ENHANCED FLIGHT VISION SYSTEMS: PORTRAYAL OF RUNWAY MARKINGS AND SENSOR RANGE EFFECTS ON PILOT PERFORMANCE

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ENHANCED FLIGHT VISION SYSTEMS: PORTRAYAL OF RUNWAY MARKINGS AND SENSOR RANGE EFFECTS ON PILOT PERFORMANCE

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SUMMARY

This thesis investigates the effects of two specific sensor limitations in enhanced flight vision systems (EFVS) on general aviation pilot performance during approach and landing: sensor range and EFVS portrayal of runway markings. The background section of this thesis describes current sensor technologies with EFVS: millimeter wave radar, forward-looking infrared, and light detection and ranging (LiDAR). In addition, the connections between pilot tasks, information requirements, visual cues and information processing level are identified. These connections show how limitations of sensor technologies could affect pilot performance. These effects were then assessed in a fixed base flight simulator of a general aviation aircraft with an EFVS system. The sensor range and portrayal of runway markings was varied while measuring pilot performance. Pilot performance during approach was measured according to FAA instrument certification standards. Landing performance was measured using standards taught during private pilot training. The results show that pilot performance in tracking an instrument approach is negatively affected by reductions in EFVS sensor range, while the vertical speed and distance from centerline had exceedances beyond acceptable standards when the EFVS did not portray runway markings. These results identify the key minimum specifications of EFVS sensor range and ability to portray runway markings for their implementation in general aviation.

CHAPTER 1.   INTRODUCTION

Enhanced sensor technologies are constantly evolving and being applied in new ways. The commercial aviation industry has applied these sensors to enhance the crew's vision in severe weather conditions using Enhanced Flight Vision Systems (EFVS). According to the Federal Aviation Administration (FAA) and current regulations (FAA 2017), an EFVS must have specific characteristics for the crew rely on it for maneuvering. In particular, the visual presentation must be driven by real-time sensors of the visual picture looking forward from the flight deck. A wide variety of sensors can be used for EFVS, where the more common are millimeter wave radar (MMW), forward-looking infrared (FLIR), and light detection and ranging (LiDAR).

EFVS can aid pilots in a variety of tasks. The main tasks this thesis examines are approach and landing in poor visibility. The FAA has recently passed a new regulation (FAA 2017) that allows operators to perform approaches and landings solely using EFVS. However, limitations of the sensor technologies to provide an effective visual presentation of the out-the-window view may impact pilot performance.

The specific limitations of EFVS sensors that this thesis examines are their ability to sense runway markings, so they can be portrayed visually to the pilot, and sensor range. Some sensors, such as millimeter wave radar, are unable to perceive runway markings yet these markings, particularly touchdown markers and the runway centerline, provide information to the pilot during the final stages of the approach, flare and landing roll out.

The sensor range reflects trade-offs where many sensors can only display long-range images with a low level of detail versus displaying shorter-range images with adequate or better detail.   The sensor range may allow pilots to see as far as the horizon or they may not be able to see the end of the runway.

Based on a literature review and an analysis of the pilot's tasks during the approach and landing, the hypothesis of this thesis is that sensor limitations will impact the pilot performance on approach and landing. The sensor range limitation will negatively impact the pilot's ability to: remain on the glideslope/localizer, predict the landing spot, and flare during landing. The lack of a portrayal runway markings is predicted to negatively impact the pilot's ability to remain on the extended centerline of the runway, touchdown on the touchdown markers, and to touchdown with an appropriate vertical speed for the aircraft.

1.1   Objective

The objective of this thesis is twofold. First, find the effect of the sensor range on pilot performance during approach and landing using an EFVS. Secondly, find the effect that the absence or portrayal of runway markings by an EFVS has on pilot performance during approach and landing.

1.2   Method

This thesis aims to look at the specific approach and landing tasks and how EFVS could lead to adverse effects on the pilot's performance. Since pilot performance during the critical phases of approach and landing is being tested safety dictates that this

research should be completed in a flight simulator. Further, a flight simulator allows for consistent, repeatable events for the pilots/participants to experience. Thus, this thesis applies a fixed based flight simulator located at Georgia Tech. The software used for the simulator is FlightGear, which allowed for generation of an EFVS presentation on a heads-up display. The simulated aircraft is a Cessna 172 which the pilot can control using a yoke, rudder pedals and throttle/mixture controls.

As stated above, this thesis looks at the effects of EFVS sensor range and portrayal of runway markings of pilot performance on approach and landing. Specifically, the independent variables are: EFVS sensor range (3 levels: 1 mile, 3 miles and 12 miles); the portrayal of runway markings (or not).

The dependent variables must be able to capture pilot performance during approach and landing. For measures of the approach, according to the FAA (FAA 2017), a pilot must maintain less than a ¾ scale deviation on localizer and glideslope as well as being +/- 10 knots on the approach speed. In addition, several other criteria can be established for the landing, including distance from runway centerline, distance from touchdown markers, and vertical speed upon touchdown.

1.3   Structure

This thesis is structured as follows: a background section discussing EFVS and sensor technologies is first, followed by a section describing pilot tasks and information processing levels. The experimental method is described, followed by the results. The discussion and conclusion are last, followed by the appendices and the references.

CHAPTER 2.   BACKGROUND

This chapter discusses the purpose of EFVS, as well as some of the explicit limitations and capabilities of specific sensors. This chapter focuses on three types of sensors: millimeter wave radar (MMW), forward-looking infrared (FLIR), and light detection and ranging (LiDAR). Although there are other sensor technologies, these three are the primary being investigated for use in EFVS.

2.1   Purpose of EFVS

The EFVS can be applied to a variety of tasks to aid pilots. The main tasks this thesis examines are approach and landing in poor landing visibility. Typically, minimum ceiling and forward visibility criteria must be met for pilots to land at an airport; however, with EFVS it is possible for a pilot to use the EFVS rather than natural vision.

2.2   Millimeter Wave Radar

2.2.1   Description

Radar is a technology widely used today for various applications, such as tracking objects or some basic imaging uses. Radar operates by emitting electromagnetic energy from the transmitter and detecting the return signal. The image generated is depicted by the return signals scattered back from the various objects on the ground; the range between the antenna and the object is found by the time it takes for the return signal to be received by the antenna. The angle of the echo can be utilized to show the angular

location of the object with respect to the antenna as well (Russell, Crain et al. 1997, Skolnik 2008).

There are a range of radar signals in use today which vary primarily in the frequency of the pulses. These frequencies vary from 3 MHz to well over 300 GHz. Each different band or group of frequencies has different advantages and disadvantages, including signal range, resolution, antenna size and various other that area outside the scope of this paper. Millimeter wave radar (MMW) typically exists within the frequency range of 40 to 300 GHz; although most frequencies above 40 GHz are considered millimeter waves (Skolnik 2008).

With the atmospheric attenuation predominately occurring around 60 GHz, and MMW frequency instead usually being around 94 GHz or 76-77 GHz, most MMW radars have the possibility to see through some weather phenomena, such as fog and light rain. Overall, compared to other visual sensors, such as LiDAR and FLIR, MMW possesses better weather penetration (Yang 1994, Russell, Crain et al. 1997, Abou-Jaoude 2003, Skolnik 2008).   However, there still exists some atmospheric attenuation at all frequencies and therefore, the range and resolution of MMW will be reduced by some amount in particular situations; this will also vary depending on the exact frequency of the specific radar (Skolnik 2008).

Images generated by MMW radar can appear grainy and sometimes hard to decipher compared to the optical and infrared cameras due to the multitude of signals that bounce back from the ground (Yang 1994). Filtering techniques are being sought that may mitigate this effect (Korn, Doehler et al. 2000). An example photo of MMW in Figure 1

that shows the particular airport and the MMW view of the airport; of note the runway markings are not fully visible in the picture (Korn, Doehler et al. 2000).
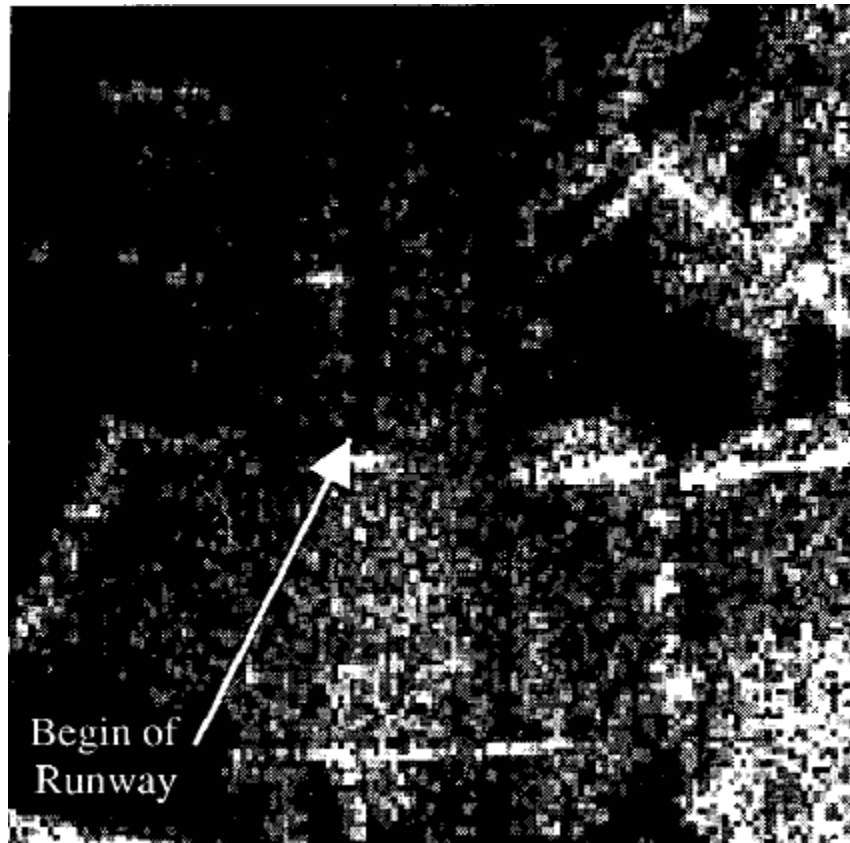
Figure 1. Example MMW Radar Imagery [Copied with Permission from (Korn, Doehler et al. 2000)]

2.2.2   Capabilities

The ability of MMW radar to see through poor weather visibility has led to its use in a variety of applications, such as autonomous cars (Clark and Durrant-Whyte 1998). One of the prime examples of current usage of the MMW sensor is in car automation. Clark 1998 showed that MMW radar can autonomously guide a car along a path with great precision; however, pylons were used as a reference in the test course (Clark and Durrant-Whyte 1998).   Additional examples apply MMW sensors for adaptive or

intelligent cruise control (Lange and Detlefsen 1991, Lowbridge 1995, Abou-Jaoude 2003, Rouveure, Monod et al. 2008). In aviation, MMW is proposed for EFVS to allow aircraft to fly below usual weather minimums and possibly land in severe weather conditions (Lowbridge 1995, Korn, Doehler et al. 2001, Sugimoto, Hayato et al. 2004).

Tests of MMW sensors have found that contrast between objects rises in fog compared to clear weather, which aids the visual interpretation of the image. Additionally, clouds and fog were not seen to adversely affect MMW sensing ability. Rain rate was not a large detriment to the MMW sensing ability either and often increased the contrast rate. Further, no major adverse effects were observed on MMW radar sensors in snow (Horne and Hudson 1993).

Supporting an effective visual portrayal of the visual scene, MMW radar returns can show different textures for each of the objects it detects. These textures can help differentiate between ground features, providing visual cues that may help the pilot.

2.2.3 Limitations

While millimeter wave sensors have the capability to perceive through weather and adverse conditions, there are several drawbacks to MMW sensors. These drawbacks include noise, low resolution and range trade-offs, as detailed next (Lange and Detlefsen 1991, Yang 1994, Korn, Doehler et al. 2000). In addition, MMW sensors are unable to detect and portray runway markings. Compared to some other sensors, MMW sensors have been qualitatively evaluated as having poor to average effectiveness for landing in aviation (Yang, 1994).

2.2.3.1 <u>Accuracy</u>

The grainy images depicted by MMW radar, as shown in Figure 1, can be affected by attenuation and can be misinterpreted or cause accuracy issues of the system (Yang 1994, Korn, Doehler et al. 2000). Accuracy issues could lead to pilots landing on grass fields next to the runway or even running into obstacles that the radar did not detect.

One mitigation for MMW radar sensor inaccuracies is filtering and checking the image against a database of the airport itself. Many different types of filters and clustering exist (Korn, Doehler et al. 2000, Rouveure, Monod et al. 2008, Vu, Farrell et al. 2013). The constraint that arises with filtering and clustering of the image is the trade-off between accuracy and time (discussed section 2.2.3.4).

Another method of mitigation is checking the image against an established database (Korn, Doehler et al. 2000, Korn and Hecker 2002, Brooker, Birch et al. 2004). The usage of a database has several limitations, the primary one being that not every airport has a MMW database. Although this database usage would work for commercial aviation, the application to general aviation would be unreasonable due to the number of smaller general aviation that the database would need to cover. Additionally, as discussed before, these experiments with automated car driving often build infrastructure to support and guide the car through a series of waypoints (Clark and Durrant-Whyte 1998), an infrastructure not available at general aviation airports.

2.2.3.2   Resolution

A typical MMW image is grainy, compromising the overall angular resolution of the image (Yang 1994, Sugimoto, Hayato et al. 2004). This lack of resolution creates a possibility for misinterpretation by the pilot. The typical range resolution for MMW radar ranges from 0.25 meters up to 3 meters, while the angular resolution ranges from 3° to 4° (Russell, Crain et al. 1997, Abou-Jaoude 2003, Rouveure, Monod et al. 2008). The misinterpretation could lead to incorrect landing locations or prevent the pilot from identifying the runway during approach.

Another issue with regards to resolution is the variation that occurs due to ground type. This variation is affected by the height of the surface, and the type and the moisture content of the surface (Horne and Hudson 1993). This variation in ground type is common across all general aviation airports and affect the pilot's perception of the runway in conditions such as rain.

2.2.3.3   Range

The main issue of range with a MMW sensor is the trade-off between sensitivity and range (Lange and Detlefsen 1991): as the range is increased, a loss of sensitivity occurs and vice versa. This trade-off may be detrimental since either the sensitivity could be too low for the pilot to gather visual cues, or the range could limit the EFVS to portraying the runway once the aircraft is already past the minimum altitude where the pilot must break off the approach.

2.2.3.4 Time Lag

Two factors can cause time lag in MMW sensors: processing of the image and initial transmission/reception. Most MMW sensors utilize a real-time processing system (Clark and Durrant-Whyte 1998). The processing time of the image has a variety of factors, but filtering mechanisms and clustering techniques process the image with little to no time delay (Korn, Doehler et al. 2000). Due to the speed of the signal and the frequency of MMW sensors, the time between transmission and reception seems negligible to contribute to time lag. Another issue would be if a rotating antenna was used, which would increase the sampling time of the MMW sensor (Clark and Durrant-Whyte 1998).

2.3   Forward-Looking Infrared

2.3.1   Description

Forward-looking infrared (FLIR) is a passive sensing system which detects changes in thermal energy over the infrared spectrum. Typical FLIR sensors use a method of detection called the iHot spot technique. This technique assumes the target infrared radiation is greatly different from the surrounding area. This assumption helps filter out unnecessary information, such as a slightly warmer wall compared to a colder one (Yilmaz, Shafique et al. 2003).

2.3.2   Capabilities

The thermal view of FLIR allows extraordinary night vision capabilities of the FLIR sensor. Night vision capabilities would allow the GA pilot to see in low lighting situations and detect objects that are usually hidden. Night vision capabilities also aid in

taxiway incursions by allowing the pilot to view unseen aircraft (Yang 1994, Doehler and Korn 2006, Prinzel, Kramer et al. 2007). Thermal imaging by FLIR also distinguishes between the runway concrete and the surrounding areas (Doehler and Korn 2006). The thermal imaging also allows FLIR to sense through haze and smoke (Prinzel, Kramer et al. 2007). Finally, the FLIR sensors can detect the threshold between the concrete and the grass surrounding the runway and FLIR sensors can isolate the runway from the thermal signatures of runway lights (Doehler and Korn 2004). The capabilities can provide more visual cues in approach and landing scenarios.

In addition to night vision capabilities, a FLIR sensor typically generates a perspective view of the surroundings. This perspective is extremely similar to the perspective that pilots currently have during visual approaches (Brooker, Birch et al. 2004, Doehler and Korn 2006).

FLIR sensors have shown to have good accuracy (Doehler and Korn 2004, Doehler and Korn 2006). Doehler 2006 shows a higher level of accuracy of the FLIR matching the runway than global positioning. This level of accuracy can prevent off-runway landings and instill a better sense of trust in the system by the pilots. Additionally, Yang 1994 found qualitative ratings by pilots of FLIR ranged from average to good for FLIR's overall effectiveness in approach and landing.

2.3.3   Limitations

The thermal sensing of FLIR sensors can be affected by several temperature phenomena. Thermal dissipation rates vary between different materials and different dissipation rates can lead to thermal reversals occurring at certain points in the day. For

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example, an image taken during the day will show that the runway is hotter than the grass surrounding it; at night, however, the image will show that the runway is colder than the surrounding grass. These reversals could lead to pilots conducting a landing in grass instead of the runway (Yang 1994). Additionally, thermal ghosting can occur, portraying a thermal signature from an object on the terrain, after the object has moved: for example, FLIR may portray the cooler shadow of an aircraft that had waited at the runway threshold for a few minutes even after the aircraft there takes off (Yang 1994).

2.3.3.1 Accuracy

FLIR accuracy depends on the conditions of the environment. As stated above, FLIR sensors measure the thermal energy of terrain and objects which mean that temperature of these objects and the weather surrounding them can have a large effect on accuracy (Yang 1994, Russell, Crain et al. 1997, Beier, Fries et al. 2001, Beier and Gemperlein 2004). Weather can change the temperature of the surfaces being measured in a variety of ways: solar load, air temperature, wind speed, moisture content or current precipitation (Yang 1994). Additionally, FLIR sensors cannot fully provide accurate information in dust or fog (Brooker, Birch et al. 2004). Due to the multitude of variations possible at general aviation airports, the weather dependency of FLIR sensors is a major constraint for implementation in general aviation.

Another accuracy issue that arises from the temperature usage of the FLIR camera is the typical spot technique utilized by the IR cameras. This technique assumes the target view is hotter than the rest of the surrounding area, which could lead to omissions of certain cues useful for approach and landing, such as traffic or different objects on the

runway (Yilmaz, Shafique et al. 2003). The low signal-to-noise ratio presents another possible issue where most filters built in with FLIR sensors may filter out objects as noise (Yilmaz, Shafique et al. 2003). The signal-to-noise ratio also affects the resolution of the sensor, which is discussed in the next section.

2.3.3.2   Resolution

The resolutions of the FLIR sensors are qualitatively better compared to the millimeter wave radar sensors discussed previously The iHot spot technique can create resolution errors by focusing on the terrain with the higher thermal energy or assuming a great difference in thermal energy occurs between the main focus and the background (Yilmaz, Shafique et al. 2003). These assumptions could prevent the FLIR sensors from picking up small changes in the thermal signatures of features, such as other aircraft or vehicles on the runway. As stated earlier, these small changes are also affected by the low signal-to-noise ratio. Additionally, if there does not exist a great difference in thermal energy between the runway and the surroundings, the sensors could group them together as one.

2.3.3.3   Range

The two main factors that affect the range of the FLIR sensors are spatial resolution and atmospheric conditions (Beier, Fries et al. 2001). Atmospheric conditions influence the ability of the sensor to detect cues at all. Due to the short transmission length of FLIR, the sensors are not very effective in fog or rain (Yang 1994). This fact is also shown at various categories of instrument flight rules weather minimums and how much the FLIR sensors aid during the flight (Beier and Gemperlein 2004). The inability to see

through fog and rain is a constraint for FLIR since EFVS is particularly need in these conditions.

The second main factor concerning the range of FLIR sensors is their spatial resolution. One way to judge the range of the FLIR sensor is to find the contrast threshold, or IR visibility, which is calculated by the power and wavelength of the camera. A study was conducted to estimate the contrast threshold correlation with range (Beier, Fries et al. 2001). A contrast threshold of 6% correlates to a probability of detection of 99%, while a contrast threshold of 2% correlates to a probability of detection of 50%; this contrast threshold is related to the spatial resolution of the sensor, specifically the higher the resolution, the higher the contrast threshold (Beier, Fries et al. 2001, Beier and Gemperlein 2004).

2.3.3.4 Time Lag

FLIR sensors have two possible issues with creating time lag: transmission/reception of the signal and processing of the data. The transmission/reception of the signal should not change greatly due to the speed at which the infrared signal travels. The processing time depends on the length of the analysis and the size of the computing device, but studies have found real-time infrared image time lag is not typically a concern (Beier, Fries et al. 2001, Doehler and Korn 2004, Doehler and Korn 2006).

2.4 Light Detection and Ranging

2.4.1 Description

Light detection and ranging (LiDAR) is a technology that utilizes a laser to scan the scenery (Stockdon, Sallenger Jr. et al. 2002, Sangam 2012). Multiple scans of the external scene are used to create a depiction of the terrain for the user. Terrain databases as well as global positioning systems are often used for LiDAR to increase accuracy (Campbell, Uijt de Haag et al. 2003, Brooker, Birch et al. 2004).

There are multiple types of scanning that LiDAR can use, but the most applicable to the scope of this report is Doppler and elastic backscatter. Doppler LiDAR detects changes in the measured object by measuring the frequency shift of the backscattered light and is frequently used to measure wind speed. Elastic backscatter LiDAR compares the magnitude of the transmitted and received signal since both signals are at the same wavelength. Elastic backscatter LiDAR is one of the simplest forms of LiDAR and is usually used for studies of aerosols and clouds (Sangam 2012).

2.4.2 Capabilities

LiDAR presents an interesting affordance to EFVS for aircraft navigation (Campbell, Uijt de Haag et al. 2003). The main measurement that LiDAR sensors provide is elevation, which would provide a distance to an object or location, such as a runway. These measures can distinguish between the different reflectivity of the runway markings (Levinson, Montemerlo et al. 2007).

(Campbell, Uijt de Haag et al. 2003) found that LiDAR at that time can be highly accurate, i.e. within 30 centimeters of the root-mean-square value for different terrain reference points. This level of accuracy can ensure correct positioning of the visual. This higher level of accuracy is also reflected in the improved resolution of LiDAR (Lowbridge 1995).

LiDAR is also shown to be applicable to several fields beyond aviation; these examples include topographical mapping (Stockdon, Sallenger Jr. et al. 2002, Sangam 2012) and automated lane detection system for automobiles (Lowbridge 1995, Levinson, Montemerlo et al. 2007).

