows from the experimental design which predicted that the Edgekey design would be more difficult. One factor that could have contributed to a larger difference in scores for the VR group could be the increased difficulty subjects had in completing the prompt, as seen in the results of the number of incorrect and incomplete prompts for the VR group using the Edgekey design (Figure 4.10). The effect of group was not shown to be significant in the ANOVA analysis, but the independent samples t-test showed a significance for the Edgekey design ($t(21) = 3.69, p < 0.01$) between the VR Group ($M = 85.6, \sigma = 11.2$) and the TS Group ($M = 69.2, \sigma = 10.1$). With the Keypad design, The effect of group was not significant ($t(21) = -1.13, p = 0.27$) between VR ($M = 54.4, \sigma = 20.4$) and TS ($M = 61.5, \sigma = 4.46$). These tests further illustrate that the VR group found a higher workload for the Edgekey design specifically, as both groups

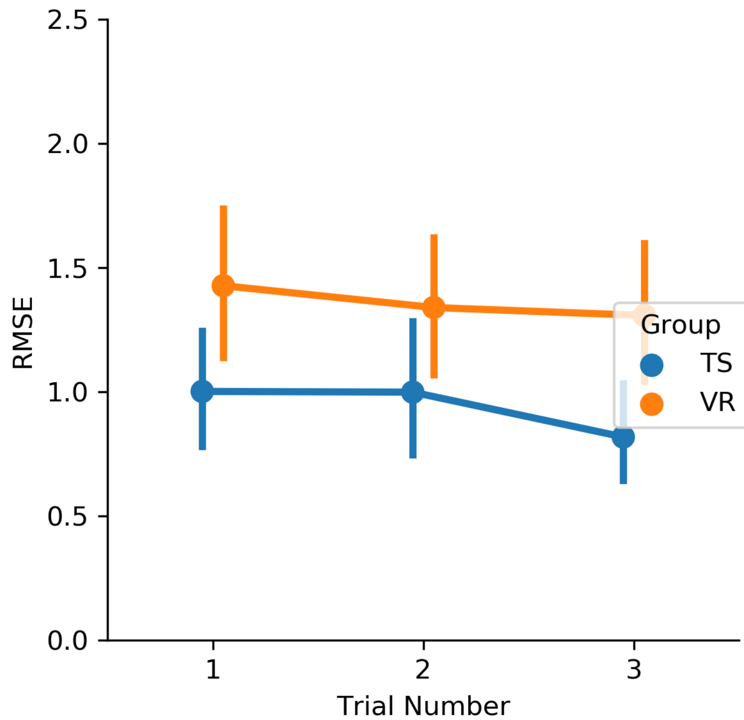


Figure 4.12: Factor Plot of RMSE for Tracking Only Trials

rated the workload in the Keypad design similarly.

Tracking Task Learning

Throughout the experiment the subjects did trials with only the tracking task, instead of both the tracking task and the prompting task. Initially, they performed a number of training trials at the beginning with only the tracking task, and then after each evaluation session there was a single trial of just the tracking task. In this section we will test the RMSE of their final training trial and the two after-evaluation trials for any significant learning effects. The trial number is chronological throughout the timeline of the experiment for each subject. This means that due to the counterbalancing, the second and third trial are done with different designs based on the subject. Since the visual environment of the tracking task was quite different for each group, the Group factor is included as a between subjects factor.

The two-way ANOVA found Group to be a marginally significant factor ($F(1, 21) = 4.94, p = 0.37$) between the VR Group ($M = 1.36, \sigma = 0.51$) and the TS Group ($M =$

$0.94, \sigma = 0.43)$. The effect of group on the tracking task was already established, so the marginal significance found here is not unexpected. Trial number was found to have no significant effect ($F(1, 21) = 3.65, p = 0.069$) between the three trials. The means of the three trials, in order, are $1.23^{circ}(\sigma = 0.54^{circ})$, $1.18^{circ}(\sigma = 0.51^{circ})$, and $1.07^{circ}(\sigma = 0.51^{circ})$. Even though the statistical test indicates no significance, the means do decrease as trial number increases. This combined with the large variance suggest that some subjects were experiencing some training effects, but overall the effect of training is not significant. The interaction effect of Group and trial number had no significance ($F(1, 21) = 0.16, p = 0.69$).