2.4.3 Limitations

One of the primary issues for the usage of LiDAR sensors is its dependence on laser scanning. Limitations on power decrease the effectiveness, specifically with range, of the laser, but increasing the power creates concerns with safety to people outside the aircraft (Lange and Detlefsen 1991, Lowbridge 1995, Campbell, Uijt de Haag et al. 2003).

2.4.3.1 <u>Accuracy</u>

LiDAR accuracy is limited by several factors including, but not limited to: aerosol/cloud particles, weather, integration drawbacks, databases and measurement techniques. LiDAR sensors are highly sensitive to aerosol and cloud particles making the sensors almost useless to aviation in particular adverse weather conditions, such as heavy clouds (Sangam 2012).

2.4.3.2   Resolution

LiDAR systems use a variety of measurement techniques to survey terrain and nearby objects. The overall resolution using the Doppler and Elastic backscatter techniques are qualitatively better than both the FLIR and MMW sensors. The quantitative range resolution for LiDAR using these techniques is typically around 5 cm, while the angular resolution is typically around 0.8° (Lowbridge 1995, Levinson, Montemerlo et al. 2007).

2.4.3.3   Range

The range of the LiDAR sensors are also affected by the safety limitations, as stated before (Campbell, Uijt de Haag et al. 2003). One example of a LiDAR range is for a theoretical Mars landing mission with an approximate range of two kilometers, which operates in real time (Johnson, Klumpp et al. 2002). This is a representative of the LiDAR system that would be utilized for a general aviation aircraft. However, it is evident that the range is currently inadequate for some approach and landing operations as pilots may not be able to see the airport on final approach until about a minute before touchdown (Yang 1994).

2.4.3.4   Time Lag

LiDAR systems typically use a combination of global positioning and inertial navigation to accurately predict the location of the system at any point. Global positioning satellites and inertial navigation systems both have been utilized in real time applications and therefore should present no time lag issues. As for the laser scanner

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portion of LiDAR, there is shown to not be a large time lag (Campbell, Uijt de Haag et al. 2003).

2.5   Summary of Sensor Limitations Relative to the Interests of the Thesis

Each of the sensors described in this section have limitations relating to sensor range and EFVS portrayal of runway markings. MMW sensors has several limitations, with the main limitations being noise, resolution, lack of runway markings, and range-sensitivity tradeoff. These limitations are all issues that need to be addressed; however, the focus of this thesis consider the latter two components: lack of runway markings and range limitations.

FLIR sensors have several limitations that can negatively affect pilot performance. The major limitations are temperature and long-range resolution issues. The temperature issues lead to detection issues of important visual cues, such as runway markings or the differentiation between grass and the runway itself.

Finally, LiDAR has several limitations that include laser safety issues, specific weather phenomenon and range sensitivity tradeoffs; however, LiDAR can detect and depict runway markings on the runway. These issues could impact pilot performance, but as stated before, this thesis is focusing on range and lack of runway markings and their possible impact on pilot performance during approach and landing.

CHAPTER 3.   PILOT TASKS AND INFORMATION

PROCESSING

Pilot tasks have information requirements that an EFVS can address through the visual cues it provides. For EFVS, these visual cues are impacted by both characteristics of the display and the attributes of the sensors. The visual cues directly inform the pilot's information processing, which can be broken down into three separate levels: perception, interpretation, and prediction.   This information processing then steers how pilots performs their tasks, as shown in Figure 2.
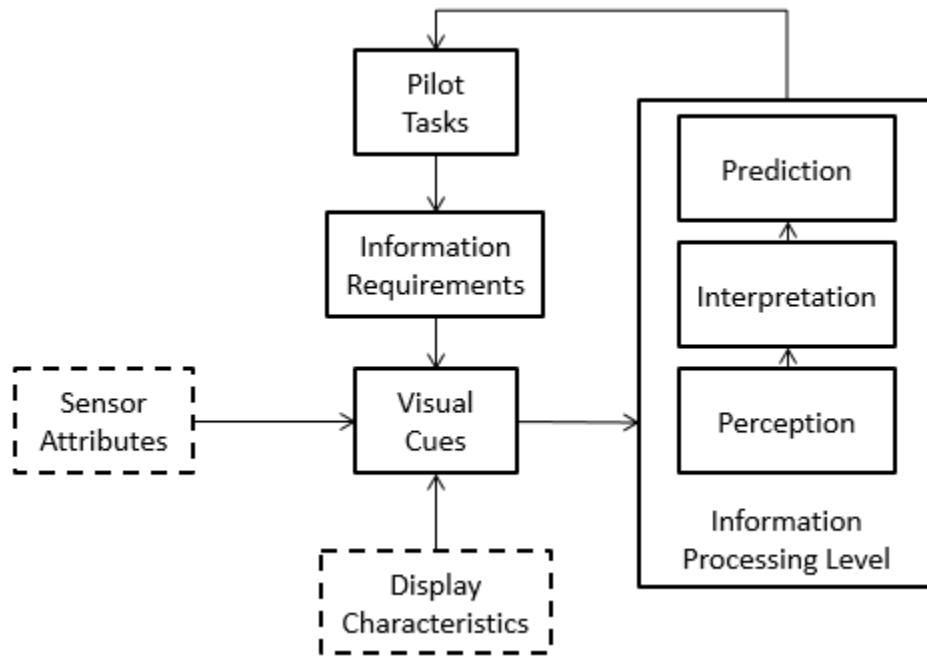

Figure 2. Flow Chart of Pilot Tasks, Information Requirements, Visual Cues, and Levels of Information Processing

3.1 Pilot Tasks

Pilots tasks depend on the phase of flight and type of flight. For a typical approach, pilots need to concern themselves with three major factors: terrain, airport environment and the factors for a stabilized approach. Terrain awareness and warning systems (TAWS) typically serve to depict the terrain during a pilot's approach; likewise, the airport environment is normally portrayed by traffic situation displays and air traffic control communications. EFVS can portray factors of a stabilized approach. An approach is considered stabilized when the following criteria are met (Marks 2017):

- Correct configuration of gears and flaps
- Appropriate speed and power settings
- On the desired glide path, typically about 3°
- On the extended centerline of the runway
- Positioned to land on the first 3rd of the runway

Additionally, the flare and landing can be broken down into a set of tasks, including:

- Judge the vertical height and descent rate of the aircraft with respect to the runway to minimize vertical speed on touchdown
- Adjust pitch to enter and maintain a proper flare attitude
- Maintain position on runway centerline
- Reduce the power
- Keep back pressure on the yoke to minimize vertical speed on touchdown
- Reduce the aircraft's speed

3.2   Information Requirements

Given the pilot tasks as just described, approach and landing have these information requirements:

- Flaps configuration
- Gear configuration
- Airspeed for flap and gear deployment
- Current airspeed
- Power setting
- Localizer deviation
- Glideslope deviation
- Location of the runway centerline
- Location of the runway sides
- Location of near and far ends of the runway
- Location of the touchdown markers on the runway
- Location of the horizon

These information requirements can relate to multiple tasks and multiple information requirements can be required for a single task. For example, a pilot on approach needs to have the correct configuration of gears and flaps, which means the flap configuration and gear configuration would both be required pieces of information.

3.3   Visual Cues

Visual cues are references in the cockpit and in the visual scene available to pilots, by which they can meet the information requirements mentioned previously. The mapping of information requirements discussed earlier to visual cues relevant to approach and landing is detailed in Table 1.

Table 1. Visual Cues Mapped to Information Requirements for Approach and Landing

Information Requirement	Typical Visual Cue
Flaps configuration	Flaps indicator
Gear configuration	Gear indicator
Current Airspeed	Airspeed indicator
Airspeed for flap and gear deployment	Airspeed indicator
Power setting	Engine RPM
Localizer deviation	Nav instruments
Glideslope deviation	Nav instruments
Location of the runway centerline	Runway centerline
Location of the runway sides	Visual of runway
Location of top and bottom of the runway	Visual of runway
Location of the touchdown markers	Touchdown markers
Location of the horizon	Horizon/attitude indicator

Some tasks require the pilot to integrate information from several visual cues; similarly, some tasks may reference any of several cues. For example, pilots can reference either (or both) the localizer deviation or the visual depiction of the runway centerline to determine if they are lined up on the extended centerline.

3.4   Information Processing Level

The information provided by visual cues needs to be processed by pilots. Figure 2 portrays this processing using the levels established by Endsley 1995 in framing situation

awareness: Information level 1 refers to perception of information in the environment; level 2 refers to the interpretation or comprehension of this information; and level 3 refers to the ability to project or predict future state.

For general aviation pilots during approach and landing based on the detailed tasks noted earlier; Information level 1 involves perceiving:

- Flaps configuration
- Gear configuration
- Airspeed for flap and gear deployment
- Power setting
- Localizer deviation
- Glideslope deviation
- Runway centerline
- Runway sides
- Top and bottom of the runway
- Touchdown markers
- Horizon

Information level 2 involves interpreting:

- Correct configuration of gears and flaps
- Appropriate speed and power settings
- On the desired glide path, typically about 3°
- On the extended centerline of the runway
- Whether the landing will be made in the first 3rd of the runway
- When to flare during landing
- Vertical descent of the aircraft with respect to the runway

Information level 3 involves projecting or predicting:

- Travel path of traffic and if it conflicts with the aircraft path
- Travel path of the aircraft and if it conflicts with any obstacles or terrain
- Location of touchdown spot on the runway

3.5   Connection from Sensor Attributes to Pilot Information Processing

As seen in Figure 3, multiple visual cues need to be perceived by pilots to inform required level 2 interpretation. EFVS sensor attributes can affect some of these visual cues and, therefore, directly affect pilots' perception and interpretation of the state of the environment relative to their approach and landing tasks. Specifically, Figure 3 shows, in red (also denoted by *), perceptions potentially impacted by a lack of visual cues of runway markings and, in blue (also denoted by **), perceptions potentially impacted by a sensor range.

On the desired glide path, typically about 3°	• Glideslope deviation • Near/far edge of the runway** • Horizon**
On the extended centerline of the runway	• Localizer deviation • Runway centerline* • Runway sides • Touchdown markers*
Positioned to land on the first 3rd of the runway	• Touchdown markers* • Near/far edge of the runway**
When to flare during landing	• Runway sides • Near/far edge of the runway** • Horizon**

Figure 3. Visual Cues for Level 1 "Perception" Information Processing, grouped with the Level 2 Interpretations They Support [Blue (or **) indicates Cues impacted by Sensor Range, Red (or *) text indicates Cues impacted by ability to Portray Runway Markings]

CHAPTER 4.   EXPERIMENTAL METHOD/DESIGN

To determine the effects of EFVS sensor range and portrayal of runway markings on pilot performance, a study was conducted using a fixed based flight simulator with general aviation pilots. This chapter discusses the flight simulator used, the independent and dependent variables, and the procedure for the experiment.

4.1   Flight Simulator

The flight simulator software used was FlightGear 4.4 2016. The flight simulator simulated a Cessna 172, which is a single engine land aircraft. Common training for the Cessna 172 is a 40-hour program while getting a private pilot's license, since no other certifications or endorsements are needed. A picture of the flight simulator is shown in Figure 4 and the simulator consisted of the following hardware:

- Yoke
- Throttle control system
- Rudder pedals
- 4 computer monitors

Figure 4. Picture of the Simulator

The simulator provides a heads-up display (HUD) on which the EFVS is portrayed. The HUD represents the instrument information overlaid on the sensor image of the outside scene. A picture of the HUD and the information provided without the EFVS is shown in Figure 5. The HUD meets the FAA required information besides path deviation and a flight path vector (FAA 2010).
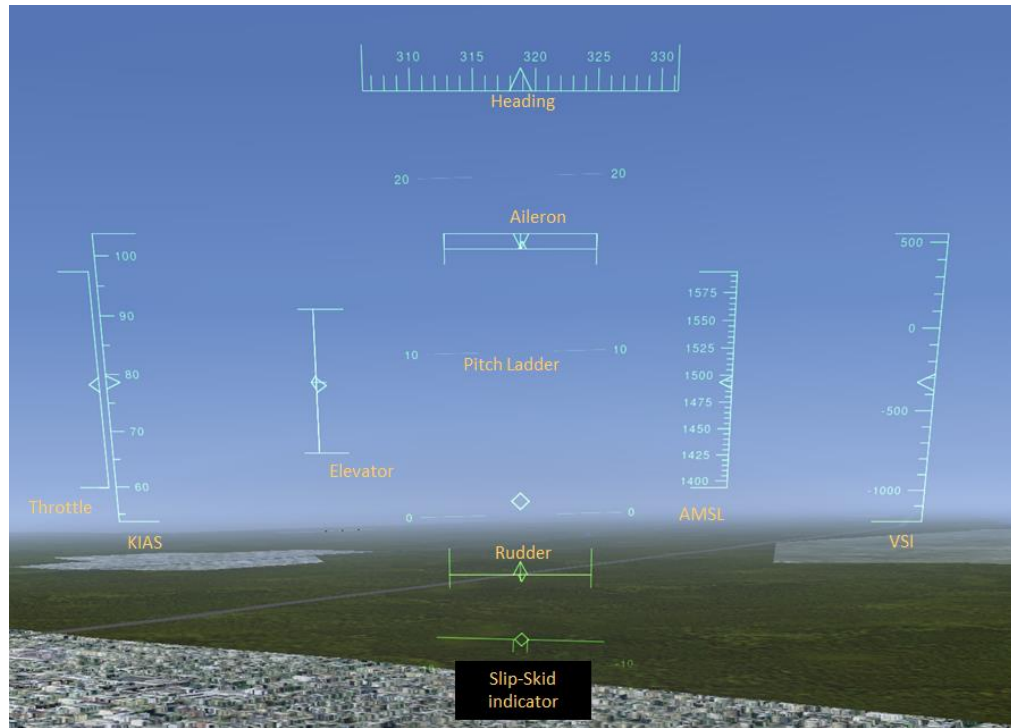
Figure 5. Heads-Up Display Provided to the Pilot During Each Scenario

The EFVS sensor portrayal can then be overlaid on the HUD. Graphical changes, can represent the EFVS sensor range and ability to portray runway markings. Therefore, the sensor limitations described earlier (EFVS sensor range and EFVS portrayal of runway markings) can be implemented to evaluate how they affect pilot performance. A picture of the sensor image with the HUD overlaid in shown in the next section.

4.2 Independent Variables

This experiment varied two attributes of EFVS sensors predicted to impact pilot performance during approach and landing: the ability of the EFVS to detect and portray runway markings, and the range at which EFVS displays the runway to the pilot. Specifically, these two attributes were tested at the following levels:

EFVS Range
- 1 Statute Mile
- 3 Statute Miles
- 12 Statute Miles

EFVS Portrayal of Runway Markings
- Present
- Not Present

The sensor ranges were chosen since 12 statute miles is a typical visual range for a pilot outside of instrument conditions; 3 statute miles is near a final approach point on most instrument approaches; and 1 statute mile represents the minimum altitude the pilot would reach on instruments alone. These conditions are shown in Figure 6 through Figure 12 with the top side being the imagery at the start of the scenario, while the bottom image shows when the runway was first visible for the participant. Since the range varies between conditions, the apparent size of the runway on the display is larger when it only comes in range at a close distance; for the long-range scenarios, where the runway is visible at the start of the scenario, the pictures are at the same range.
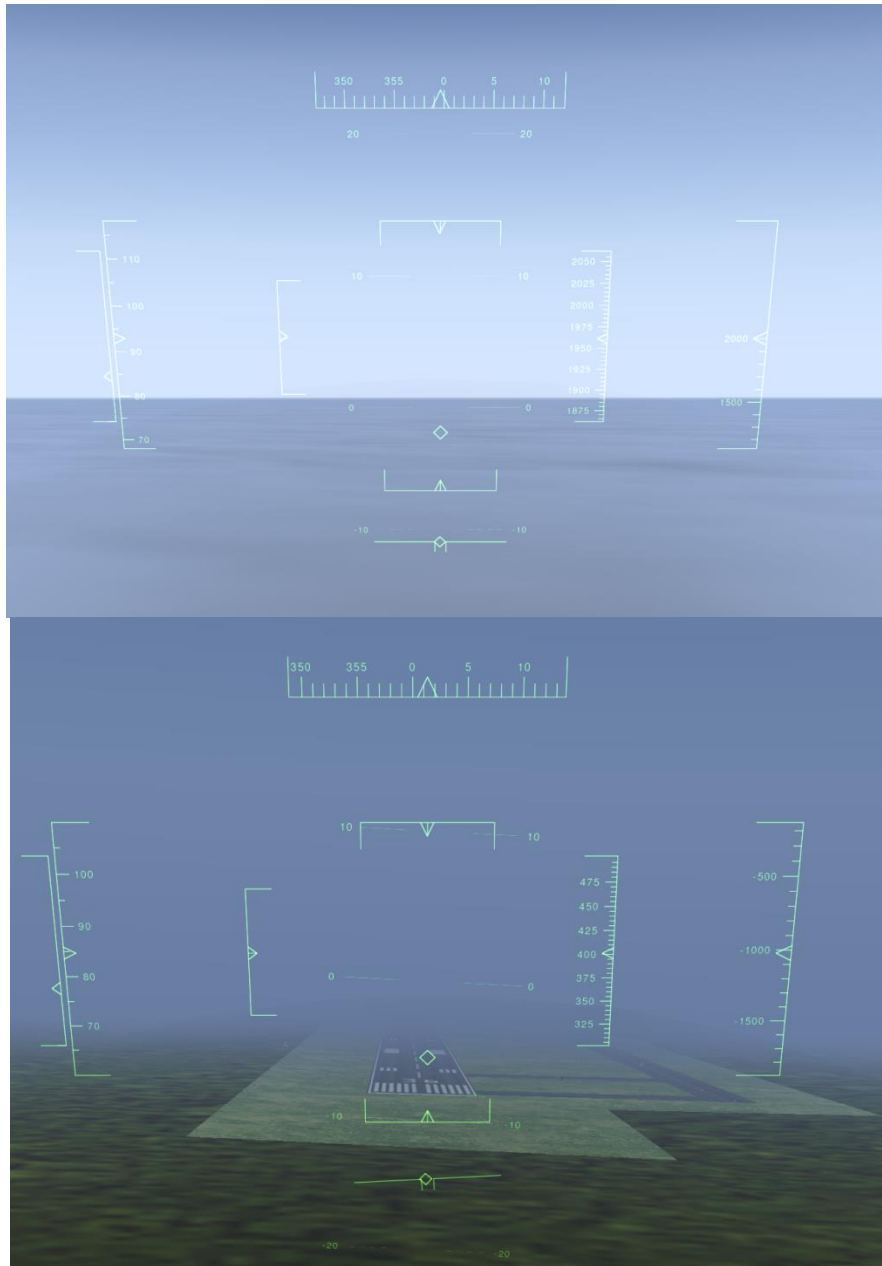
Figure 6. Normal Vision Conditions [Top shows beginning of scenario, Bottom shows Runway Visual Acquisition at 1 Statute Mile]
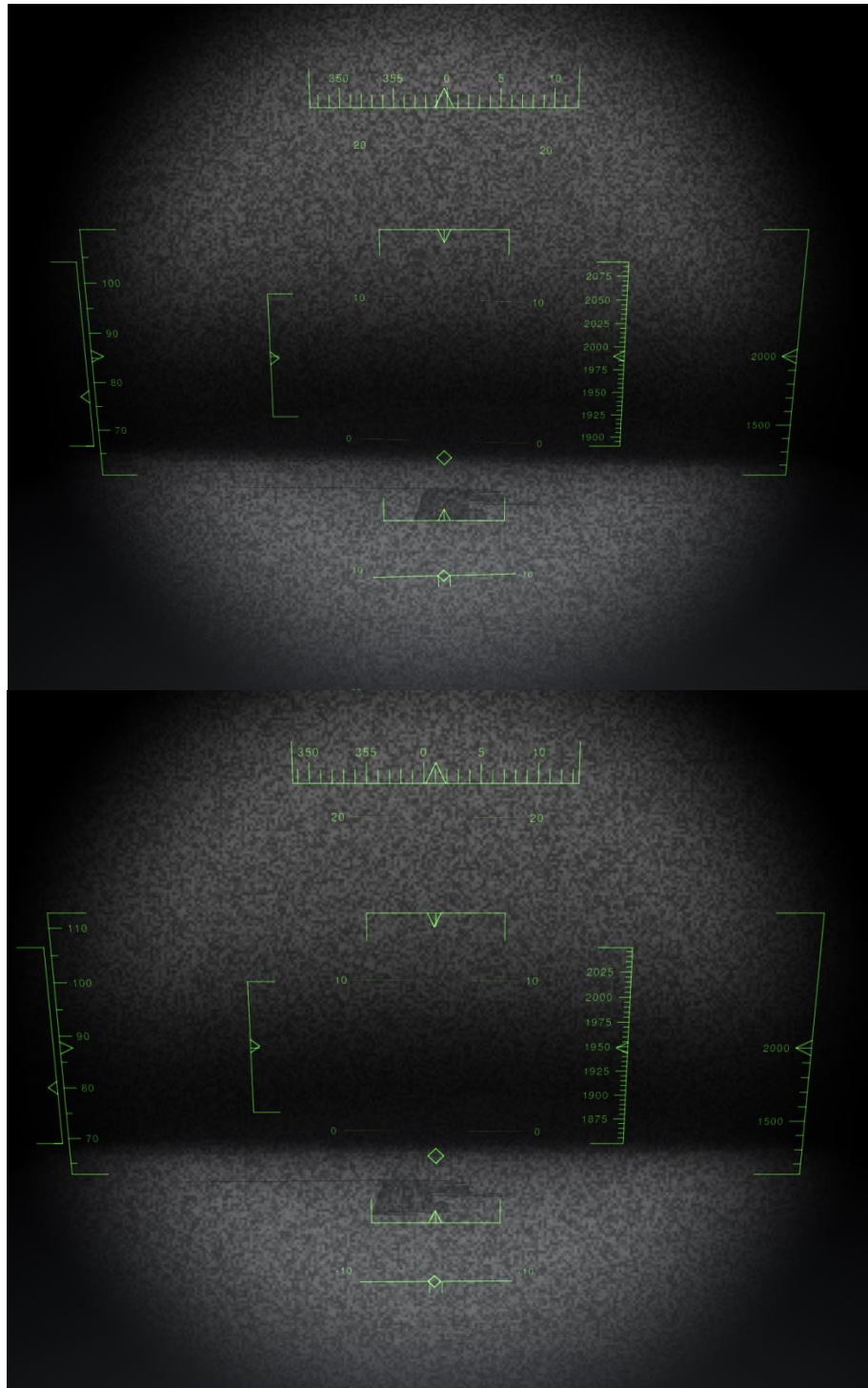
Figure 7. Long-Range EFVS with Runway Markings [Top shows beginning of scenario, Bottom shows Runway Visual Acquisition]
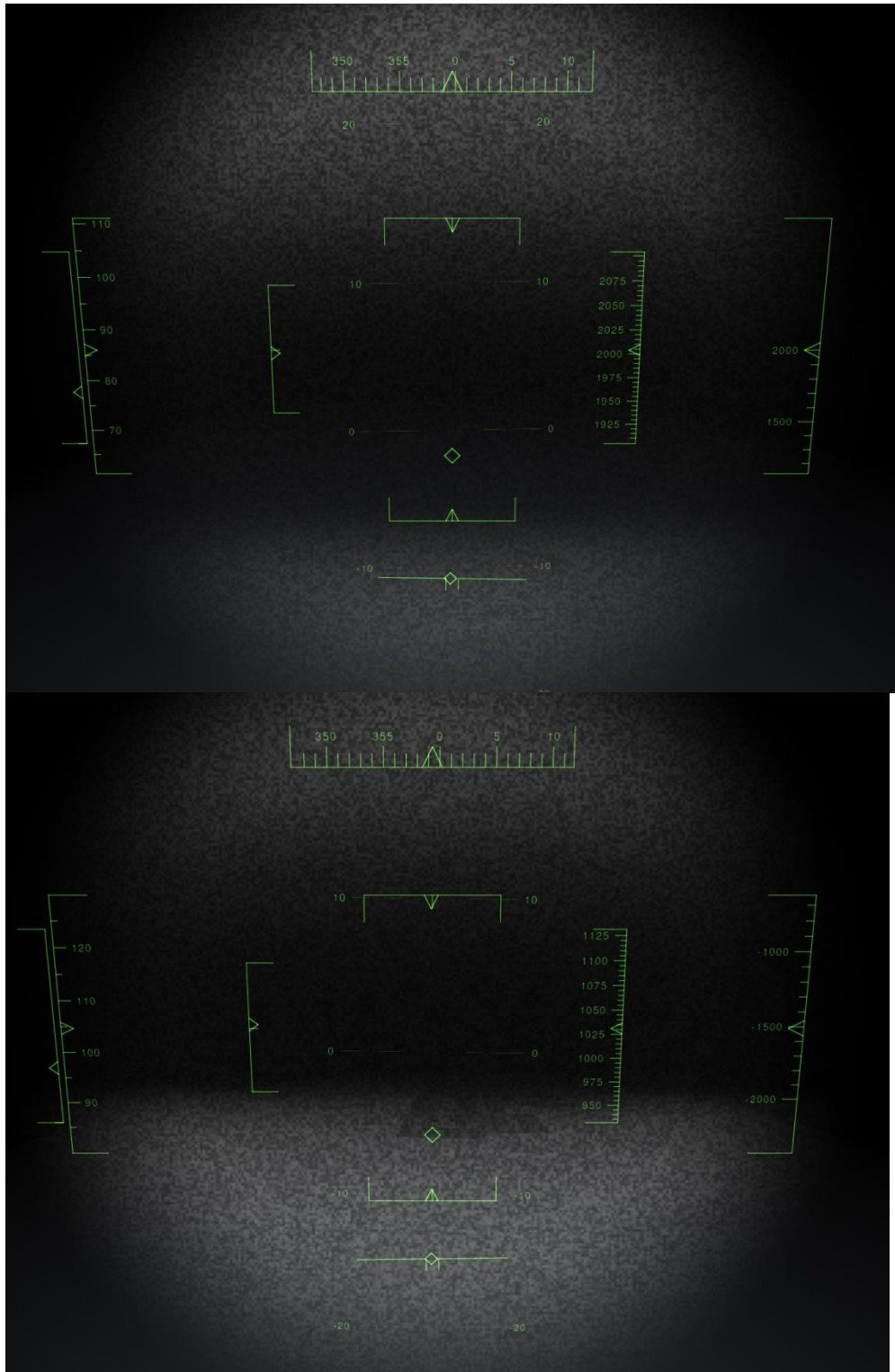
Figure 8. Mid-Range EFVS with Runway Markings [Top shows beginning of scenario, Bottom shows Runway Visual Acquisition]
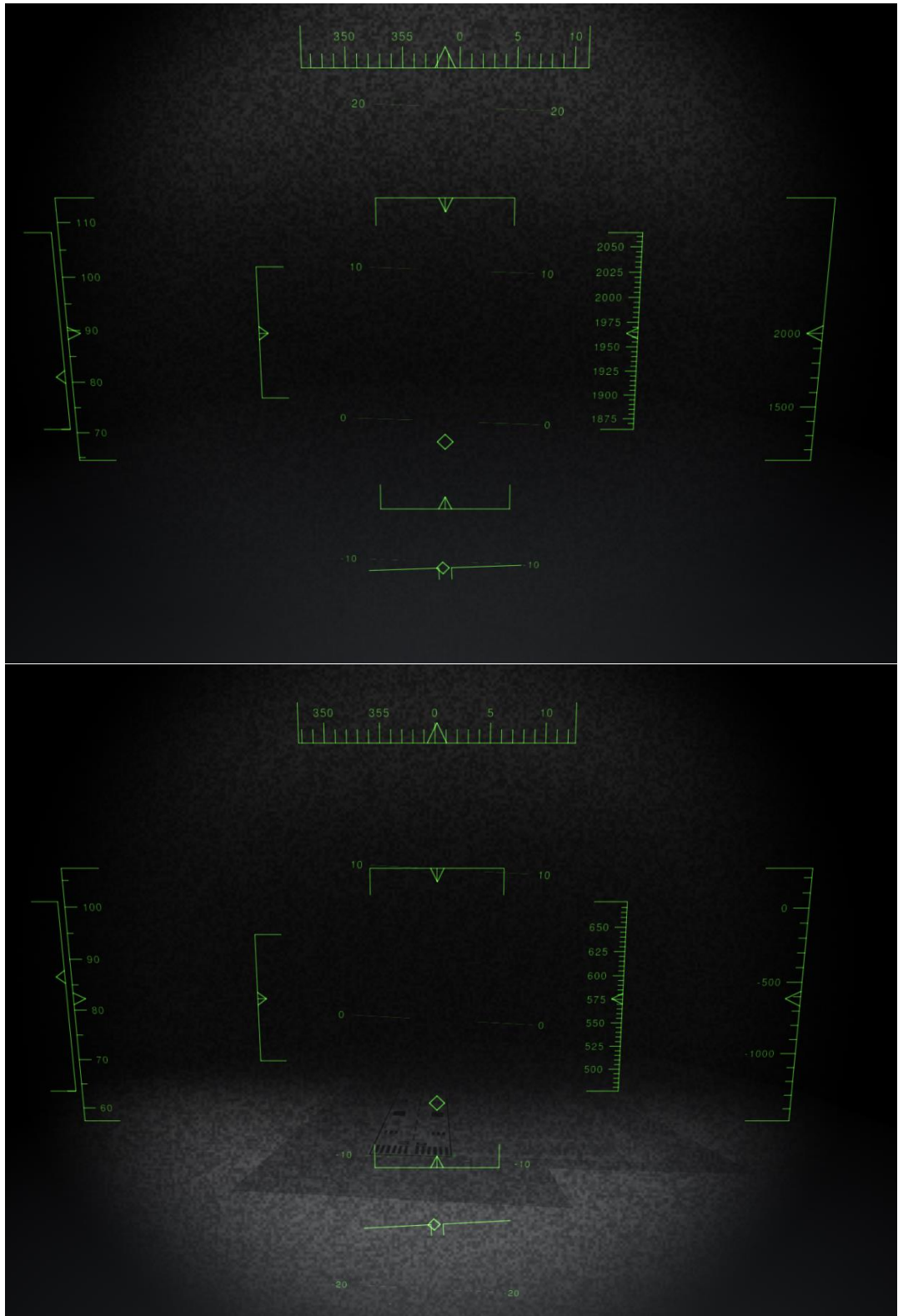
Figure 9. Short-Range EFVS with Runway Markings [Top shows beginning of scenario, Bottom shows Runway Visual Acquisition]
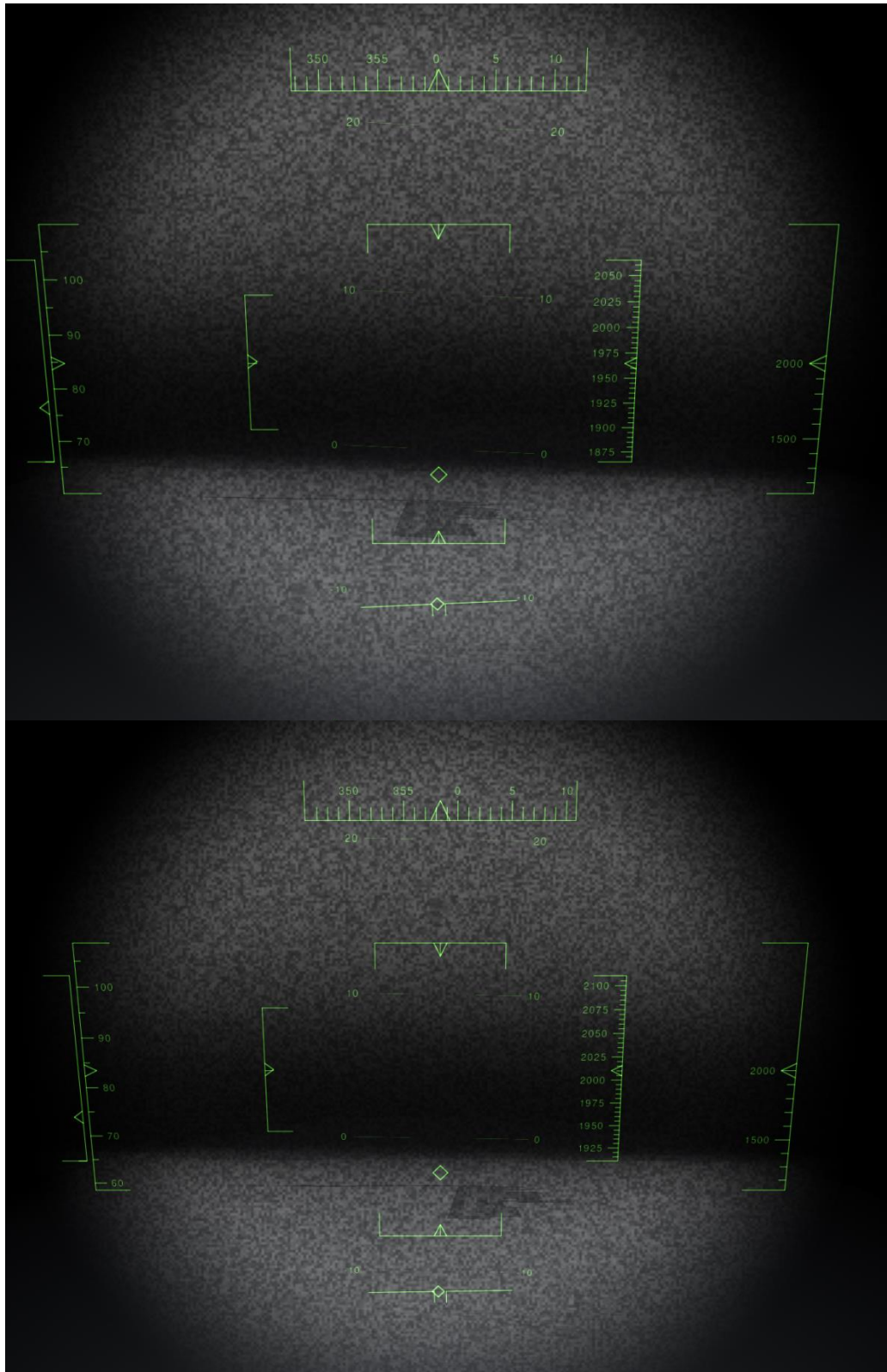
Figure 10. Long-Range EFVS without Runway Markings [Top shows beginning of scenario, Bottom shows Runway Visual Acquisition]
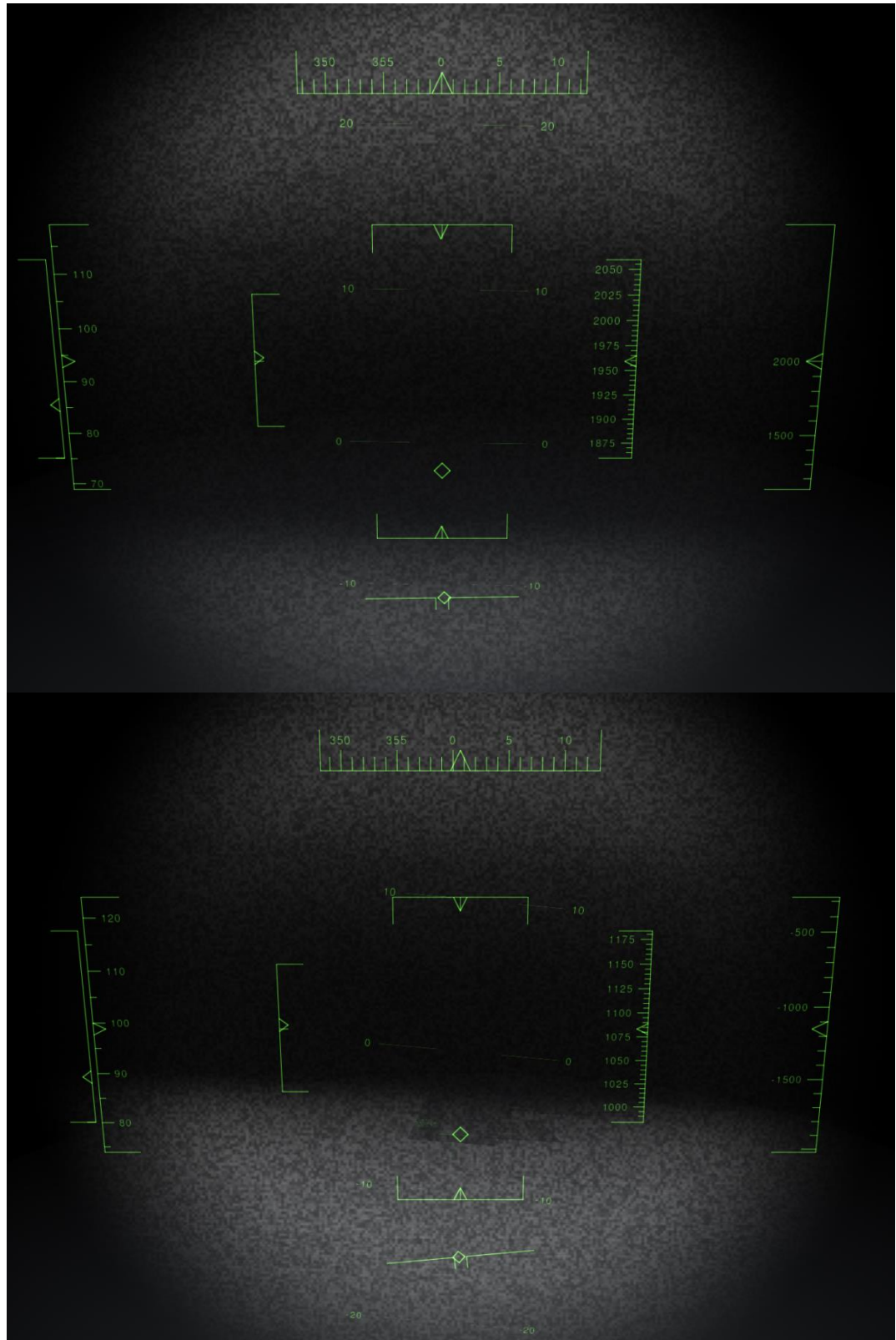
Figure 11. Mid-Range EFVS without Runway Markings [Top shows beginning of scenario, Bottom shows Runway Visual Acquisition]
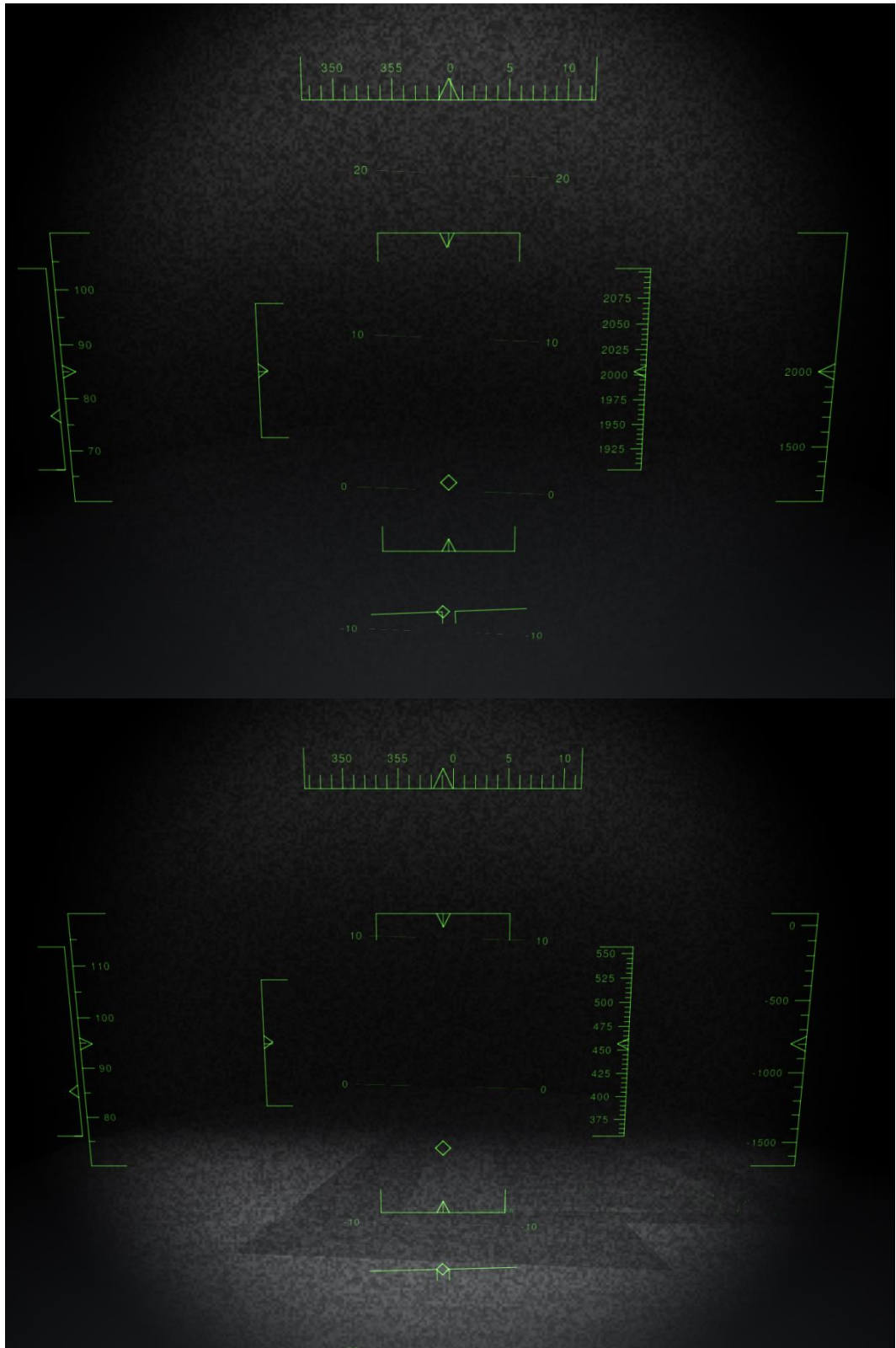
Figure 12. Short-Range EFVS without Runway Markings [Top shows beginning of scenario, Bottom shows Runway Visual Acquisition]

4.3 Experiment Scenario

Pilots were asked to fly instrument approaches starting from these initial conditions:

- 3-nautical mile final approach
- No flaps
- Nav instruments tuned to the ILS
- On the glideslope and localizer
- KIAS approximately 100 knots
- No wind
- Clearance to land from the tower

The participants were told to bring the aircraft to their preferred approach speed and configure the aircraft with typical flaps settings while maintaining the approach, looking out for the runway via EFVS or their natural vision, and ultimately land the aircraft.

4.4 Procedure

The procedure for the experiment had two major stages, training and experimental flights, as detailed next. The training consisted of getting the participant familiar with the simulator and experiment tasks. The experimental flights consisted of 7 different approaches, each followed by a questionnaire, ending with a post experiment questionnaire.

4.4.1.1 Training

The training consisted of four flights, listed below:

- Normal Vision – Instrument approach
- EFVS – Long sensor range with markers
- EFVS – Long sensor range without markers
- EFVS – Short sensor range with markers

To advance to the next stage of training and then the experiment, the participant's performance was assessed relative to these requirements after each approach:

- Localizer and glideslope deviation must not exceed 1 full scale deviation at any point during the approach
- Vertical speed at touchdown must be less than 150 fpm
- A subjective assessment of whether the participant was in control of the aircraft

All the pertinent information regarding the simulator and the training flights was presented to the participants in a briefing before training began, given in Appendix A. After the training flights were completed, the pilots completed a sample questionnaire, so that they were familiar with it before starting any experimental flights.

4.4.1.2 Experiment Flights

The participant flew 7 experiment flights, each with different EFVS capabilities. The experimental conditions each flew the same scenario as described earlier. To fully account for ordering effects, the conditions were counterbalanced using a Latin square design. Each of the experimental conditions and their associated number are listed in Table 2.

Table 2. Experiment Conditions Labels and Descriptions

Label	Description
A1	Basic approach, no EFVS
B1	Approach with EFVS, runway markings and 12 sm visibility
B2	Approach with EFVS, runway markings and 3 sm visibility
B3	Approach with EFVS, runway markings and 1 sm visibility
C1	Approach with EFVS, no runway markings and 12 sm visibility
C2	Approach with EFVS, no runway markings and 3 sm visibility
C3	Approach with EFVS, no runway markings and 1 sm visibility

4.4.2   Dependent Variables

The dependent variables were chosen to capture pilot performance during approach and landing. For instrument approaches, the FAA (FAA 2017) has specific criteria for a pilot to demonstrate mastery sufficient for their instrument flight rating. These criteria are:

- No more than +/- 10 knots deviation on approach speed
- No more than ¾ scale deviation on either the localizer or glideslope

These criteria also align with the stabilized approach criterion mentioned earlier. Therefore, glideslope deviation and localizer deviation were recorded and the following statistics were generated:

- RMS over the entire flight
- Maximum value
- Number of times exceeds the FAA limits and duration

Several other criteria can be established for landing performance, including distance from runway centerline, distance from touchdown markers, and vertical speed upon touchdown. The runway in the scenarios is 150 feet wide, therefore, any value over 75 feet means the aircraft lands off the runway. Additionally, a vertical speed larger than 200 feet per minute could damage the aircraft in real-life.

The questionnaire at the end of each scenario measured workload of each participant. The workload assessment utilized in this experiment was the NASA TLX. Its workload scale is based upon these six metrics:

- Mental Demand – How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
- Physical Demand – How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
- Temporal Demand – How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
- Performance – How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
- Effort – How hard did you have to work (mentally and physically) to accomplish your level of performance?
- Frustration Level – How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

Each of these tasks were rated by the participant on a scale of 0-100 after each experiment flight. During the final questionnaire, the participants weighted the six categories using pairwise comparisons. This allows the generations of two main data sets

for each participant: participant ratings of each of the six scales for each condition, as well as an overall workload for each condition.