Summary

A summary of the significance results from the ANOVA and post-hoc t-tests for all the performance measures are shown in Table 4.1. The significance is indicated by '$*$' for $p < 0.01$, '+' for $0.01 < p < 0.05$, and '-' for no significance. For the measures with significant interaction effect, the post-hoc t-tests are shown per group and per design.

4.3.3 Design Feedback

As discussed in Section subsection 4.2.5, the long-form feedback questions were synthesized and summarized into categories. The categories and the counts of comment occurrence for each group is summarized in Table 4.2. Categories which only received one comment are not included in this table in interest of brevity, the full table is shown in Appendix A.23.

By far the issue that received the most feedback was the difficulty of using the switch key (Edgekey, Switch Difficult). Most of the complaints stated the extra difficultly of having to press another button. Some of the other complaints from this category were: it took extra time (with no extra time given), it added to the mental demands of the task, and it was difficult to see which mode the instrument was in. Both groups disliked the switch key, and mentioned it just as frequently.

> "Switching from numbers to letters was hard, especially if I was trying to compensate for turbulence and was struggling at the time." (TS Subject)

> "I did not like how much extra work it was. It took so much extra focus that I forgot I was flying with the joystick" (VR Subject)

	ANOVA		
	Group	Design	Group:Design (Interaction)
Tracking RMSE	$*$	+	-
Response Time	-	-	-
Prompts Correct	$*$	$*$	$*$
NASA TLX	-	$*$	$*$

	t-tests			
	Design		Group	
	VR Group	TS Group	Keypad Design	Edgekey Design
Prompts Correct	$*$	+	$*$	$*$
NASA TLX	$*$	+	-	$*$

Table 4.1: Statistical Significance Test Results. '$*$' indicates significance at the $p < 0.01$ level, '+' indicates marginally significant ($0.01 < p < 0.05$), and '-' indicates no significance.

Many subjects noted the familiarity of the Keypad design (Keypad, Familiar) and that having the buttons close together (Keypad, Buttons Proximal) as things they like about that design. The familiarity was noted more often for the TS Group, but both were some of the more frequent comments within each group.

One comment about the Edgekey design that got more frequent mentions from the TS Group was that they found having the flight task in the middle of the display, centered between the buttons, was preferred (Edgekey, Centered Flight Task Better). The subjects who chose the Edgekey as their preferred design nearly unanimously cited this as their reason for their preference[2]. The comments that fed into this category also included subjects who noted the difficulty of splitting their focus back and forth with the Keypad design. Interestingly, two of the TS Group subjects noted that they would have found the Keypad easier if they had tactile feedback to guide their input. This could suggest that the

[2]The one holdout did not explain why they preferred the Edgekey design.

Topic	Feedback Summary Category	VR Group	TS Group
Edgekey	Switch Difficult	14	12
Keypad	Familiar	6	11
Edgekey	Centered Flight Task Better	3	13
Keypad	Buttons Proximal	6	7
Keypad	Buttons Always Visible	5	5
Other	Hand Tracking Issues	9	0
Edgekey	Hand Blocks View	3	4
Fatigue	Prompting Arm	4	1
Edgekey	Clean Design	3	2
Fatigue	Fatigue from Joystick	0	4
Edgekey	Easier	0	4
Keypad	Buttons Confusable	0	4
Other	Colors Disliked	2	2
Fatigue	Eye Fatigue	3	0
Keypad	Easy Focus Switch	2	1
Keypad	More Mistakes	1	2
Edgekey	Accuracy Worse	1	2
Keypad	Buttons Bad Layout	2	0

Table 4.2: Counts of Design Feedback Comments per Group. Sorted by sum of comments.

reason the VR Group subjects did not find the centered flight task advantageous is because with the tactile feedback of the 3D-printed instruments they were able to keep visual focus on the left half of the screen in the Keypad design, thus not seeing benefit from the centering of the flight task display.