At the end of each experiment flight, in addition to NASA TLX, the participants filled out a survey. The three questions were:

- In real-life, do you think you had sufficient information for a safe approach and landing or do you think you would have elected to go around?
- Beyond the raw measure of being able to find the information at some time, were there any points during the approach or landing where the information was not available at the specific time you needed it?
- Do you think you changed your visual scan in some way because of the EFVS portrayal?

4.4.3 Participants

A total of 21 participants were recruited to fully counterbalance the experimental conditions and reduce ordering effects. The participants were all current instrument rated pilots. Additionally, a minimum of 150 flight hours was required. The participants were recruited from local Atlanta flight clubs by means of emails and posters. The pilots total hours ranged from 150 to 9500 hours with most participants being current in C172 or similar single engine land aircraft. For the specific requirements and other details concerning the pilot recruiting, see Appendix A.

CHAPTER 5.   RESULTS

This chapter describes the results of the flight simulator experiment evaluating the effects on pilot performance during approach and landing of two attributes of EFVS sensors: sensor range and their ability to detect and portray runway markings.

Pilot performance during approach was assessed by examining glideslope deviation and localizer deviation. Pilot performance on landing was assessed by examining at touchdown vertical speed, distance from runway centerline, and distance from touchdown markers. For these ratio data, the following analyses were conducted:

- Identification of any exceedances of acceptable operational limits
- For subsequent statistical analysis, removal of outliers outside of 2 standard deviations
- Two-way ANOVA examining for any significant interaction effects between the independent variables
- Likelihood ratio test for random effects due to participants
- Mixed-effects or one-way ANOVA (as appropriate) to find the relationships between the independent and dependent variables

Additionally, questionnaires asked about workload (via NASA TLX), visual cues, and other safety questions concerning the EFVS. For the ordinal data collected with questionnaires and the frequency of outliers noted above, non-parametric statistical analysis methods were used.

Outliers outside of two standard deviations were removed to account for some experimental errors. These experimental errors included, but were not limited to, graphical freezes in some of the experimental scenarios, control sensitivity issues, and unnoticed operator errors. The ANOVAs were conducted on the data both with and without outliers and the results did not vary significantly between them.

5.1 Pilot Performance during Approach

Plots, detailed results, and statistical analysis discussed in this chapter are given in Appendix B and Appendix C. All data examined by ANOVA had outliers outside of 2 standard deviations removed.

5.1.1 Number of Times Glideslope Deviation Limit Exceeded

The glideslope deviation was measured on a scale of 0 to 1, with 1 being a full-scale deviation. As stated before, the FAA defines ¾ of a full-scale deviation on the glideslope as unacceptable, which is 0.75 on this scale. Figure 13 shows the number of times per flight the ¾ scale deviation was exceeded as a function of EFVS portrayal of runway marking. As shown in Figure 13, all but one of these exceedances occurred with some form of EFVS; these exceedances occurred in 36/147 approaches, i.e. 24.4%. Overall, the glideslope exceeded the limit in 33.33% of approaches where pilots were provided with an EFVS portraying runway markings conditions, and 22.22% of conditions where pilots were provided with an EFVS not portraying runway markings. Seven of these exceedances were more than two standard deviations from the mean and removed as outliers for the subsequent statistical analysis.
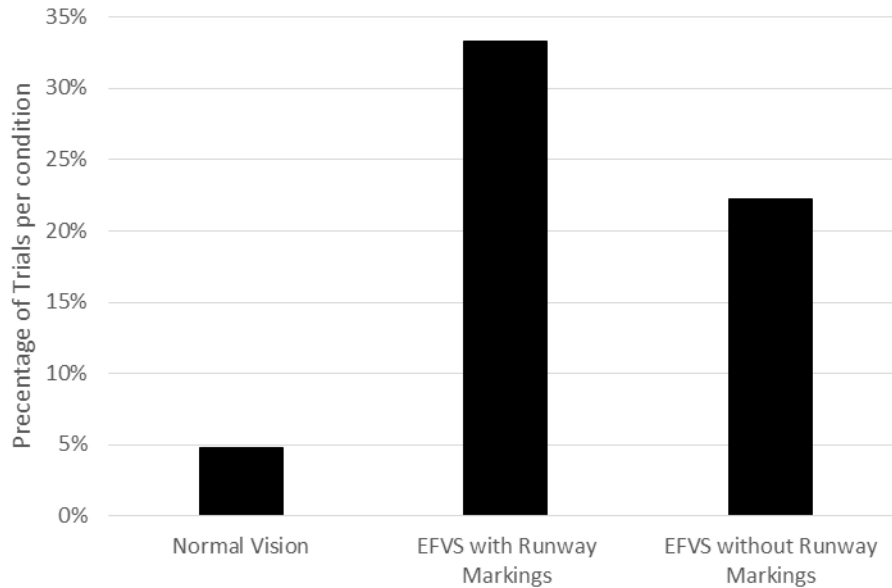
Figure 13. Number of Times Glideslope Deviation Limit was Exceeded in Any Flight as a Function of EFVS Portrayal of Runway Markings

Figure 14 shows the number of exceedances as a function of EFVS sensor range. As shown in Figure 14, the majority of the exceedances occur in mid/short range conditions. These exceedances occurred 35 times out of the 126 EFVS scenarios, which is approximately 27.7% of the time. The percentage of exceedances in all of the long, mid, and short sensor range conditions separately are 16.67%, 38.10%, and 28.57%, respectively. Seven of these cases were removed as outliers: three in long range, one in mid-range, and three in short sensor range conditions.
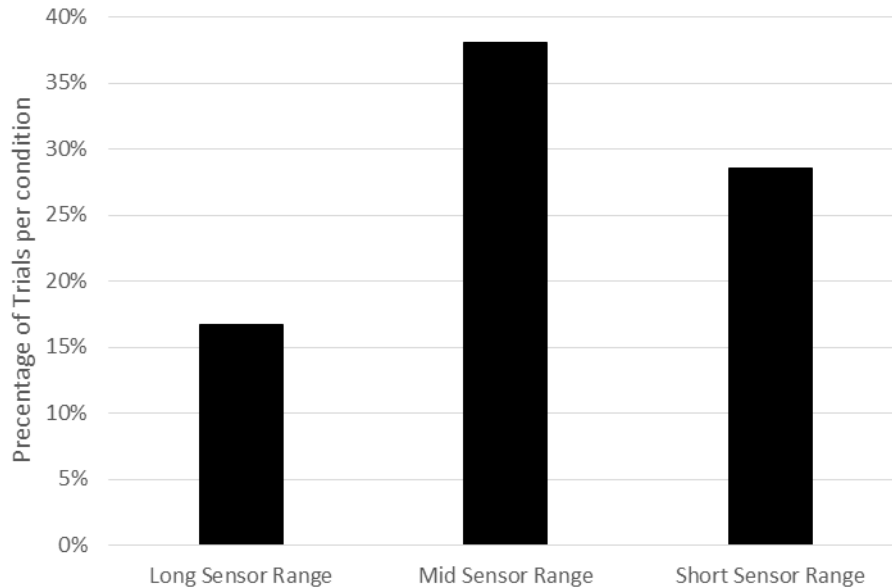
Figure 14. Number of Times Glideslope Deviation Limit was Exceeded in Any Flight as a Function of EFVS Sensor Range

5.1.2 Glideslope RMS

A two-way ANOVA of glideslope RMS examined if interaction effects were present between the two independent variables (portrayal of runway markings and sensor range). No significant interaction was found.

Analyzing the independent variables separately with outliers removed, a likelihood ratio test determined that participants are a source of variance when analyzing for the effects of portraying runway markings. A linear mixed effects model showed that there are marginally significant differences depending on the portrayal of runway markings ($p = 0.0931$), as shown in Figure 15. A Cohen's d test found small effects between: EFVS portraying runway markings and not portraying runway markings ($d = 0.2629$), and normal vision compared to EFVS portraying runway markings ($d = -0.4143$).

44
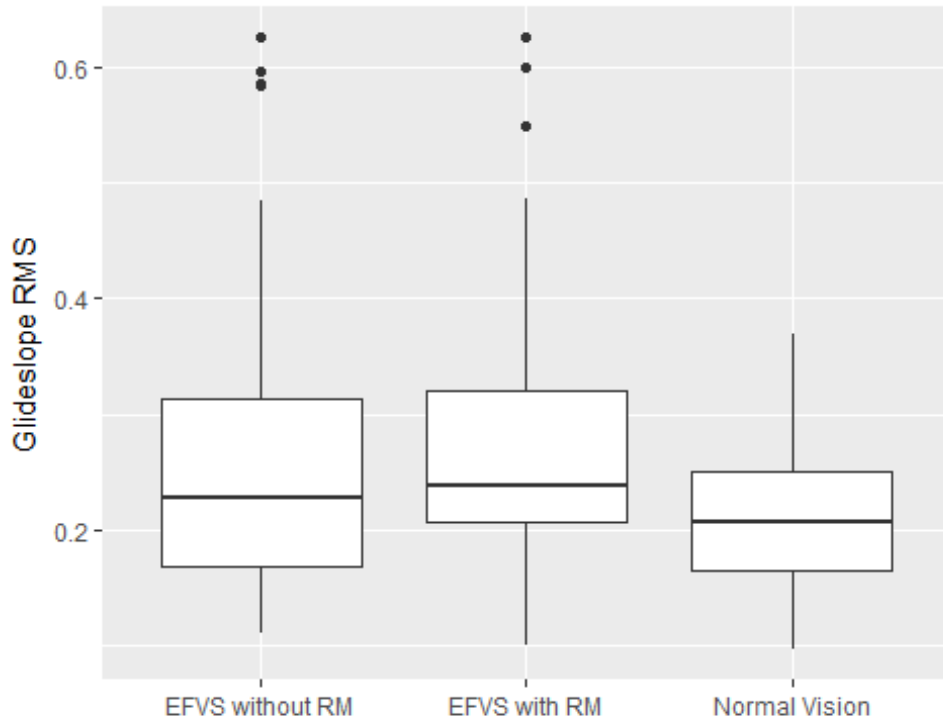
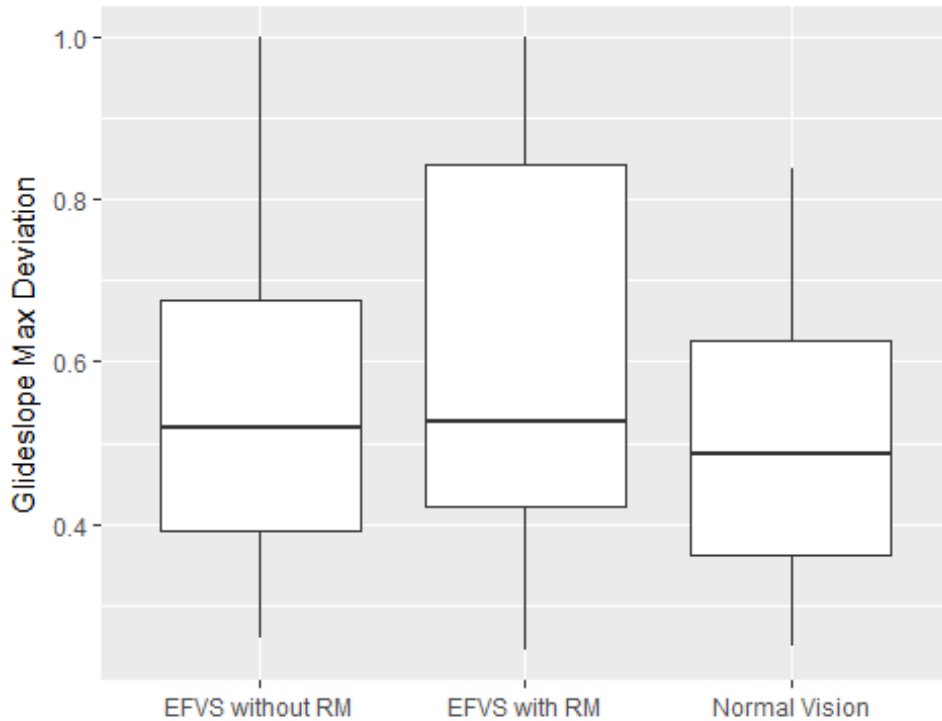**Figure 15. Glideslope Deviation as a Function of EFVS Portrayal of Runway Markings**

Additionally, analyzing the glideslope deviation with respect to sensor range, participants were found to be a significant contribution to variance. A mixed effects model also identified a significant effect due to EFVS sensor range ($p = 0.0074$), as shown in Figure 16. A Tukey test was conducted and showed a statistically significant difference in long compared to mid sensor range ($p = 0.0274$) and a marginally significant difference between short and mid sensor range ($p = 0.0793$). A Cohen's d test found a medium effect between long and mid sensor range ($d = -0.5776$), and a small effect between mid and short sensor range ($d = -0.4063$).
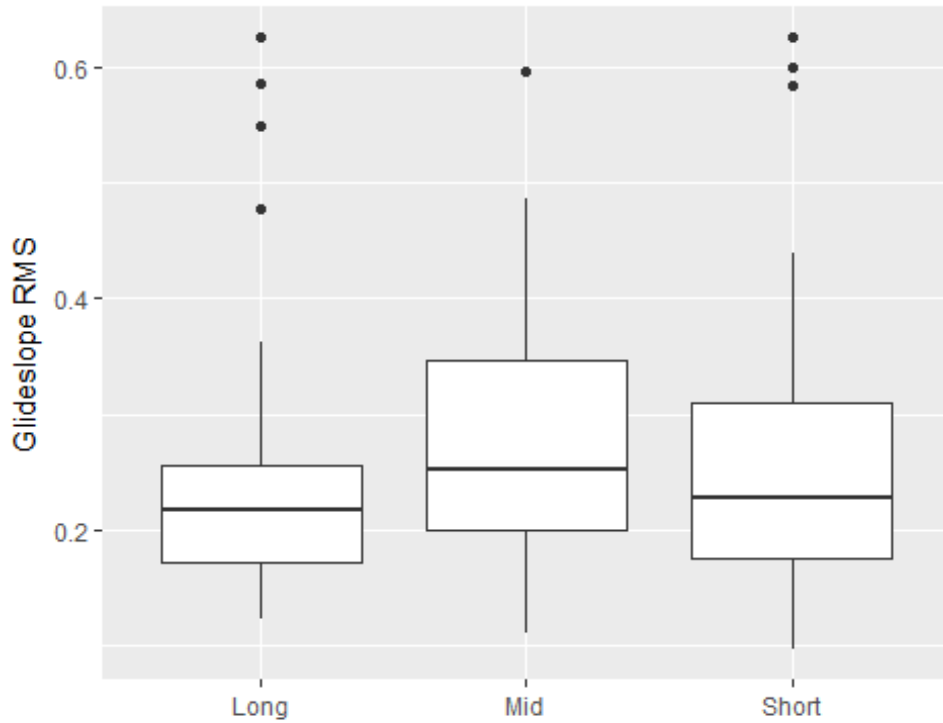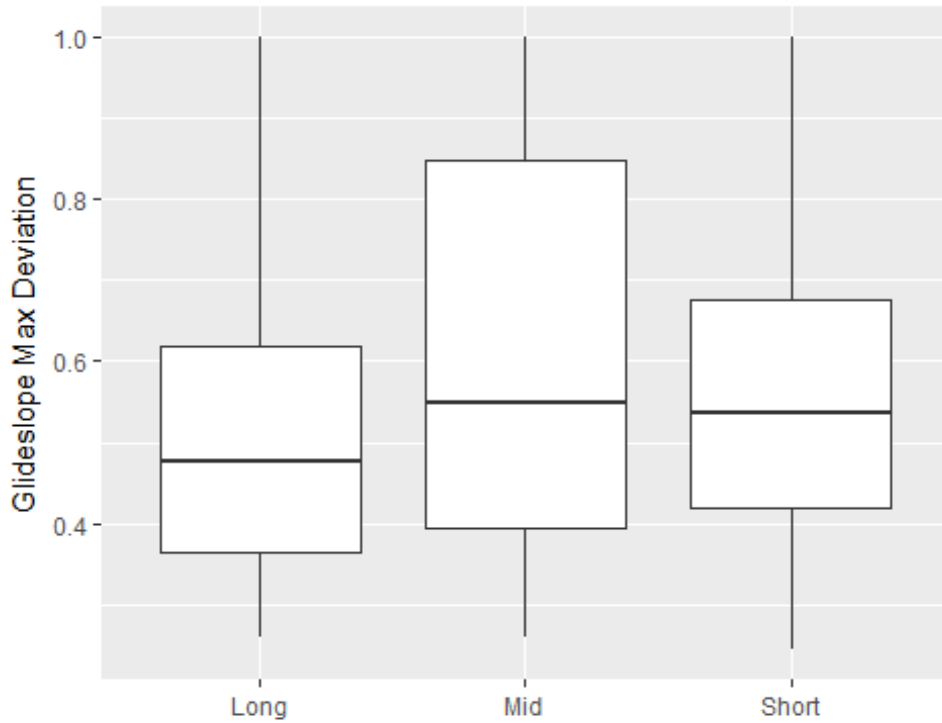
Figure 16. Glideslope Deviation as a Function of EFVS Sensor Range

5.1.3   Glideslope Maximum Deviation

Similar to the glideslope RMS deviation, the maximum deviation is measured upon a scale of 0 to 1, where 1 represents a full-scale deviation in either direction along the glideslope.   The first test conducted was a two-way ANOVA, which showed no interaction effects between the independent variables for this measure.   After removing the outliers, the independent variables were analyzed separately.

Analyzing the EFVS portrayal of runway markings first, a likelihood ratio test determined participants are a significant source of variance.   A mixed effects ANOVA identified a marginally significant effect due to EFVS portrayal of runway markings ($p =$ 0.067), as seen in Figure 17.   A Cohen's d test found small effects between: normal

vision and EFVS not portraying runway markings (d = -0.4517), and normal vision

compared to EFVS portraying runway markings (d = 0.4827).

Figure 17. Glideslope Max Value as a Function of EFVS Portrayal of Runway Markings

Analyzing the maximum glideslope deviation with respect to EFVS sensor range, a

likelihood ratio test found that participants are a significant source of variance. As seen

in Figure 18, a mixed effects ANOVA indicated a marginally significant effect due to

EFVS sensor range (p = 0.0801). A Cohen's d test found a small effect between long and

mid sensor range (d = -0.4365); and a small effect between long and short sensor range (d

= -0.1630).

Figure 18. Glideslope Max Value as a Function of EFVS Sensor Range

5.1.4   Number of Times Localizer Deviation Limit Exceeded

The localizer deviation was measured on a scale of 0 to 1, with 1 being a full-scale deviation and 0 being no deviation. As stated before, the FAA defines ¾ of a full-scale deviation on the localizer as unacceptable, which would be 0.75 on this scale.

Figure 19 shows the number of times the ¾ scale deviation was exceeded as a function of EFVS portrayal of runway markings. As shown in Figure 19, these exceedances occur only with EFVS; 6 of these approaches are without runway markings and 4 are with runway markings while 3 occur at the mid-range condition and 7 occur at the short-range. These exceedances occur 10 out of the 147 trials, which is approximately 6.8% of the time. Overall, the localizer exceeded the limit in 6.35% of

approach with EFVS portraying runway markings, and 9.52% of all conditions with EFVS not portraying runway markings. The percentage of exceedances in all the long, mid, and short sensor range conditions separately are 0%, 7.14%, and 16.67%, respectively. Six of these exceedances were removed as outliers, three of which were in flights with an EFVS with short-range sensors and no portrayal of runway markings, two were with an EFVS with short-range with portrayal of runway markings and one was with an EFVS with mid-range sensors and portrayal of runway markings.
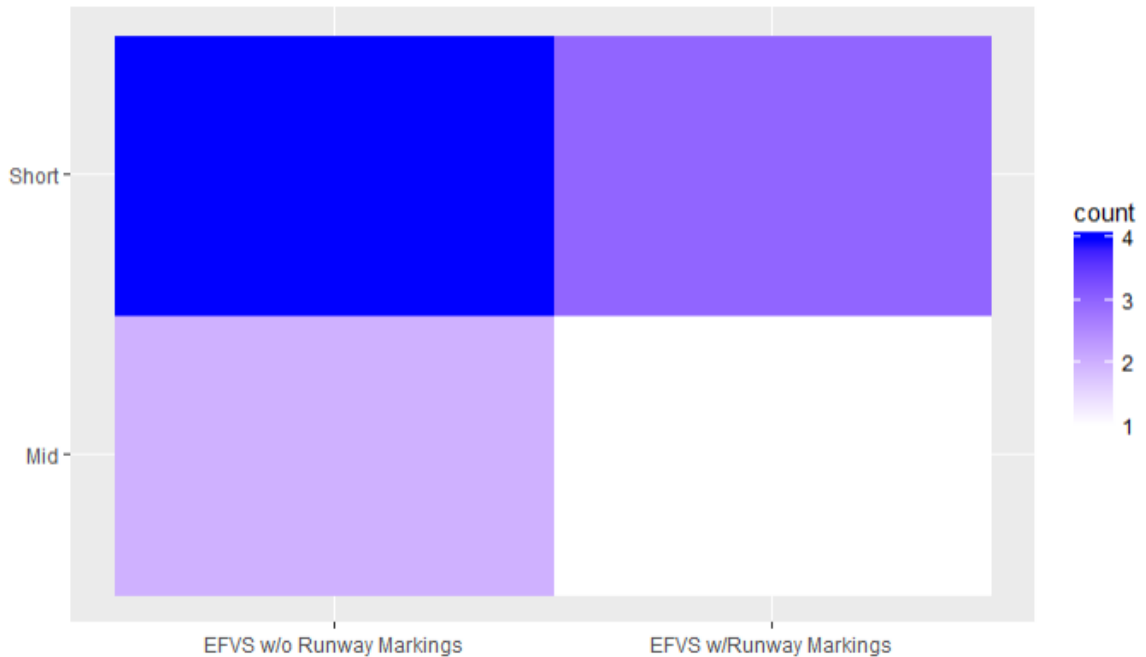
Figure 19. Number of Times Localizer Deviation Limit was Exceeded for All Flights