> "[The Edgekey design] forced me to pay more attention to what I was typing, this wouldn't have been a problem if the keypad was a physical device that allowed me to locate the numbers and letters without looking, much like the dots on a computer keyboard." (TS Subject)

> "I like that the flight control was cent[e]red, so you could see it even when you were looking at the buttons." (VR Subject)

The most notable exceptions to providing similar feedback between groups are the categories that relate to fatigue issues. Many subjects in the TS group noted fatigue caused from using the joystick, yet none in the VR group did, despite using the same joystick setup, and seated in the same location. The VR group did note more fatigue in their other arm that was used for the prompting task. This fatigue seemed to be caused by the additional effort needed to have the hand tracker recognize the hand. For example, one subject wrote:

> "My right wrist was somewhat fatigued. Though I think this is mostly from positioning my hand for the simulator to recognize my input." (VR Subject)

Some of this additional effort was due to subjects learning to hold their prompting task hand "hovering" while waiting for the next prompt. This was done to keep the hand in view of the hand tracker as when the hand leaves the field of view, the re-acquisition will slow down the entry of first button. Many subjects organically learned this, and kept their arm in front of the instrument between prompts.

Similar to the fatigue issues being different, there were some comments that were due to the technology being used more-so than the designs themselves. Obviously, the subjects who noted difficulty using the hand tracker, or the one subject who mentioned touchscreen issues, are specific to the simulator technology the used. However, some of the other categories had comments that may have been indirectly caused by the different technologies and their limitations. For example, some subjects noted the keypad design caused them to make more mistakes. For the TS Group, this was due to the touchscreen being too responsive to the button presses:

> “[S]ince I was able to go more quickly with this layout, I had more mistakes in the entry.” (TS Subject)

One subject in VR who complained of more mistakes in the Keypad design, identified a common problem caused by the hand tracker. When the hand tracker was having registration issues it would sometimes mistakenly place the other fingers in the activation zone of the buttons underneath the one being targeted, causing multiple buttons to be pressed in a short period of time.

> “There’s more unintended register since other fingers might trigger the buttons.” (VR Subject)

Although only one subject noted this, it was observed happening to many subjects. In fact, for the VR group, eight of the twelve subjects had the wrong button register within 200 milliseconds of the last button in the Keypad design. In the other designs and groups this happened to only one or two subjects.

4.4 Discussion

The motivation of this experiment was to determine the differences between using an R3C simulator system and a traditional simulator system to perform a design evaluation experiment. We had two groups of subjects perform the same evaluation task on two different designs of a cockpit instrument, one group using the R3C system and the other a touchscreen system. The evaluation task included a pitch disturbance tracking task and a call and response prompting task. In addition to the quantative performance measures of the task, subjects were asked for their feedback on the two designs at the conclusion of the experiment.

The results are summarized using their two independent variables: Group and Design. Group, a between subjects factor, refers to the technology the subject used: either Virtual Reality/R3C (VR) or Touchscreen (TS). Design is a within subjects factor, and is the instrument design the subject was evaluation: Edgekey or Keypad.

The VR Group had worse performance than the TS Group with the RMSE of the tracking task. Subjects from both groups had a marginally significant difference in tracking task performance due to Design, with subjects performing better with the Keypad design. It was also shown that, on control trials that had only the tracking task (no prompting task), the effect of Group was reduced to marginally significant. The response time of the prompting task had no significant effect based on Group nor Design. Neither of these two previous measures had interaction effects between Group and Design. The number of correct prompts had a significant interaction effect. While the TS Group was able to complete significantly more prompts correctly overall than the VR group (averages of 10.2 vs. 6.1, respectively) the VR group had a significant effect with the Design and the TS group only had marginal significance. This interaction can be clearly seen in the factor plot of correct prompts (Figure 4.9). The NASA TLX workload scores also had an interaction effect between Group and Design. The TLX scores for the VR group had a significant effect in Design, with subjects rating the Edgekey design over 30 points higher than the Keypad design (averages of 54.4 to 85.6, respectively). However, like the number of prompts correct measure, the TLX score was found to be only marginally significant for the TS group, rating the Keypad at 61.5 to the Edgekey's 69.2.

Our results suggest that tasks or performance measures which are dominated by a cognitive portion, such as the prompt response time, provide similar results. Tasks which rely on visual resolution or time pressured responses may not produce the same results between designs using the R3C system. None of the effects reversed slope between designs, however, and the only change is in magnitude of the effect. In fact, for both the number of prompts correct and the workload ratings, which had significant interaction effects, the use of the VR system amplified the effect of design within the groups from a marginally significant effect to a significant effect.

The results of the subjective feedback analysis found that there was no omission of major feedback items on the design of the two instruments from either group. The only feedback comments that did not transfer were the fatigue issues, and of course technology-specific issues. We did discover that some issues were mentioned at differing frequencies, which is to say, one group would have more subjects mention it than the other. These results suggest that the use of the R3C system for receiving feedback from a design would be appropriate.