5.1.5   Localizer RMS

Analyzing the independent variables separately with outliers removed, the first comparison was with the EFVS portrayal of runway markings. A likelihood ratio test identified significant source of variance due to participants. A mixed effects ANOVA identified that no statistically significant effect ($p = 0.2443$) due to EFVS portrayal of

runway markings, as seen in Figure 20. A Cohen's d test found small effects between: normal vision and EFVS not portraying runway markings ($d = 0.2673$), and normal vision compared to EFVS portraying runway markings ($d = 0.4149$).
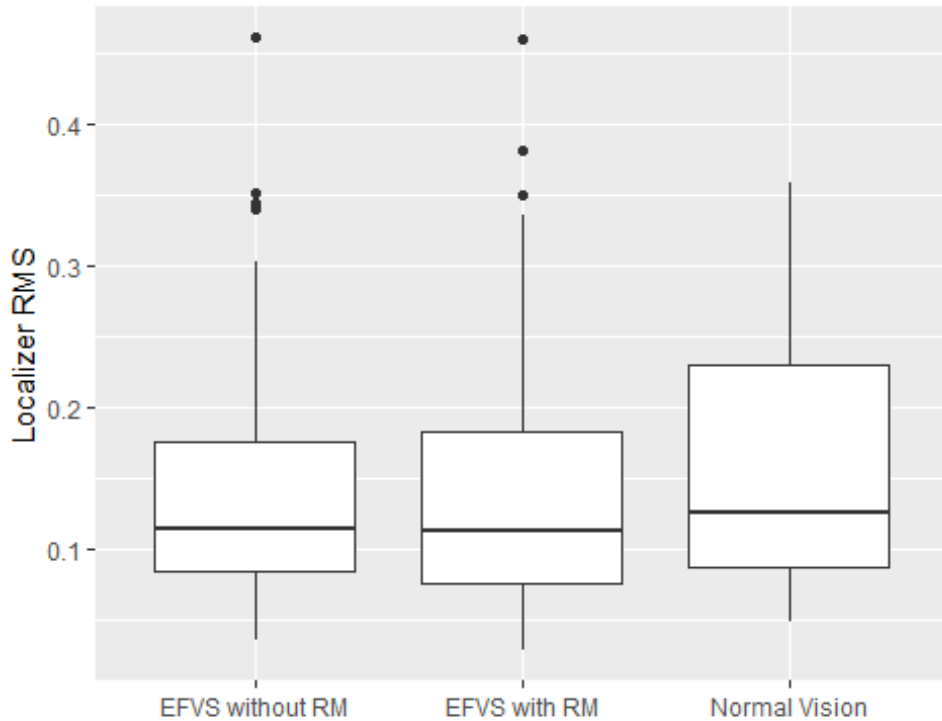

Figure 20. Localizer Deviation RMS as a Function of EFVS Portrayal of Runway Markings

The independent variable of EFVS sensor range was also analyzed, for this independent variable, a likelihood ratio test identified participants as a significant source of variation. A mixed effects model ANOVA identified a significant effect ($p = <0.0001$) on localizer RMS due to EFVS sensor range, as shown in Figure 21. A Tukey test showed a significant difference in both mid to long sensor range ($p = 0.0112$) and short to long sensor range ($p < 0.0001$). A Cohen's d test found a large effect between long and

short sensor range ($d = 0.9824$), a medium effect between long and mid sensor range ($d = -0.7404$), and a small effect between mid and short sensor range ($d = 0.2369$).
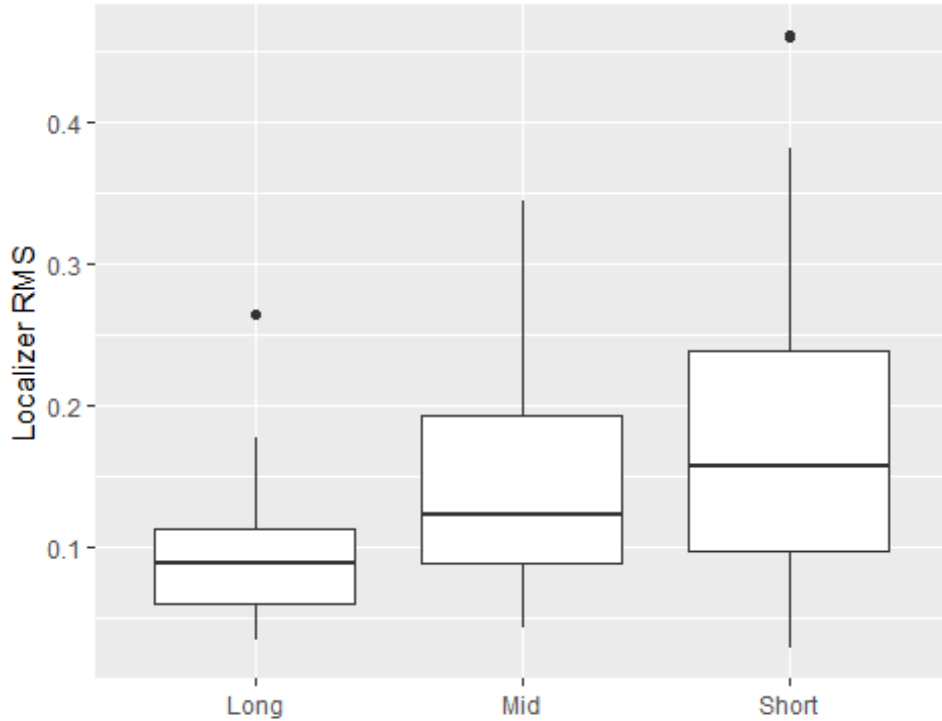

Figure 21. Localizer Deviation as a Function of EFVS Sensor Range

5.1.6   Localizer Maximum Value

Similar to the previous deviation values, the localizer maximum value was on a scale of 0 to 1, where 0 represents no deviation and 1 represents a full-scale deviation. As a reminder, the FAA limit for an instrument approach is no more than a ¾ scale deviation, which would equal 0.75 for this scale. A two-way ANOVA showed no interaction effect between the independent variables for the localizer maximum value, therefore, the independent variables were analyzed separately with outliers removed.

For the independent variable of EFVS portrayal of runway markings, a likelihood ratio test determined that participants were a significant source of variation. A mixed effects ANOVA identified no significant interaction ($p = 0.4497$) between the EFVS portrayal of runway markings and localizer maximum value. This data is shown in Figure 22. A Cohen's d test found small effects between: normal vision and EFVS not portraying runway markings ($d = 0.3002$), and normal vision compared to EFVS portraying runway markings ($d = 0.2454$).
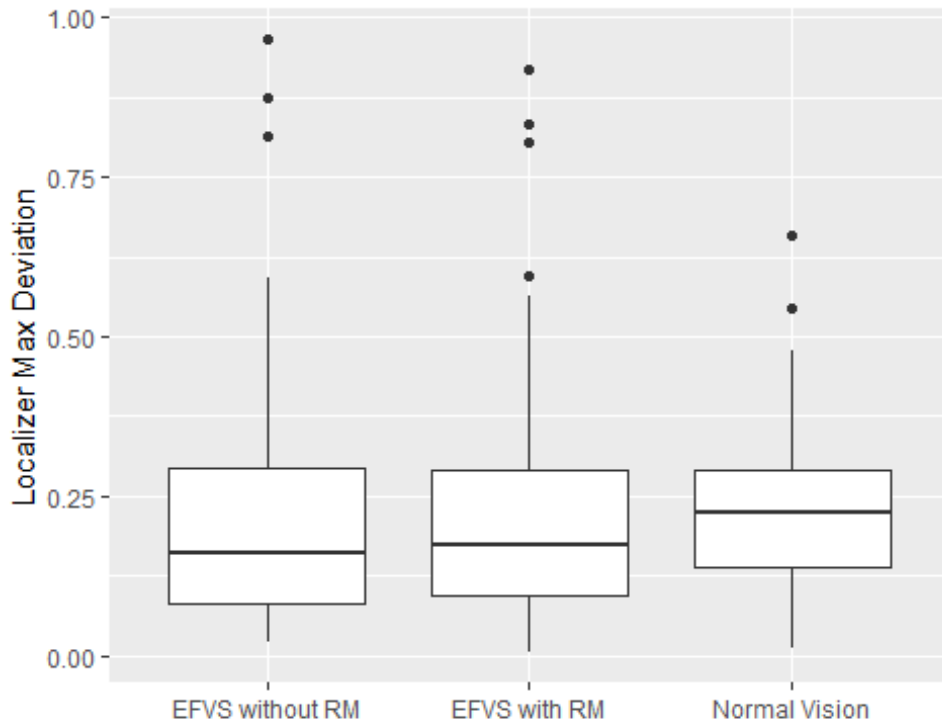

Figure 22. Localizer Maximum Value as a Function of EFVS Portrayal of Runway Markings

Additionally, the localizer max value was compared to EFVS sensor range. The participants were found to be a significant source of variance. The mixed effects ANOVA identified a significant effect due to EFVS sensor range ($p = <0.0001$), which is

shown in Figure 23. A Tukey test showed a significant difference in both mid to long sensor range ($p = 0.0054$) and short to long sensor range ($p < 0.0001$). A Cohen's d test found a medium effect between long and mid sensor range ($d = -0.7274$), and a large effect between long and short sensor range ($d = 0.9781$).
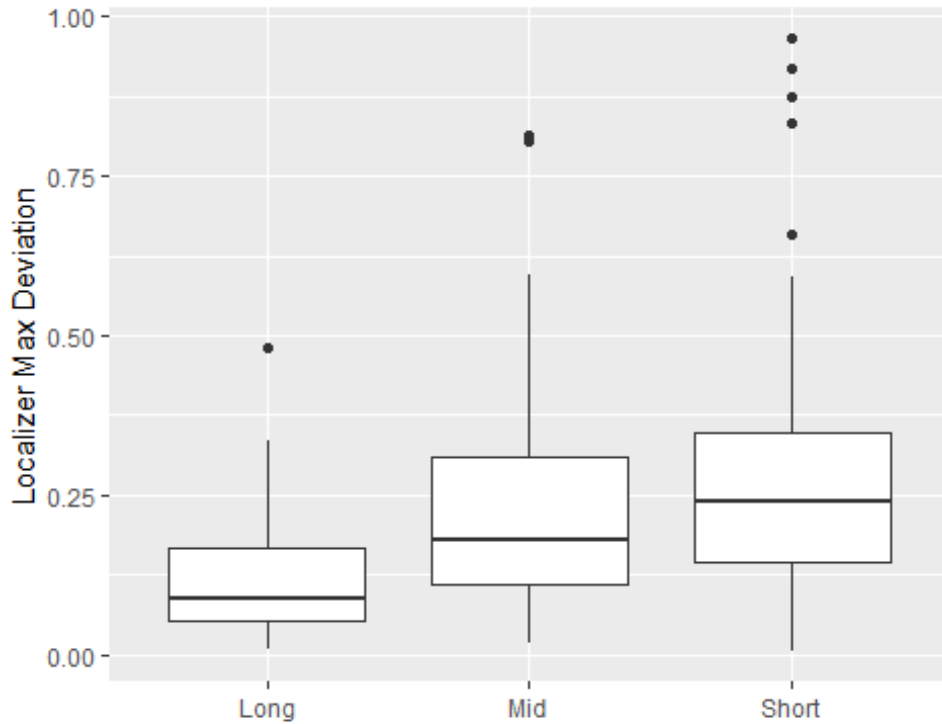

Figure 23. Localizer Maximum Value Relative to EFVS Sensor Range

5.2   Pilot Performance During Landing

All data recorded, including plots and statistical analysis discussed in this section is given in Appendix B and Appendix C. This section discusses the analyses, highlighting significant results.

5.2.1   Vertical Speed

The training required that pilots touchdown with a vertical speed under 150 feet per minute, but typically 100-200 feet per minute is acceptable; any higher and the aircraft could be damaged. Overall, the vertical speed exceeded 200 feet per minute during 47.62% of normal vision conditions; 25.40% in flights with EFVS portraying runway markings; and 46.03% in flights with EFVS not portraying runway markings. All vertical speed values are negative since the pilot is descending. A two-way ANOVA identified no significant interaction between independent variables for vertical speed.

Analyzing the independent variables separately with outliers removed, the effect EFVS portrayal of runway markings on vertical speed was analyzed first. A likelihood ratio test identified a significant source of variance due to participants. A mixed effects ANOVA found a marginally significant effect ($p = 0.0583$) due to the EFVS portrayal of runway markings, as seen in Figure 24. A Tukey test showed a marginally significant difference between EFVS portraying and not portraying runway markings ($p = 0.0982$). A Cohen's d test found small effects between: EFVS portraying and not portraying runway markings ($d = 0.3763$), and normal vision compared to EFVS portraying runway markings ($d = -0.4406$).
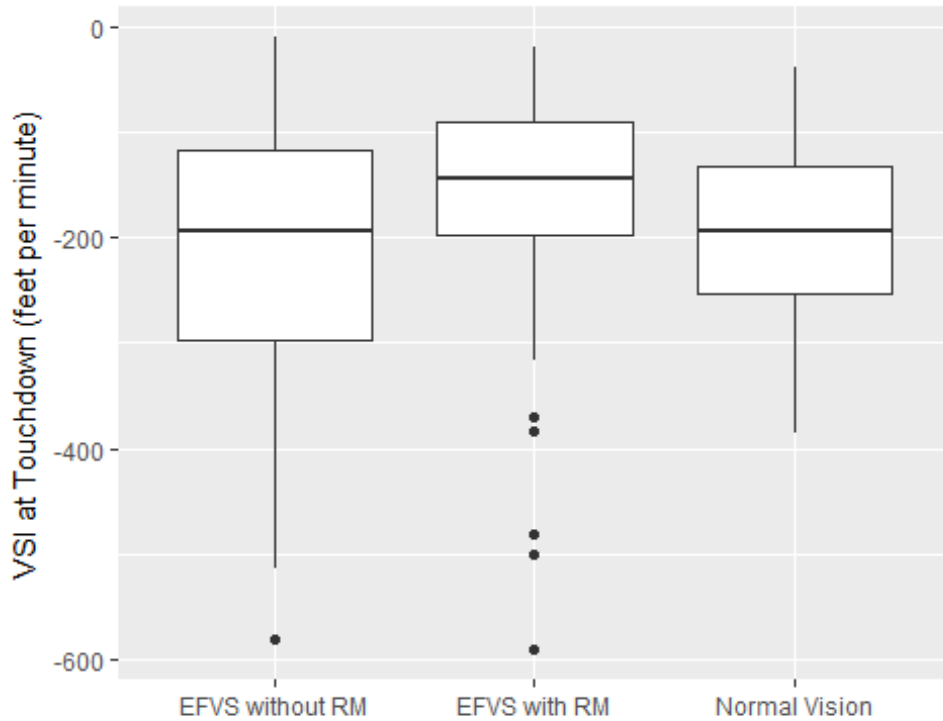
Figure 24. Vertical Speed on Touchdown as a Function of EFVS Portrayal of Runway Markings

Additionally, the effect of EFVS sensor range on vertical speed was analyzed. A significant source of variance due to participants was found by a likelihood ratio test. A significant (p = 0.041) effect due to EFVS sensor range was found by a mixed effects ANOVA. The data is shown in Figure 25. The percentage of exceedances in all the long, mid, and short sensor range conditions separately are 42.86%, 33.33%, and 54.76%, respectively. A Tukey test showed a marginally significant difference mid and long sensor range (p = 0.0775). A Cohen's d test found a small effect between long and mid sensor range (d = -0.4712), and a small effect between long and short sensor range (d = 0.2979).
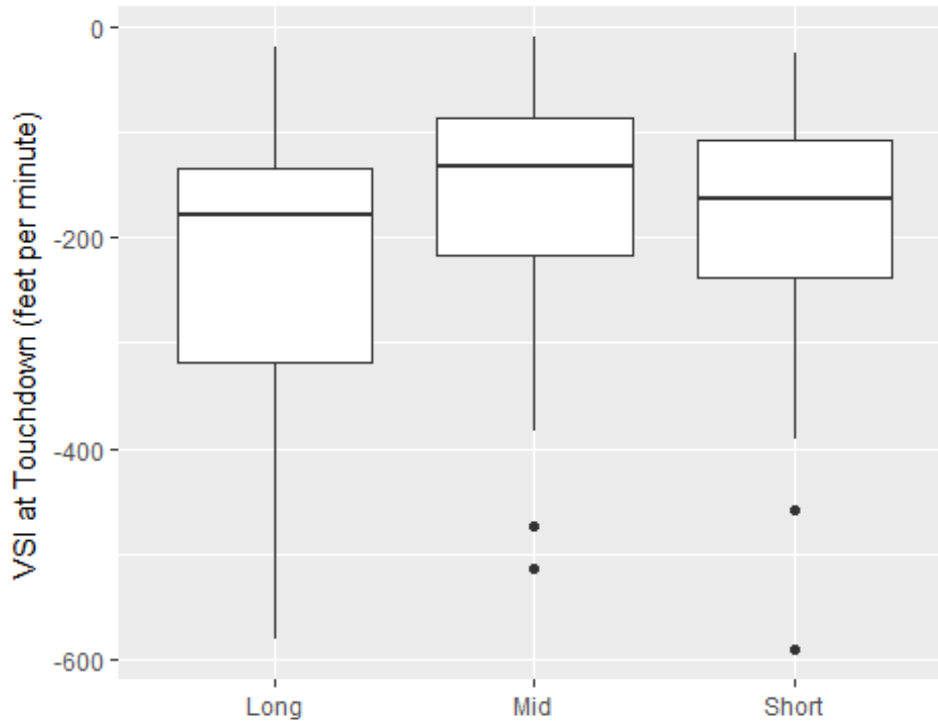
Figure 25. Vertical Speed on Touchdown as a Function of EFVS Sensor Range

5.2.2   Distance from Centerline

The distance from centerline was measured upon touchdown.   Distance from centerline is measured as an absolute value.   Four of the landings were more than 75 feet off of the centerline, which means the participant landed off the runway.   Three of these occurred with EFVS not portraying runway markings, while a fourth occurred with EFVS portraying runway markings.   Overall, the pilot went off the runway 1.59% of the time during flights with EFVS portraying runway markings conditions; and 4.76% of flights with EFVS not portraying runway markings.

A two-way ANOVA found no interaction effects between the independent variables on distance from centerline.   Relative to EFVS portrayal of runway markings after

removing outliers, a likelihood ratio test found participants as a significant source of variation. A mixed effects ANOVA then identified no significant effect ($p = 0.3779$) due to EFVS portrayal of runway markings, as shown in Figure 26. A Cohen's d test found small effects between: EFVS portraying and not portraying runway markings ($d = -0.2249$), and normal vision compared to EFVS portraying runway markings ($d = -0.2059$).
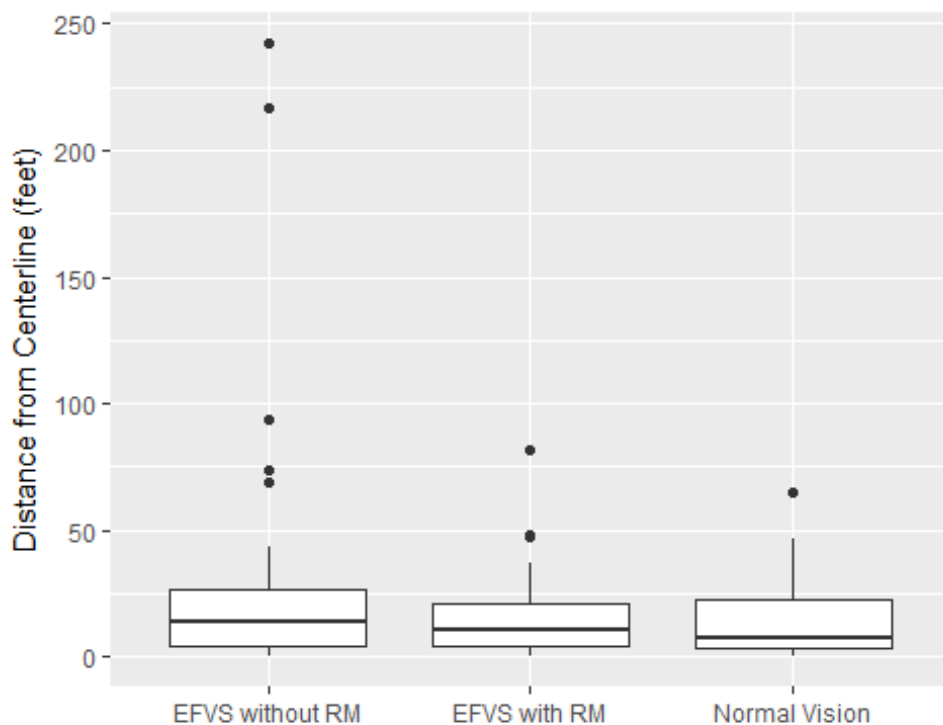
Figure 26. Distance from Centerline as a Function of EFVS Portrayal of Runway Markings

The distance from centerline compared to EFVS sensor range as shown in Figure 27. The participants were found to be a significant source of variance by a likelihood ratio test. A mixed effects ANOVA found no statistically significant effect ($p = 0.5504$) due to the EFVS sensor range for the distance from centerline. The percentage of exceedances

in all the long, mid, and short sensor range conditions separately are 0%, 0%, and 9.52%, respectively.
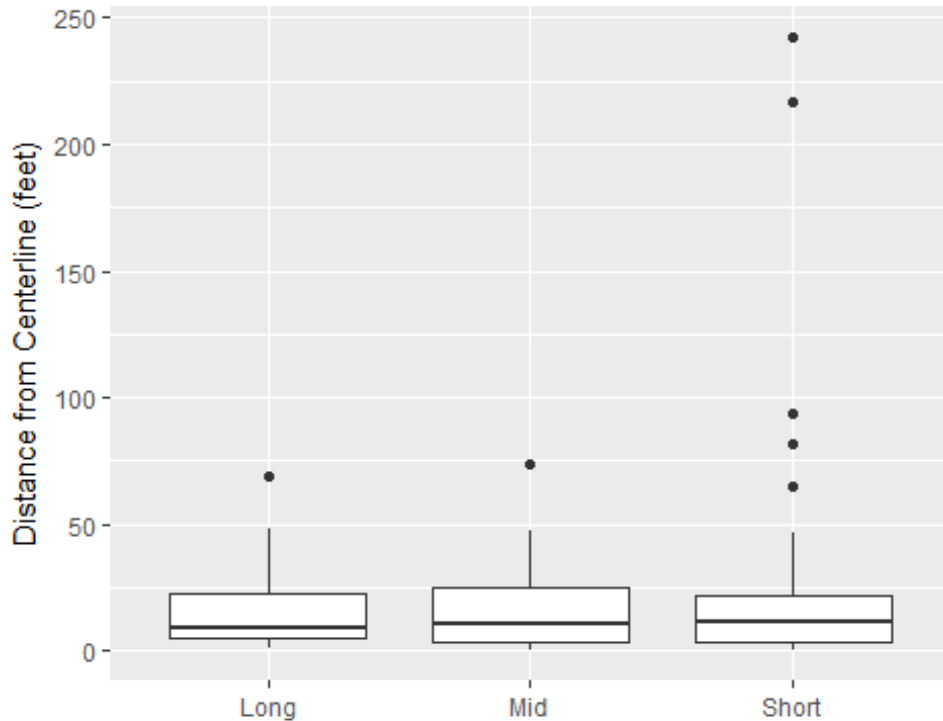
Figure 27. Distance from Centerline as a Function of EFVS Sensor Range

5.2.3   Distance from Touchdown Markers

The distance from touchdown markers is meant to measure how far down the runway the pilot travelled before landing. These values are presented both in positive and negative values since pilots could land before the runway markings. For this dependent variable, a two-way ANOVA identified no significant interaction between the independent variables.

The independent variables were analyzed separately with outliers removed. For EFVS portrayal of runway markings, a significant source of variance was found due to

participants by a likelihood ratio test. A mixed effects ANOVA identified no effect ($p = 0.2701$) due to EFVS portrayal of runway markings, as shown in Figure 28.
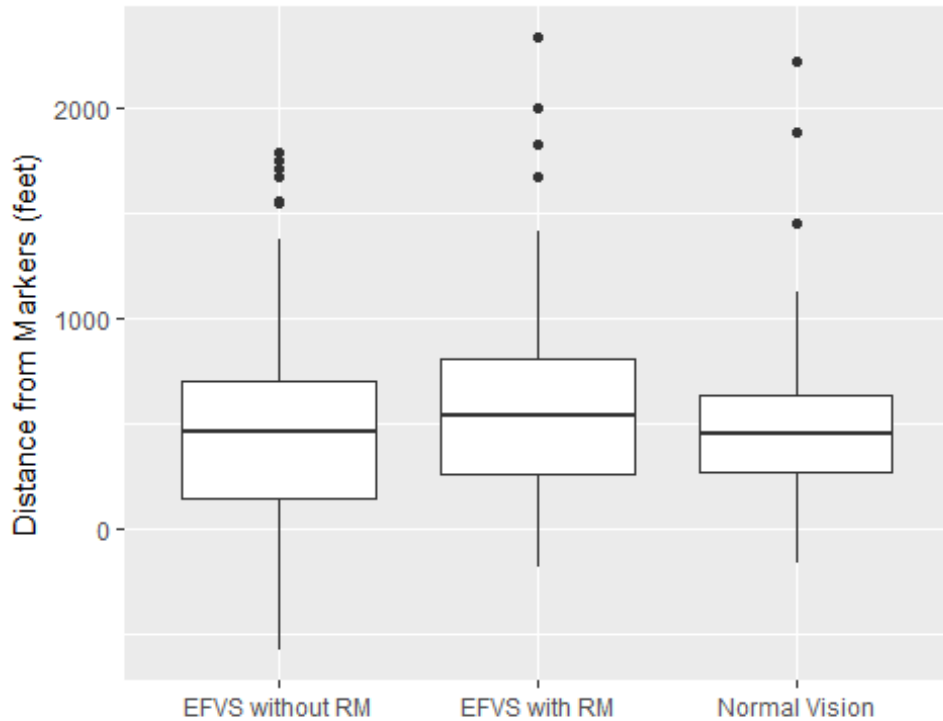
Figure 28. Distance from Touchdown Markers as a Function of EFVS Portrayal of Runway Markings

With respect to the EFVS sensor range, a likelihood ratio test determined participants as a significant source of variation. The mixed effects ANOVA shows that no significant effect ($p = 0.3895$) can be drawn between the variables, as shown in Figure 29. A Cohen's d test found a small effect between long and mid sensor range ($d = -0.3086$), and a small effect between long and short sensor range ($d = 0.2216$).
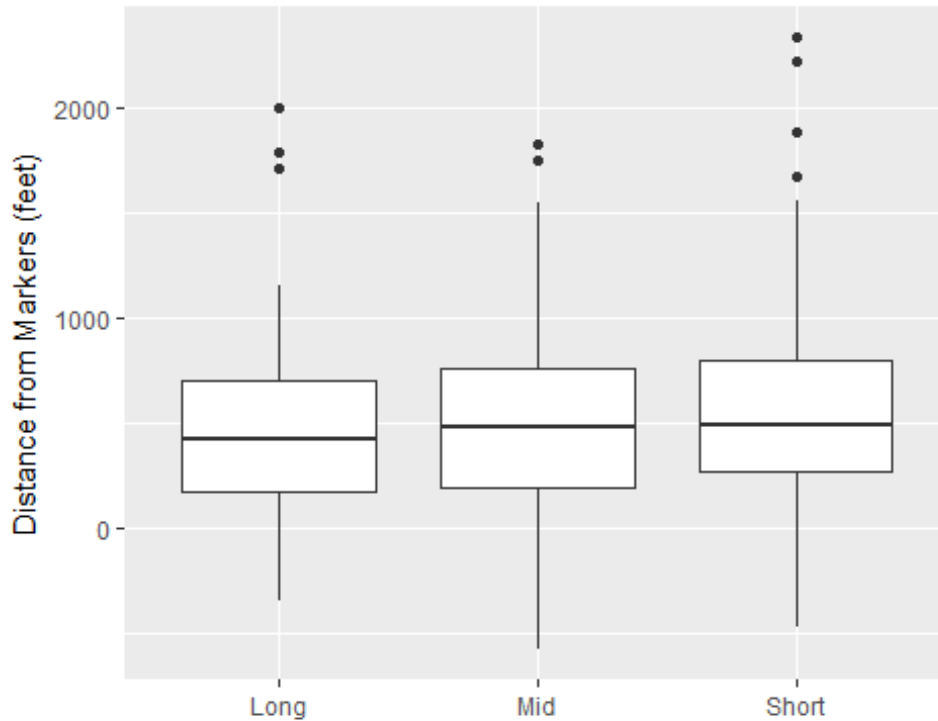
Figure 29. Distance from Touchdown Markers as a Function of EFVS Sensor Range

5.3 Questionnaires

This section discusses the subjective data collected both from the survey after each scenario as well as the survey after the participant had completed all the experimental conditions. These surveys consist mainly of NASA TLX workload assessment, a visual cue questionnaire, information questions for each experiment condition, and participant opinion on EFVS. All graphs are shown in Appendix D.

5.3.1 Workload Assessment (NASA TLX)

The workload for each scale and each experiment condition is averaged across participants and shown in Figure 30. The overall workload for each participant was

calculated utilizing the weights given for each scale. An average overall workload for

each experimental condition is shown in Figure 31.
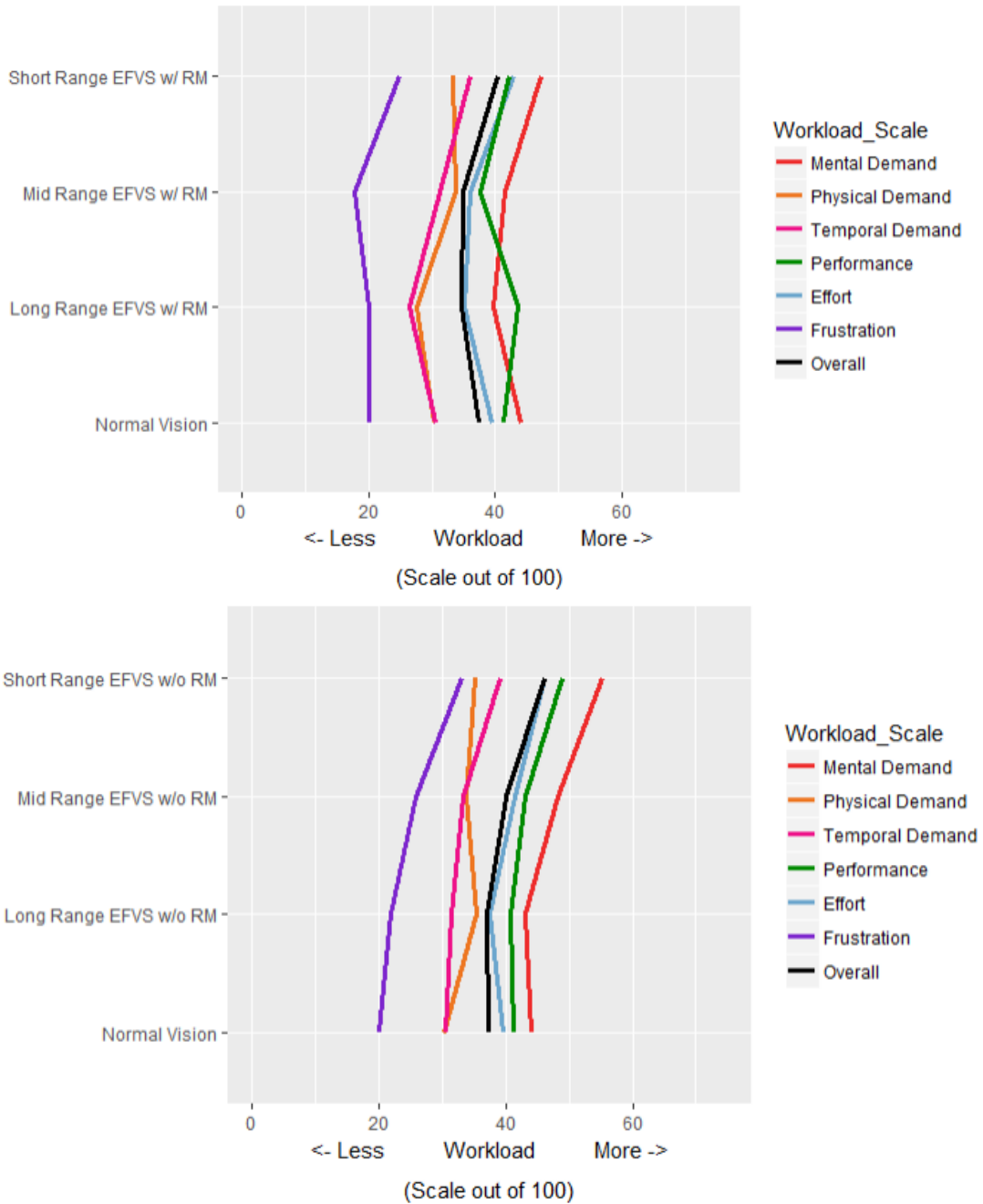
Figure 30. Average Workload Per Scale for Each Scenario (Broken into two graphs)
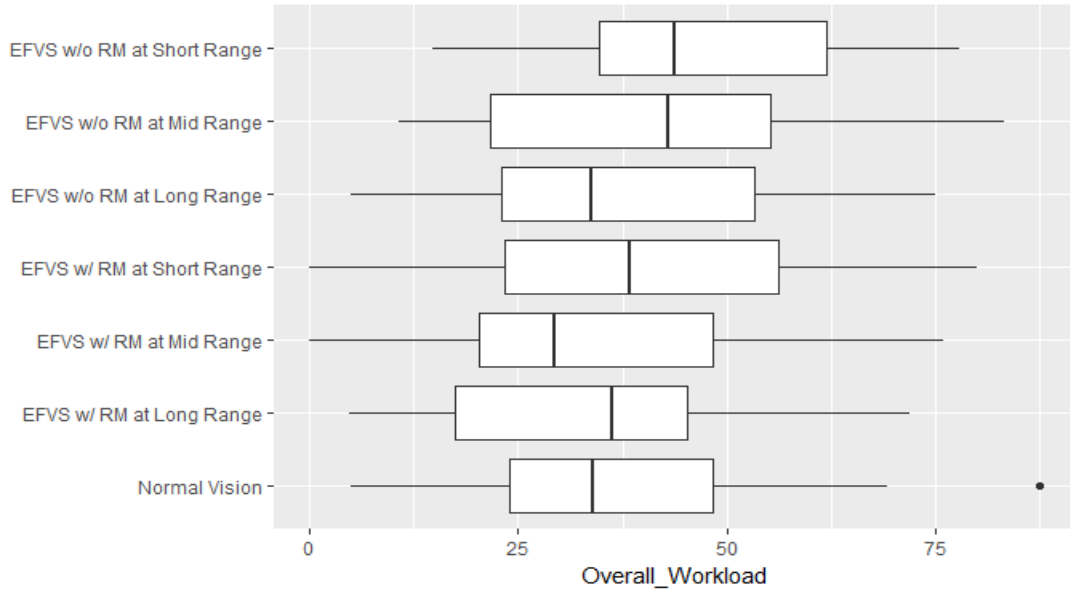
Figure 31. Average Overall Workload Assessment for Each Experiment Condition

For the overall workload per condition, it can be seen from the means in Figure 31, that both range and runway markings influenced participants workload. Approaches without runway markings increased the overall workload greater than a decreasing sensor range. This is probably since the landing is the most stressful portion of the approach and landing scenario. On the other hand, the different conditions do not show an obvious trend in any of the six sub-scales. Frustration seems to be more based off the order of experiment conditions and it appears that some participants misjudged the performance scale as 'poor to good' rather than 'good to poor'.

5.3.2 Visual Cues

After each experiment flight, the participants were asked to complete the matrix of visual cue questions shown in Table 3. This matrix asks which visual cues the pilot wanted, where they could find visual cues, and if they were unable to find any visual cues.

Table 3. Visual Cue Questionnaire Matrix

What visual cues did you want?	Which visual cues did you find with the EFVS?	Which cues did you find from your instruments?
Localizer deviation	Localizer deviation	Localizer deviation
Glideslope deviation	Glideslope deviation	Glideslope deviation
Visual of the runway centerline	Visual of the runway centerline	Visual of the runway centerline
Visual of the runway sides	Visual of the runway sides	Visual of the runway sides
Visual of top and bottom of the runway	Visual of top and bottom of the runway	Visual of top and bottom of the runway
Visual of the touchdown markers	Visual of the touchdown markers	Visual of the touchdown markers
Visual of the horizon	Visual of the horizon	Visual of the horizon
Runway Lights	Runway Lights	Runway Lights
Other:	Other:	Other:
Which visual cues did you find in a your normal vision out the window?	**Which visual cues did you want, but were unable to find?**	
Localizer deviation	Localizer deviation	
Glideslope deviation	Glideslope deviation	
Visual of the runway centerline	Visual of the runway centerline	
Visual of the runway sides	Visual of the runway sides	
Visual of top and bottom of the runway	Visual of top and bottom of the runway	
Visual of the touchdown markers	Visual of the touchdown markers	
Visual of the horizon	Visual of the horizon	
Runway Lights	Runway Lights	
Other:	Other:	

As shown in Figure 32 through Figure 38, the visual cue matrices show that participants recognized that certain visual cues are missing in specific experiment conditions. However, many participants were still able to find the sides of the runway even with no runway markings, meaning the visual cue was not completely eliminated. Additionally, many participants were looking for the visual cue of runway lights, especially on short-range conditions.
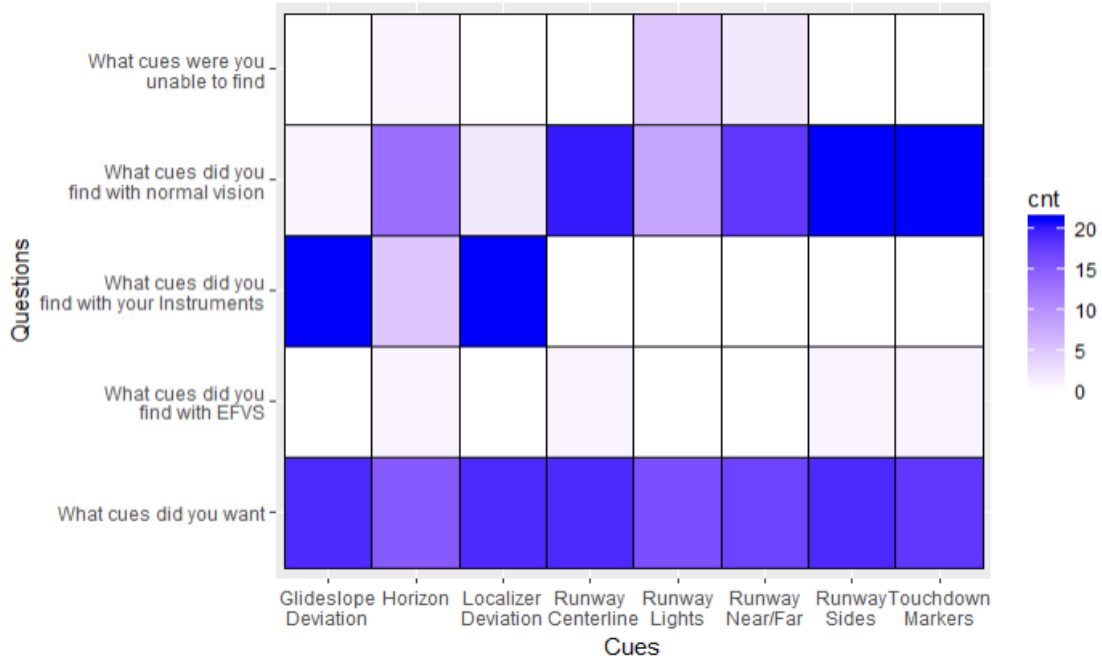
Figure 32. Visual Cue Matrix for Normal Vision Condition
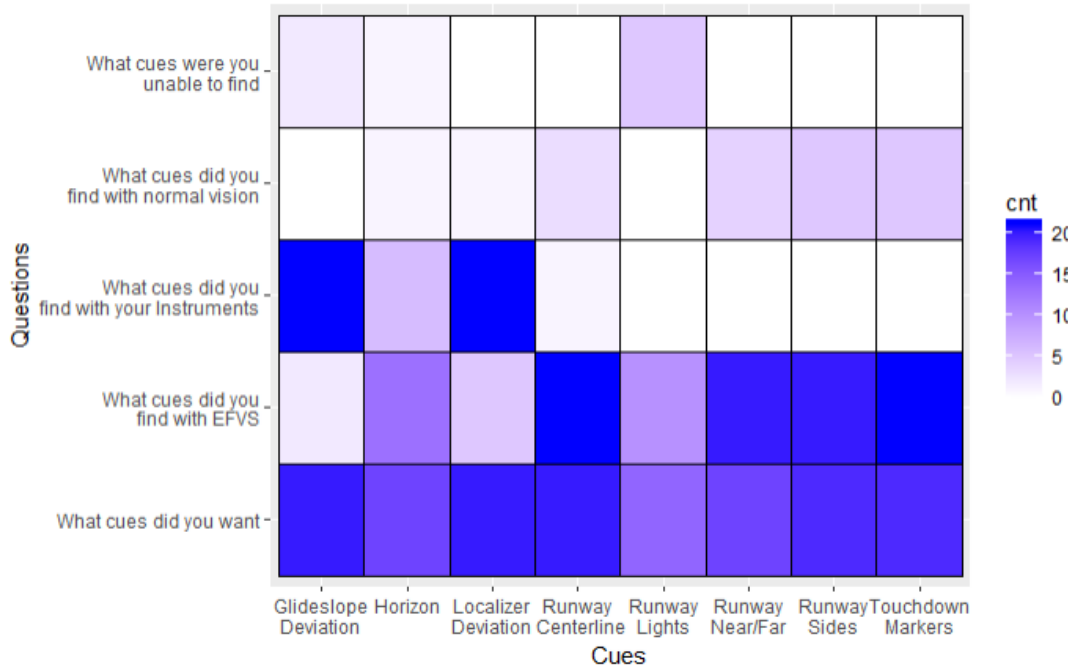
Figure 33. Visual Cue Matrix for Long EFVS Sensor Range and EFVS Portraying Runway Markings
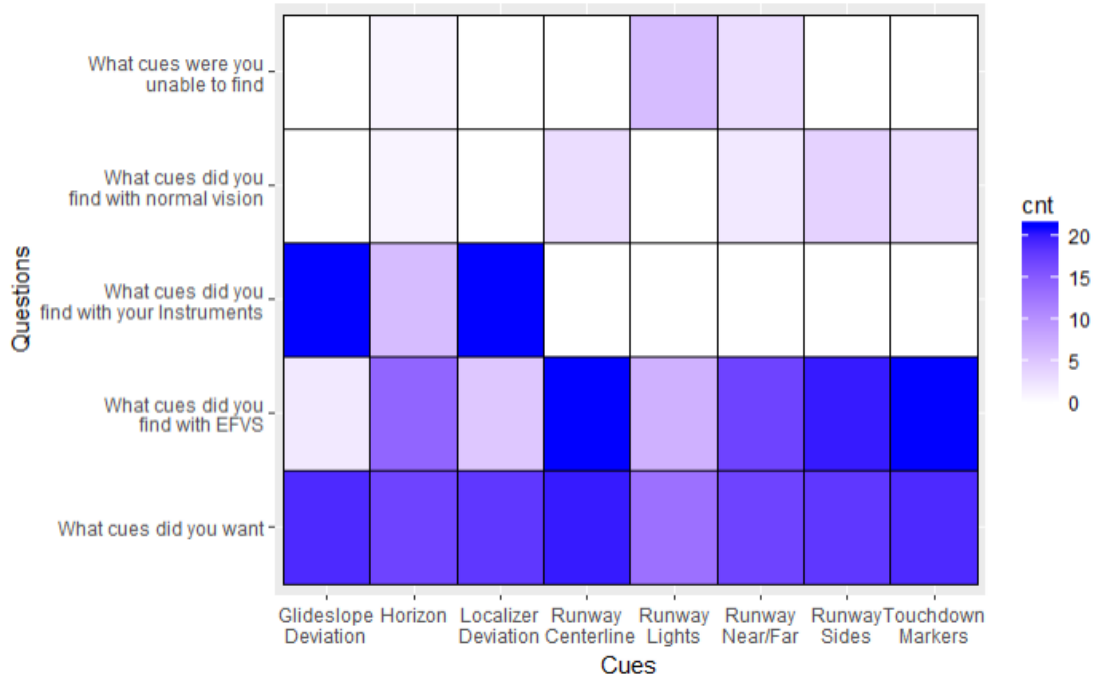
Figure 34. Visual Cue Matrix for Mid EFVS Sensor Range and EFVS Portraying Runway Markings
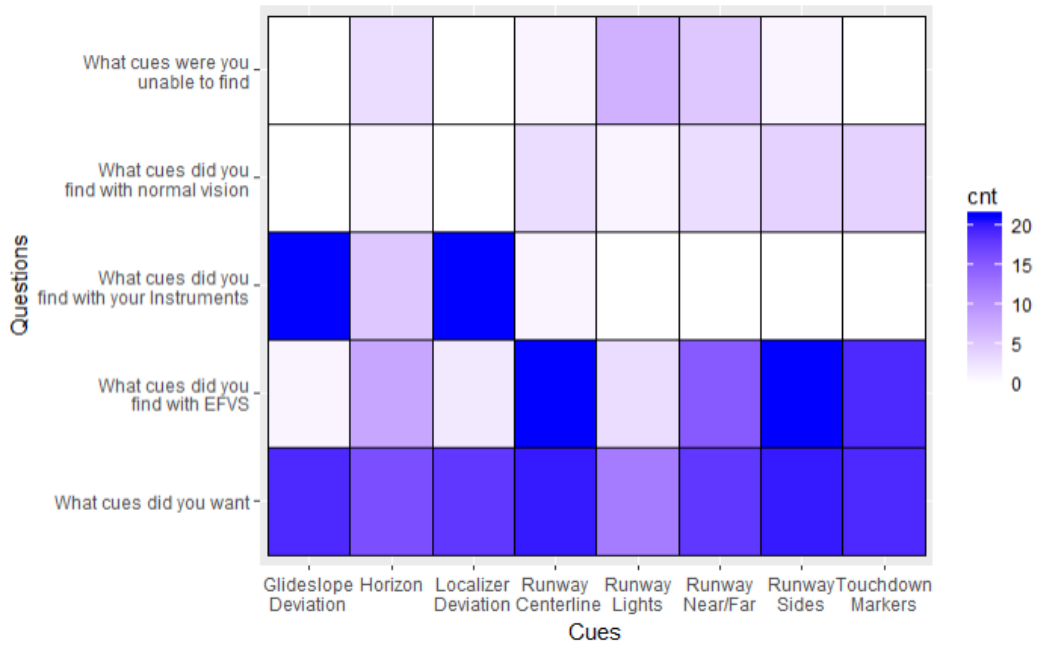
Figure 35. Visual Cue Matrix for Short EFVS Sensor Range and EFVS Portraying Runway Markings
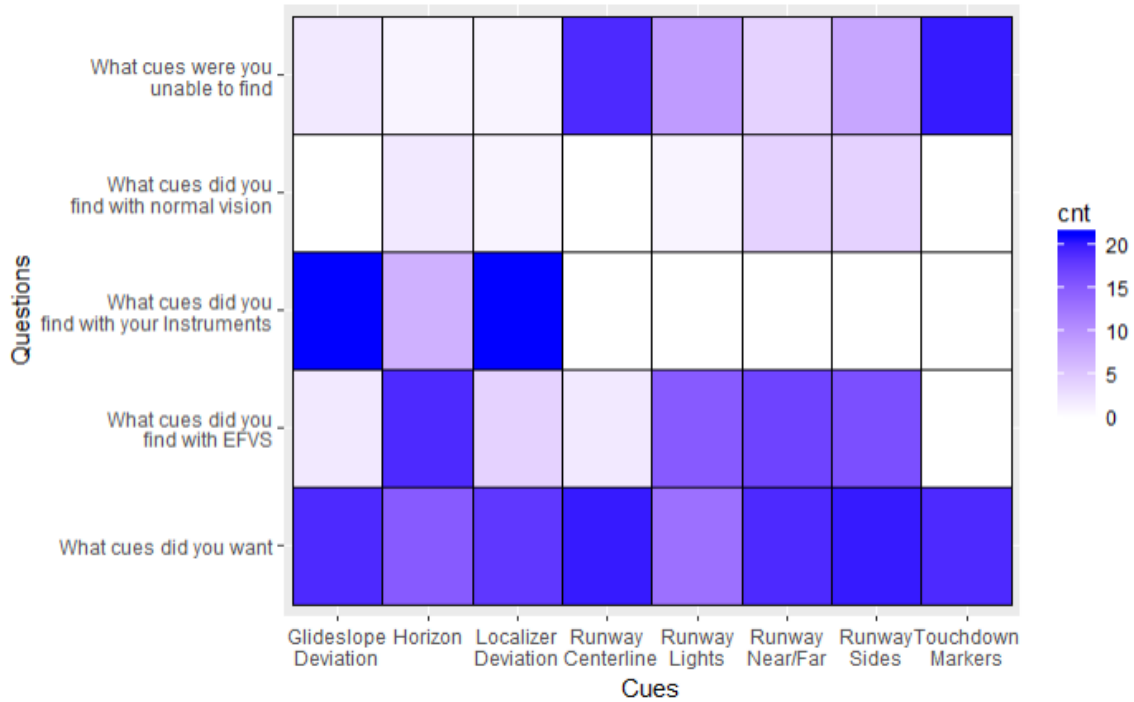
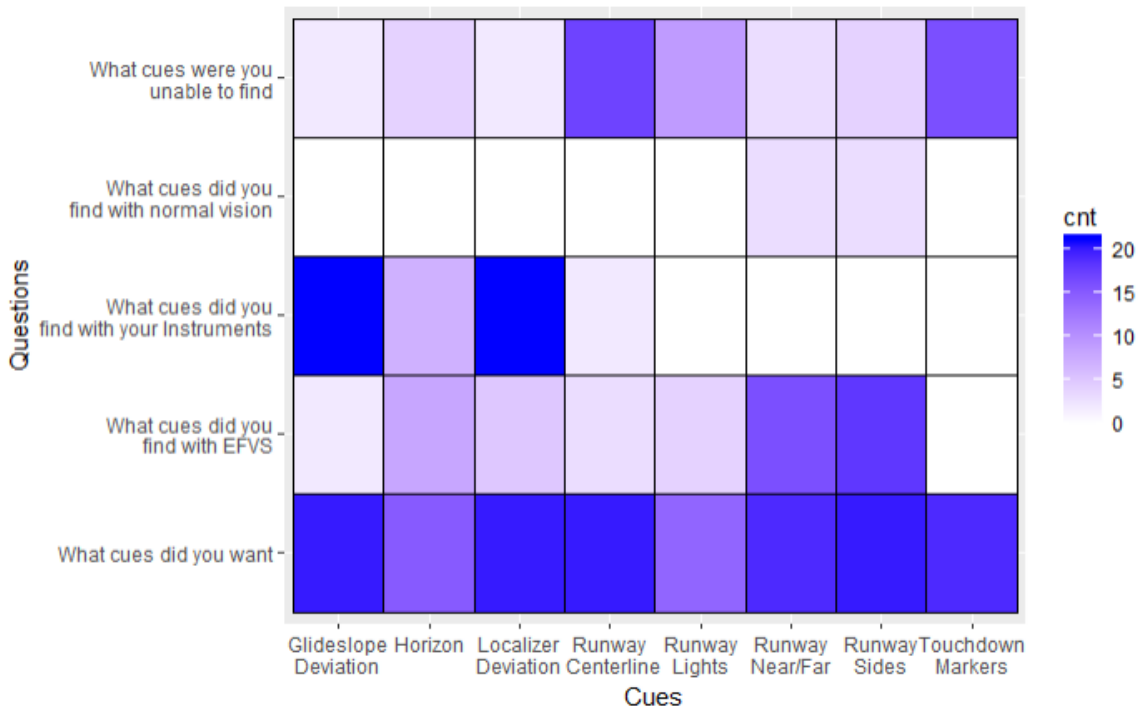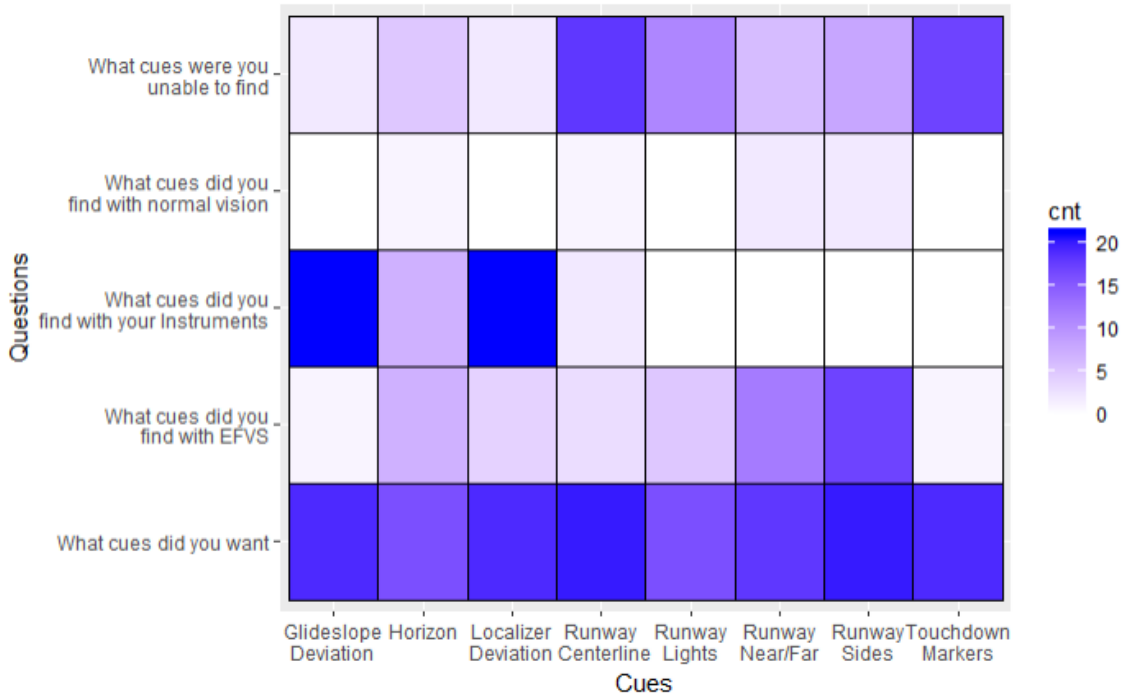**Figure 36. Visual Cue Matrix for Long EFVS Sensor Range and EFVS not Portraying Runway Markings**