Many design evaluation studies would be concluded with both paper questionnaires as well as open interviews to receive the feedback from the subject. Our experimental design avoided the use of the interview for two reasons. First, since our subjects were not subject domain experts or experienced evaluators, we wanted to ensure that the prompting of the questions were consistent. Second, the primary goal of the design feedback for this experiment was not to evaluate the designs, but rather to compare evaluations. The use of a proctor interviewing the subjects could introduce accidental bias into the responses of the subjects. This can often be useful when evaluating a new interface, for example, an interviewer could ask subjects about a flaw they had not mentioned yet to determine if they did not notice it or did not care about it. However, in our case, we forgoed this additional information to ensure no bias was introduced in the collection of their opinions.

This was a limited study of the utility of VR/R3C for design evaluation purposes. The task and instrument design was kept simple in nature for this study in order to limit the amount of confounding variables as well as keep it easy to learn for the subject population. Future studies could investigate this system in a more involved design study, with multiple instruments or designs, or more complex behavior in the cockpit. At this point, it would become more essential to use subject domain experts (i.e. experienced pilots) in order to validate these results.

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Appendices

Appendix A

Result Tables

A.1 Passive Haptics Experiment

Sequence	Haptics	Mean	Std. Dev.
NH First	—	3.877	0.5265
PH First	—	3.99	0.3684
—	NH	3.71	0.3805
—	PH	4.157	0.412
PH First	NH	3.879	0.3892
PH First	PH	4.1	0.3284
NH First	NH	3.541	0.3007
NH First	PH	4.213	0.4934

Table A.1: Throughput Means

Factor	F ratio	p value
Sequence	0.5297	0.4761
Haptics	35.53	1.221×10^{-5}
Sequence:Haptics	9.062	0.007516

Table A.2: Throughput ANOVA

Sequence	Haptics	df	t	p value
PH First	—	9	2.547	0.03135
NH First	—	9	5.503	0.0003787
—	PH	18	−0.602	0.5547
—	NH	18	2.176	0.04309

Table A.3: Throughput t-tests

Sequence	Haptics	Mean	Std. Dev.
NH First	—	77.5	10.56
PH First	—	71.2	8.764
—	NH	71	9.701
—	PH	77.7	9.565

Table A.4: Presence Score Means

Factor	F ratio	p value
Sequence	4.089	0.05828
Haptics	6.079	0.02396
Sequence:Haptics	0.7164	0.4084

Table A.5: Presence Score ANOVA

Haptics	Cronbach's alpha
No Haptics	0.9139
Passive Haptics	0.9191

Table A.6: Presence Score Cronbachs alpha

Sequence	Haptics	Mean	Std. Dev.
NH First	—	15.07	2.948
PH First	—	13.1	3.523
—	NH	14.72	2.854
—	PH	13.45	3.762
PH First	NH	14.5	3.064
PH First	PH	11.7	3.529
NH First	NH	14.95	2.773
NH First	PH	15.2	3.259

Table A.7: Arm Fatigue Ratings Means

Factor	F ratio	p value
Sequence	2.119	0.1627
Haptics	9.717	0.00595
Sequence:Haptics	13.9	0.001538

Table A.8: Arm Fatigue Ratings ANOVA

Sequence	Haptics	df	t	p value
PH First	—	9	-4.583	0.001323
NH First	—	9	0.4596	0.6567
—	PH	18	-2.304	0.03336
—	NH	18	-0.3443	0.7346

Table A.9: Arm Fatigue Ratings t-tests

Please circle the number that best describes the amount of fatigue you feel in your arm. Try to consider the overall sensation of fatigue, soreness, and exertion level. Consider the arm to include shoulder muscles that you use to move the arm.	
6	No fatigue
7	Very, very lightly fatigued
8	
9	Very lightly fatigued
10	
11	Lightly fatigued
12	
13	Somewhat fatigued
14	
15	Heavily fatigued
16	
17	Very heavily fatigued
18	
19	Very, very heavily fatigued
20	Maximal fatigue

Table A.10: Borg RPE Scale as used

A.2 Design Evaluation Experiment

Group	Design	Mean	Std. Dev.
TS	—	1.277	0.3789
VR	—	1.967	0.378
—	Edgekey	1.704	0.5188
—	Keypad	1.57	0.5068