Figure 37. Visual Cue Matrix for Mid EFVS Sensor Range and EFVS not Portraying Runway Markings

Figure 38. Visual Cue Matrix for Short EFVS Sensor Range and EFVS not Portraying Runway Markings

5.3.3   Pilot Comments on EFVS

At the end of each experiment flight, the participants filled out a survey, with three main questions, described in the Dependent Variables section. This section discusses the results of those questions.

5.3.3.1   Sufficient Information to Land

The first question asks the participants whether they feel like they had sufficient information to perform the landing. An answer of "Yes" meant the participant felt they had satisfactory information to land the aircraft; while an answer of "No" meant the participant would have chosen to go-around.   Figure 39 shows the tally of Yes/No answers for the sufficient information question in relation to the EFVS portrayal of

runway markings. The "N/A" responses represent questions that were left blank by the

participants. The percentage of each condition with participants answering "Yes" goes

from 100% to 96.72% to 68.25% for normal vision to EFVS portraying/not portraying

runway markings.
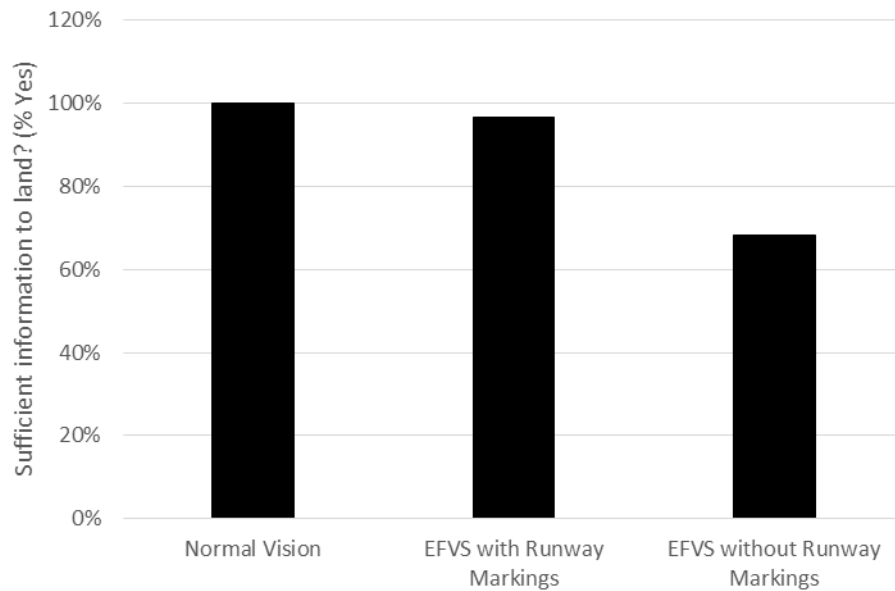
Figure 39. Sufficient Information to Land as a Function of EFVS Portrayal of Runway Markings

The same question was sorted by EFVS sensor range. Figure 40 shows the counts of

the answers of Yes/No for this question. Examining long, mid and short sensor range

conditions, their respective percentages are 90.48%, 85.37% and 69.05%.
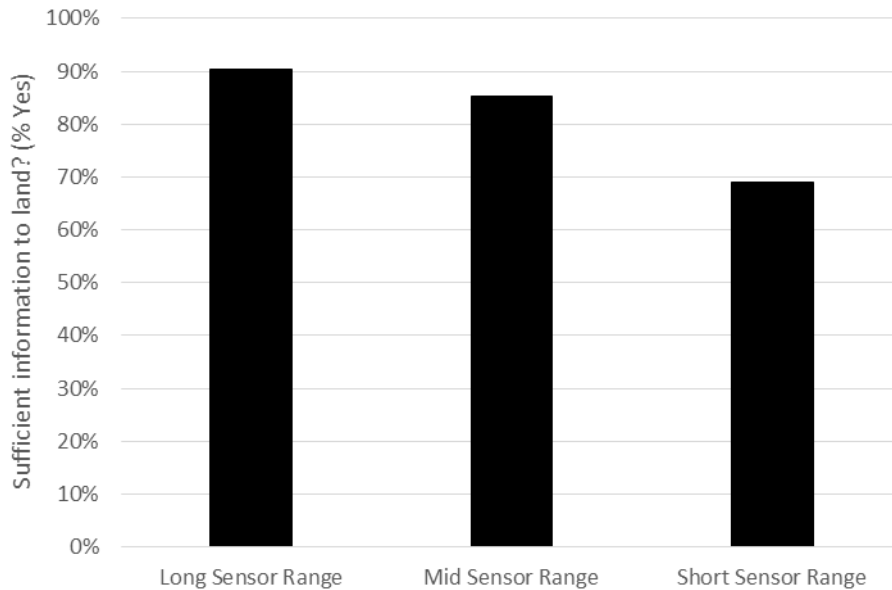
Figure 40. Sufficient Information to Land as a Function of EFVS Sensor Range

5.3.3.2   Lacking Information during the Approach/Landing

The next question for each individual experiment survey asked if there were any points during the approach or landing where the information was not available at the specific time the participant needed the information. For this question, if the participant answered "Yes", then information was lacking according to their model, while "No" meant the information was available to them throughout the approach and landing. Figure 41 shows the tall of Yes/No answers for the EFVS portrayal of runway markings. The percentage of answers for each condition was taken for comparison of answers. For the normal vision, EFVS portraying runway markings and EFVS not portraying runway markings, the participants answered "No" for 90%, 78.69% and 46.77% of each condition respectively.
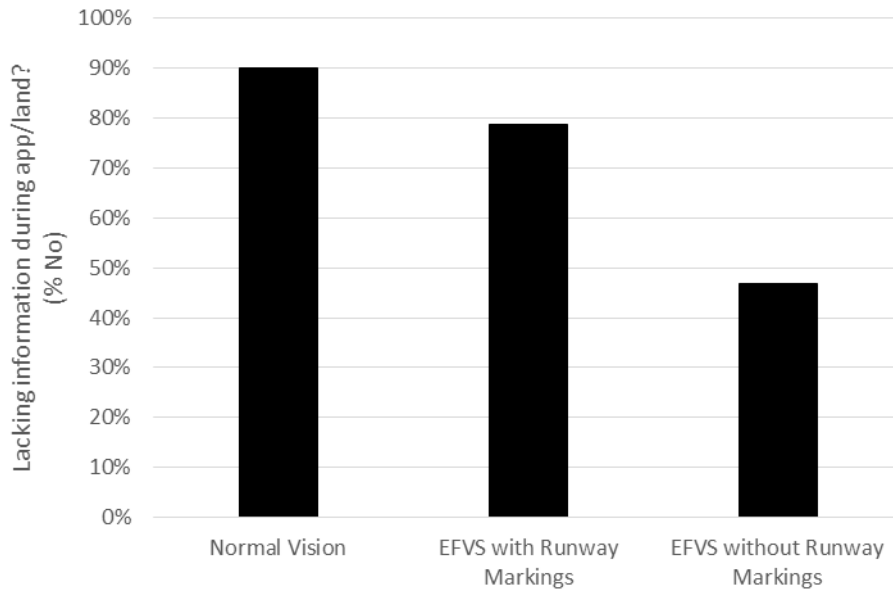
Figure 41. Lacking Information during the Approach/Landing as a Function of EFVS Portrayal of Runway Markings

The percentage of "No's" for each sensor range condition was 66.67%, 85.37% and 60% for the long, mid and short conditions respectively (Figure 42). Many participants added details in the responses detailing what information was lacking. The most common elaborations were runway markings, localizer/glideslope on HUD, and simulator issues.
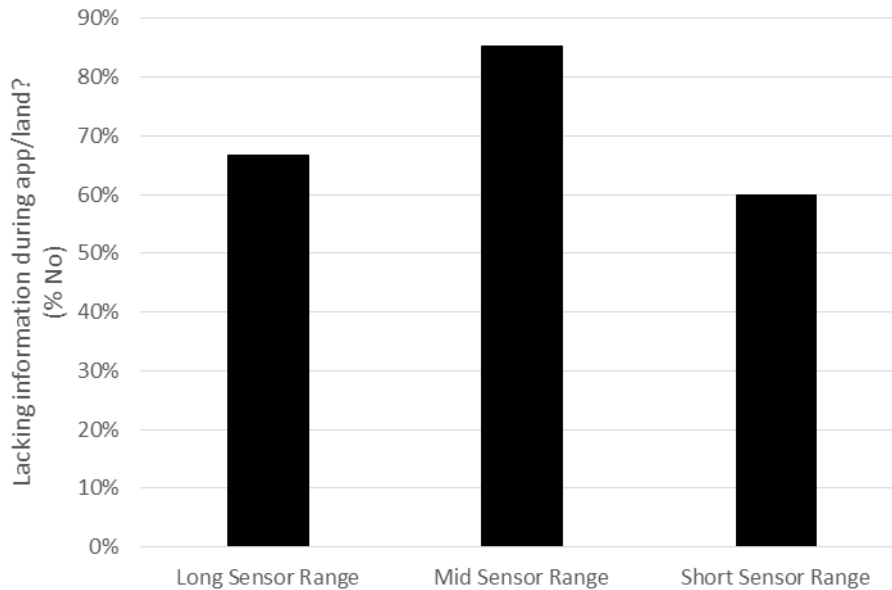
Figure 42. Lacking Information during the Approach/Landing as a Function of EFVS Sensor Range

5.3.3.3   Change of Visual Scan

The final question posed to participants after each experiment flight was if the participant modified his/her visual scan due to the EFVS. Figure 43 shows the data as a factor of the EFVS portrayal of runway markings. Some participants did not report modifying their visual scan and elaborated that a choice was made to follow instruments to decision height each time, regardless of the EFVS capability. The percentage of "Yes" for each set of conditions is given as follows: 19.05% for normal vision; 81.97% for EFVS portraying runway markings; and 77.42% for EFVS without portraying runway markings.
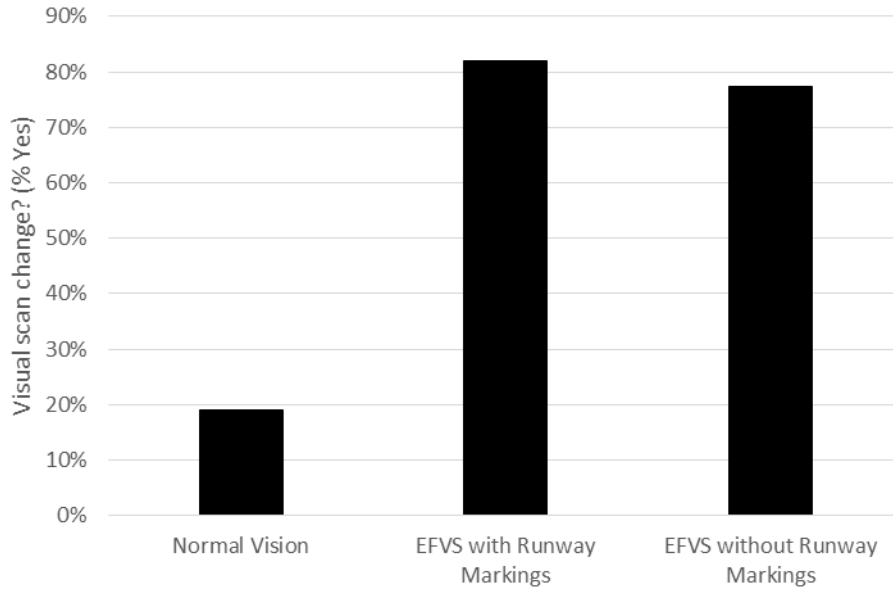
Figure 43. Visual Scan Change for EFVS Portrayal of Runway Markings

5.4 Summary of Results

A summary of the statistical tests performed on the dependent variables is provided in Table 4. Additionally, Table 5 shows a breakdown of the percentage of exceedances per flight as a factor of the independent variable. Table 6 shows a summary of questionnaire data.

Table 4. Parametric Statistics Summary

	IV Interaction Effects	Participant Significant Source of Variance	Significant wrt Runway Markings	Significant wrt Range
Glideslope Deviation RMS	No	Yes	Marginal (<0.1)	Yes
Glideslope Deviation Max Value	No	Yes	Marginal (<0.1)	Marginal (<0.1)
Localizer Deviation RMS	No	Yes	No	Yes
Localizer Deviation Max Value	No	Yes	No	Yes
Vertical Speed at Touchdown	No	Yes	Marginal (<0.1)	Yes
Distance from Centerline at Touchdown	No	Yes	No	No
Distance from Markers at Touchdown	No	Yes	No	No

Table 5. Exceedance Summary

	Portrayal of Runway Markings			Sensor Range		
	Normal Vision	EFVS with Runway Markings	EFVS without Runway Markings	Long	Mid	Short
Glideslope Deviation (>0.75)	4.76%	33.33%	22.22%	16.67%	38.10%	28.57%
Localizer Deviation (>0.75)	0.00%	6.35%	9.52%	0.00%	7.14%	16.67%
Vertical Speed at Touchdown (> 200 fpm)	47.62%	25.40%	46.03%	42.86%	33.33%	54.76%
Distance from Centerline at Touchdown (> 75 feet)	0.00%	1.59%	4.76%	0.00%	0.00%	9.52%

Table 6. Summary of Questionnaire Data

	Portrayal of Runway Markings			Sensor Range		
	Normal Vision	EFVS with Runway Markings	EFVS without Runway Markings	Long	Mid	Short
Sufficient information to land? (% Yes)	100.00%	96.72%	68.25%	90.48%	85.37%	69.05%
Lacking information during app/land? (% No)	90.00%	78.69%	46.77%	66.67%	85.37%	60.00%
Visual scan change? (% Yes)	19.05%	81.97%	77.42%	85.71%	82.93%	70.00%

CHAPTER 6.   DISCUSSION AND CONCLUSIONS

The objective of this thesis was to find the effect on pilot performance of two potential limitations of EFVS sensors: sensor range, and sensing of runway markings such that they can be portrayed to the pilot by the EFVS. As noted earlier in Chapter 1, this thesis hypothesized, based on the analysis of pilot information requirements, pilot tasks and visual cues, that EFVS sensor limitations would have these effects:

- The lack of runway markings is predicted to negatively impact the pilot's ability to remain on the extended centerline of the runway (aka minimize localizer deviation), touchdown distance from the touchdown markers, vertical speed on touchdown, and touchdown distance from runway centerline
- Range will negatively impact the pilot's ability to remain on the glideslope/localizer, the prediction of the landing spot, and the vertical speed at touchdown

The method for this thesis has some limitations, specifically with the simulator. While all participants were instrument rated and had sufficient recent experience with instrument approaches, some still failed to meet the criteria for safe approaches and safe landings, even with normal vision. This, together with the TLX frustration measures' tendency to be higher for participants in their initial flights, suggests that there is an effect of the simulator overall. The simulator is simple, with no motion base and simple monitors rather than a projection screen being used. However, this thesis assumes that the simulator effect is applied evenly to the different independent variables on average, and that any run-order effects are mitigated through the Latin square design. Thus, while the overall frequency of unsafe landings and approaches may not reflect the participants would normally experience, the differences between the conditions can be assumed to

allow for their comparison. Further, the workload effects may serve as predictors of where concerns may arise, by highlighting conditions where greater pilot compensation is required to overcome missing or difficult-to-interpret visual cues, leading to the greater potential for poor performance.