Table A.11: RMSE Means

Factor	F ratio	p value
Group	21.42	0.000145
Design	5.944	0.02374
Group:Design	0.1669	0.687

Table A.12: RMSE ANOVA

Group	Design	Mean	Std. Dev.
TS	—	2595	567.3
VR	—	2813	383.2
—	Edgekey	2688	471.1
—	Keypad	2729	512.5

Table A.13: Response Time Means

Factor	F ratio	p value
Group	1.199	0.2859
Design	0.6814	0.4184
Group:Design	0.00184	0.9662

Table A.14: Response Time ANOVA

Group	Design	Mean	Std. Dev.
TS	—	10.2	1.242
VR	—	6.056	2.889
—	Edgekey	6.768	3.525
—	Keypad	9.304	1.831
VR	Edgekey	4	2.37
VR	Keypad	8.111	1.616
TS	Edgekey	9.788	1.393
TS	Keypad	10.61	0.964

Table A.15: Correct Prompts Means

Factor	F ratio	p value
Group	43.56	1.552×10^{-6}
Design	63.93	8.309×10^{-8}
Group:Design	26.89	3.872×10^{-5}

Table A.16: Correct Prompts ANOVA

Group	Design	df	t	p value
VR	—	11	8.039	6.234×10^{-6}
TS	—	10	2.287	0.04526
—	Keypad	21	4.441	0.0002262
—	Edgekey	21	7.053	5.839×10^{-7}

Table A.17: Correct Prompts t-tests

Group	Design	Mean	Std. Dev.
TS	—	65.35	8.535
VR	—	70.01	22.65
—	Edgekey	77.74	13.4
—	Keypad	57.83	15.18
VR	Edgekey	85.61	11.21
VR	Keypad	54.42	20.4
TS	Edgekey	69.15	10.06
TS	Keypad	61.55	4.468

Table A.18: NASA TLX Means

Factor	F ratio	p value
Group	1.688	0.208
Design	23.57	8.455×10^{-5}
Group:Design	8.252	0.009113

Table A.19: NASA TLX ANOVA

Group	Design	df	t	p value
VR	—	11	−4.205	0.001474
TS	—	10	−2.718	0.02164
—	Keypad	21	1.132	0.2703
—	Edgekey	21	−3.693	0.001351

Table A.20: NASA TLX t-tests

Group	Trial	Mean	Std. Dev.
TS	—	0.9402	0.425
VR	—	1.359	0.5176
—	1	1.225	0.5421
—	2	1.177	0.5144
—	3	1.074	0.5053
VR	1	1.428	0.5754
VR	2	1.34	0.4877
VR	3	1.308	0.5244
TS	1	1.002	0.4223
TS	2	0.9994	0.5038
TS	3	0.8188	0.3488

Table A.21: Tracking Only Trials RMSE Means

Factor	F ratio	p value
Group	4.937	0.0374
Trial	3.649	0.06987
Group:Trial	0.1621	0.6913

Table A.22: Tracking Only Trials RMSE ANOVA

Topic	Feedback Summary Category	VR Group	TS Group
Edgekey	Accuracy Worse	1	2
Edgekey	Busy Design	0	1
Edgekey	Centered Flight Task Better	3	13
Edgekey	Clean Design	3	2
Edgekey	Easier	0	4
Edgekey	Familiar	1	0
Edgekey	Hand Blocks View	3	4
Edgekey	Labels Easy to Read	1	0
Edgekey	Labels Hard to Read	1	0
Edgekey	Switch Difficult	14	12
Edgekey	Switch Neutral	0	1
Fatigue	Eye Fatigue	3	0
Fatigue	Fatigue from Joystick	0	4
Fatigue	Prompting Arm	4	1
Keypad	Buttons Always Visible	5	5
Keypad	Buttons Bad Layout	2	0
Keypad	Buttons Confusable	0	4
Keypad	Buttons Proximal	6	7
Keypad	Easy Focus Switch	2	1
Keypad	Familiar	6	11
Keypad	Labels Good	1	0
Keypad	Labels Hard to Read	1	0
Keypad	More Mistakes	1	2
Keypad	More Successful	0	1
Keypad	Tracking Easier	1	0
Other	Colors Disliked	2	2
Other	Hand Tracking Issues	9	0
Other	Prompt Location Bad (Both)	1	1
Other	Single Finger Hard	1	1
Other	Touchscreen Issues	0	1

Table A.23: Full Feedback Comments by Category.