6.1 Impact of EFVS Sensor Limitations on Pilot Performance

The hypotheses that the pilot would be negatively affected by the lack of runway markings, specifically in the areas of localizer deviation, touchdown distance from centerline, and vertical speed on touchdown was found partially supported. As the runway markings were removed, the main issues that occurred with pilot performance occurred within the landing portion of the scenario, rather than the approach. Vertical speed, distance from centerline, and distance from touchdown markers were all negatively affected by the portrayal runway markings. The effect was only marginally significant when analyzing the data's central tendency using ANOVA, but a small effect from Cohen's d test between EFVS portraying runway markings and not portraying runway markings for both vertical speed and distance from centerline.

When the runway markings were removed, one of the primary flare cues given to pilots was taken away. One of the main tasks of the pilot during flare is to judge the descent of the aircraft, where visual cues for this task mainly consist of ground movement and runway sides. Since the runway markings helped ensure the pilots perceive the edges of the runway, removing them caused the pilots to flare incorrectly and typically land with a larger vertical speed, with 46.03% of conditions with EFVS not portraying runway markings exceeding 200 feet per minute. Additionally, approximately ¼ of the landings

without runway markings landed with a vertical speed over 300 feet per minute, which could result in severe damage to the aircraft.

Other cues that can be utilized to perceive the descent of the aircraft during flare are the top and bottom of the runway and the horizon. These cues are mainly affected by the visual range of the sensors; for example, the pilot may not see the end of the runway during the conditions with short range EFVS sensors. However, a larger sensor range hurts the vertical speed more than a short range. Looking at the percentage of exceedances, the long-range conditions exceeded 200 feet per minute on 42.86% of the trials, while the short-range conditions exceeded the vertical speed limit on 54.76% of the time. The higher percentage of exceedances on the short-range conditions show that, although the horizon and near/far edge of the runway can serve as visual cues for flare, they are not a major factor.

Landing off centerline or even off runway is another concern. For this experiment, the runway was 150 feet wide; meaning any distance greater than 75 feet off centerline is technically off the runway. Participants landed off the runway in 4 cases while using the EFVS. Landing off runway occurred in 4.76% of conditions with EFVS not portraying the runway markings, also occurred in 9.52% of short range conditions. The shorter-range exceedances could be attributed to the pilot not being able to see the runway after reaching decision height due to a localizer exceedance. The off-runway landings with no runway markings reflects on the earlier discussion of not have a runway centerline and touchdown markers as a visual cue would negatively affect the pilots' ability to land on the runway.

The different range conditions were also hypothesized to negatively impact the pilot's ability to remain on glideslope/localizer, prediction of the landing spot, and the ability to flare during landing. The main issues that were seen during the experiment due to range was increased localizer/glideslope deviation, off centerline landings, and the vertical speed on touchdown, previously discussed.

The localizer deviation and localizer max value were both shown to vary significantly between sensor range condition ($p =$ <0.0001). Additionally, the percentage of exceedances from the long-range to the short-range condition goes from 0% to 16.67%. Overall, the short-range conditions cause larger localizer deviations. These deviations are the cause of two issues: the pilots not being able to reference anything besides instruments, and the expectation that the runway would be displayed. Both issues can be partially linked to the HUD not having the glideslope and localizer deviation on it since the pilots would reference the exterior environment and then have to return to the gauges to keep deviations low.

In the mid and short-range EFVS conditions, where the participants may have continually viewed the EFVS when they expected they would be able to see the runway. Since the HUD display does not show the localizer and glideslope deviation, this visual transition may have created more localizer deviation for the participants. While not using the EFVS, the pilots expected nothing and did not make this visual transition as frequently; this is also reflected in the comments given by participants. Similarly, the percentage of glideslope exceedances was 38.10% in the mid-range conditions; while an exceedance only occurred in 28.57% of short-range conditions.

Although the hypotheses of this thesis mainly predicted the negative impact of lack of runway markings and visual range in EFVS, the experiment conducted also found some positive aspects of EFVS. These positive aspects also refer to the judgment seen in the participants as well as their performance on approach and landing.

The main performance benefit found in the experiment was that a longer sensor range decreases the localizer deviation throughout the approach. Many participants commented that the EFVS was useful for these longer-range conditions since they allowed a perspective not usually found in typical instrument approaches. This longer range EFVS, especially with runway markings, aided the pilot in maintaining the stabilized approach criteria.

In addition to performance during approach and landing, the questionnaires reveal that the participants can recognize when important information is lacking as well as when a go-around procedure should be initiated. Figure 39 and Figure 40 show that pilots realize when the aircraft could be in an incorrect state such as off localizer during a short-range approach. Additionally, several pilots reported they normally would not have landed without runway markings due to the lack of information. When asked if they lacked information during the approach, many pilots recognized both cases of EFVS changing some aspect of information for the approach (shown in Figure 41). These observations are important since the purpose of EFVS is not to extend instrument minimums for pilots but allow them to use the EFVS to acquire the same visual cues as normal vision. This recognition of visual cues is also apparent in the visual cue matrix.

6.2   Contributions

In conclusion, this thesis has identified the connections between pilot tasks, information requirements, visual cues, information processing level (perception, interpretation and prediction), and sensor attributes. These connections allowed a hypothesis to be formed about how sensor limitations, specifically sensor range and portrayal of runway markings, could affect the pilots' information processing level and their performance during approach and landing. A flight simulator study was conducted to determine the effects on pilot performance during approach and landing due to EFVS sensor range and EFVS portrayal of runway markings.

The results of this study showed that specific visual cues such as runway centerline affected the pilot performance during landing. For the conditions when no runway markings were present, the vertical speed on touchdown increased. Additionally, the distance from the runway centerline at touchdown was negatively impacted by the lack of runway markings, as several off-runway landings occurred in these conditions.

The EFVS sensor range mainly affected the pilot's ability to maintain the extended centerline of the runway, causing exceedances in localizer deviation as well as glideslope. These exceedances were due to a lack of the visual cue of the runway in the distance. Additionally, the EFVS sensor range negatively affected the pilot's vertical speed on touchdown due to a late acquisition of the runway during the approach.

Overall, this thesis recommends the following guidelines for approving EFVS systems for general aviation aircraft:

- A heads-up display should display all information required by the FAA, allowing for a lower visual transition time between instruments and EFVS
- Projection of the runway markings on to the runway, whether via a sensor image or a database generated image. This will provide a better reference for pilots to land on the centerline and prevent off-runway accidents
- A flare cue should be added to prevent any landings that would occur with excessive vertical speed
- A cue giving the sensor status should be given to the pilot when the EFVS believes it has acquired the runway, therefore avoiding excessive visual transitions between the HUD and heads-down in instruments

6.3   Recommendations for Future Work

The experiment conducted in this thesis was just the start of developing a more concrete relationship between pilot performance and EFVS limitations. Recommendations for future research on this topic should aim to:

- Increase the fidelity of the simulator, improving the realism of the controls and HUD
- Improve the accuracy of the EFVS to real-life, specifically using a system currently in production
- Utilize approaches at different airports

APPENDIX A. PILOT BRIEFING

<u>Welcome Briefing</u>

Welcome, you are here to participate in an experiment regarding the effects of enhanced flight vision systems (EFVS) on pilot performance during approach and landing. EFVS is a technology that uses sensors, such as infrared or millimeter wave radar, to depict an outside view of the airplane on a heads-up display. After training on the simulator, the experiment will consist of seven different scenarios with different EFVS scenarios. Remember you are free to leave at any time with no consequences; all pilots who attempt to participate in good faith will be entered in the drawing for the $100 Amazon gift card, even if they cannot complete the experiment.

Before beginning the actual experiment, we would like to step through some training scenarios.

<u>Approach and Landing Training</u>

The objective of the experiment is to conduct an approach and landing using an enhanced flight vision system (EFVS). Most of the meteorological conditions in these scenarios are always 0'-0', meaning the approach and landing must be completed using the enhanced flight vision system. There are a couple scenarios where you will break out at the decision height and continue the approach on natural vision. The range and the objects portrayed on the EFVS will vary from scenario to scenario.

The aircraft you will be flying is a C172. Each scenario and training stage will begin approximately 3 nautical miles from the runway with the aircraft lined up on the glideslope and localizer. The nav instruments will be tuned to the correct localizer and glideslope and you have already gained permission to land, so no further communication with the tower is required.

The approach and landing will be scored on the following:

1. Deviation from the localizer and glideslope
2. Deviation from approach speed
3. Deviation from the centerline at touchdown
4. Vertical speed at touchdown

After completion of the scenario, you will be asked to fill out a questionnaire regarding your thoughts, the visual cues, and your workload.

Introduction to the Simulator

Out-the-window View with EFVS

Eye tracker

Instrument panel

Yoke

Throttle and engine controls
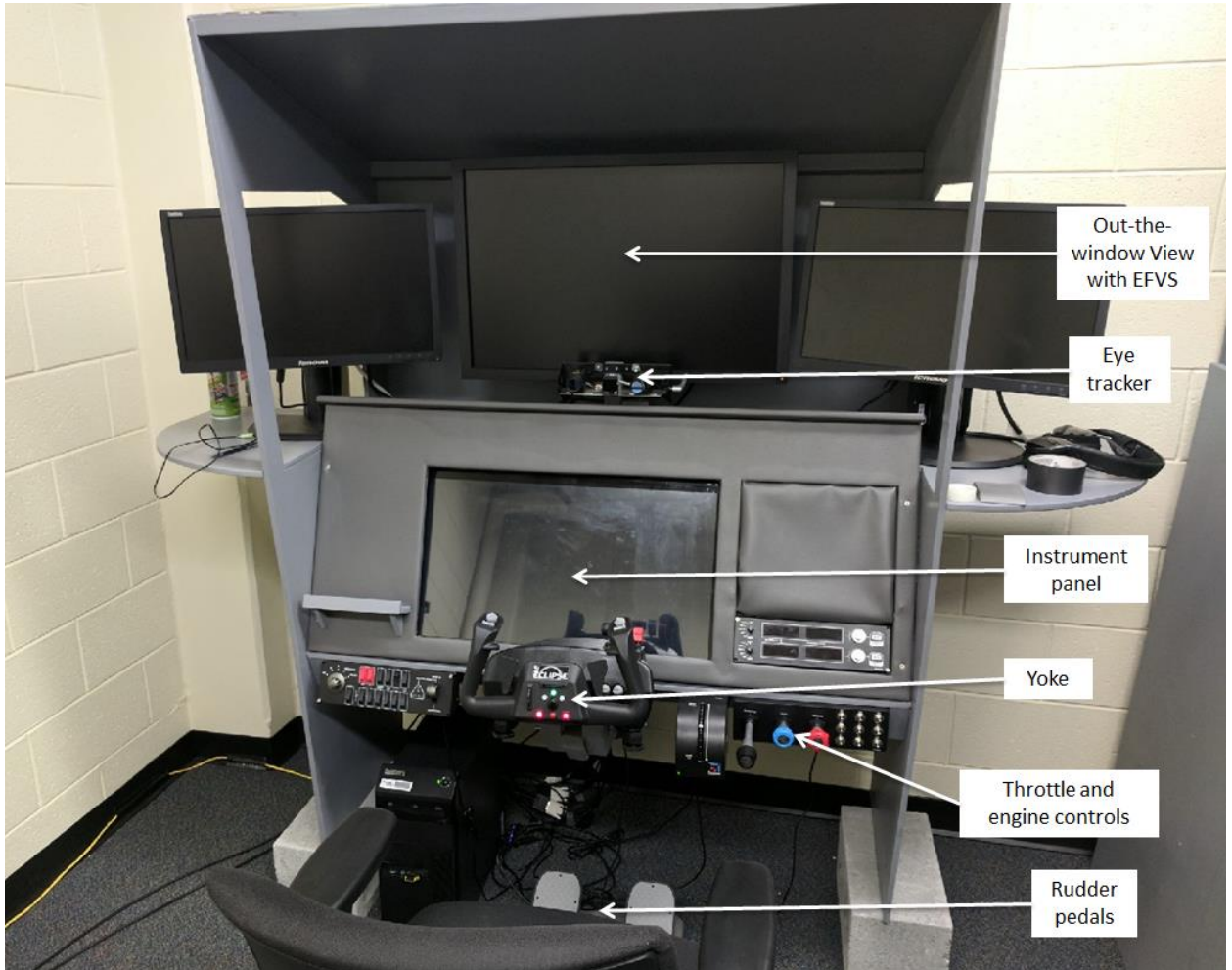
Rudder pedals

The simulator has a yoke, rudder pedals, and throttle/engine controls. The vertical dial on the yoke controls the trim and the left lever switch controls the flaps. The rest of the buttons on the yoke should be ignored.
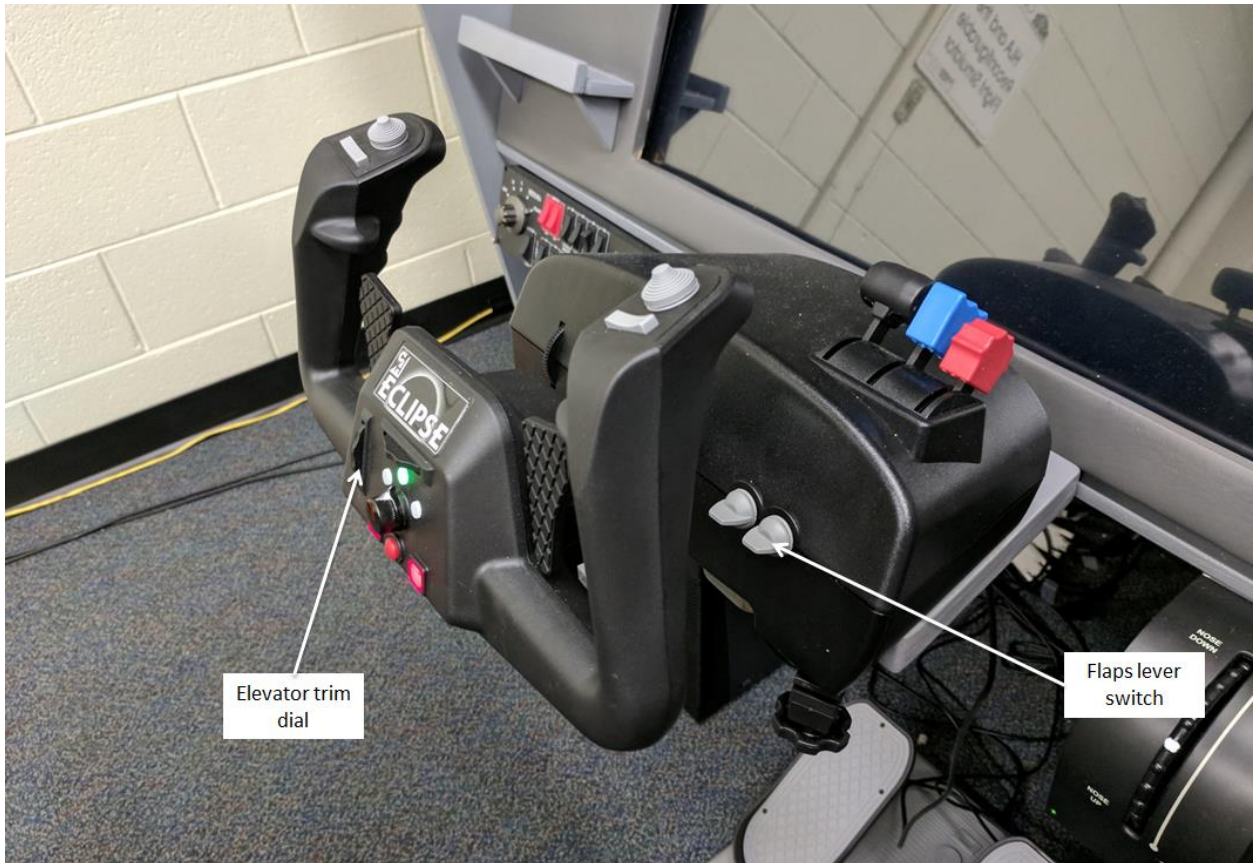
The instrument panel of the simulator is on the lower panel behind the yoke. The panel is a basic C172 panel with no glass instruments. The 6 pack is shown as well as engine instruments and navigation instruments for instrument approaches. NAV 1 will be tuned in to the localizer and glideslope for the runway.

Additionally, the EFVS will be on a heads-up display overlaid on the out-the-window view screen. Besides the information provided by the sensor, flight information including heading, airspeed, and vertical speed are provided on the heads-up display.
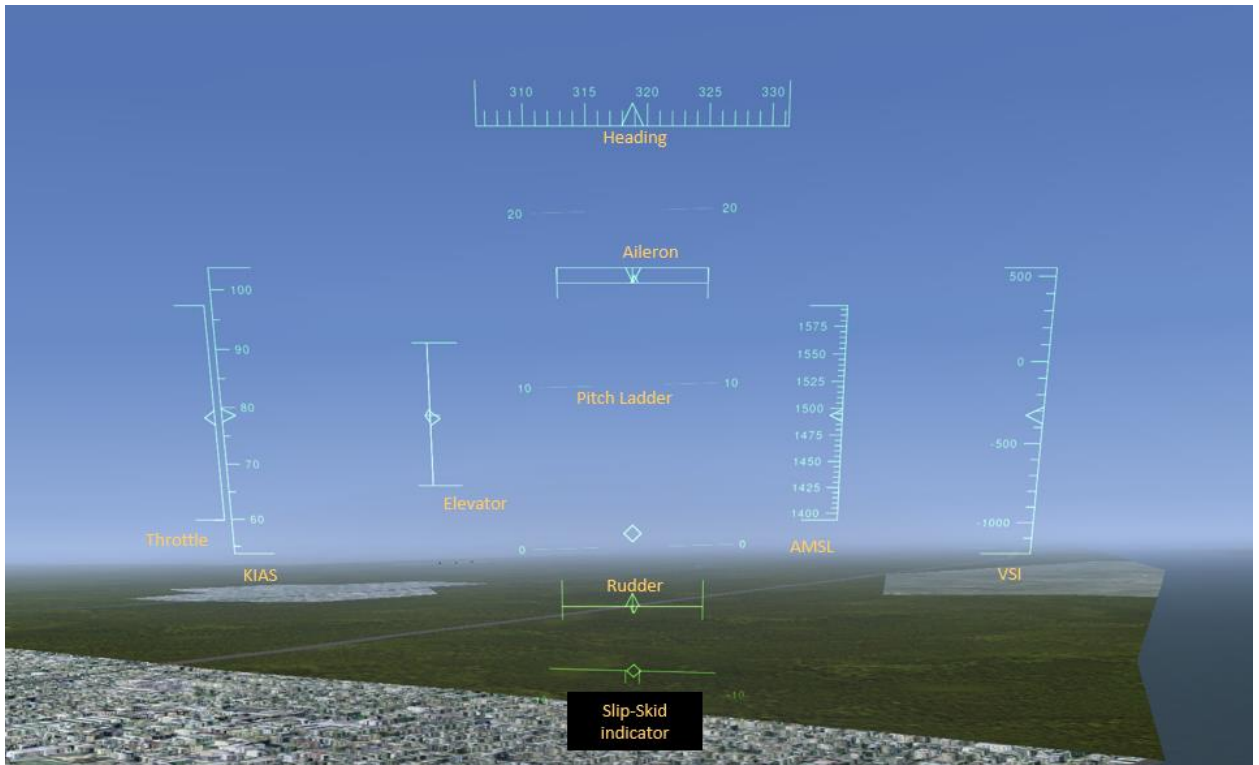
Approach Base Conditions

For each training approach, you flight will start in these conditions:

- 3-nautical mile final approach
- No flaps
- Nav instruments tuned to the ILS
- On the glideslope and localizer
- KIAS approximately 100 knots
- No wind
- You have clearance to land from the tower

So, you need to slow the aircraft to V_{ref} (65-70 knots) and configure the aircraft for landing (flaps 30°) while maintaining the approach, looking out for the runway via EFVS or your natural vision, and ultimately land the aircraft. To advance to the next stage of training and then the experiment, your performance will be assessed relative to these requirements: repeats of stages may be required and you can also choose to fly any stage again

- Localizer and glideslope deviation must not exceed 1 scale deviation at any point during the approach
- Vertical speed at touchdown must be less than 150 fpm
- A subjective assessment of whether or not you were in control of the aircraft

Stage 1 – Basic Simulator

The first training stage is a standard instrument approach with no EFVS equipped on the aircraft.

Stage 2 – EFVS

In the second training stage, instead of viewing only the outside scene, the EFVS will be used until touchdown. As you will be able to tell, the EFVS has a large sensor range in this case, such that it will portray the runway (and beyond) from the start of the scenario.

Stage 3 – No Runway Markings EFVS

In the third training stage, EFVS will still be utilized until touchdown. However, this EFVS on this stage will not be able to portray the runway markings.

Stage 4 – Short Range EFVS

Here, EFVS will still be utilized until touchdown. However, this EFVS has a limited sensor range of approximately 1 mile.

[After training] Now, please fill out the same questionnaire that will be at the end of each scenario, to give you a heads-up on its questions. It has two portions, a visual cue questionnaire and a workload assessment. To assess workload, we are using this set of six rating scales developed by NASA:

- <u>Mental Demand</u> – How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
- <u>Physical Demand</u> – How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
- <u>Temporal Demand</u> – How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
- <u>Performance</u> – How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
- <u>Effort</u> – How hard did you have to work (mentally and physically) to accomplish your level of performance?
- <u>Frustration Level</u> – How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

After performing each of the approaches in the experiment, you will be asked to give a rating on each of the scales. You will select a point on the scale that best matches your experience for the task, relative to the two descriptors on either end. Note that performance goes from 'good' on the left to 'bad' on the right.

APPENDIX B. STATISTICAL ANALYSIS

B.1 Two-Way ANOVA to Identify Interaction Effects

B.1.1 Glideslope RMS

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
EFVS_Runway_Markings	2	0.02827	0.01414	1.88981	0.15514
Sensor_Range	2	0.05117	0.02558	3.41999	0.03562
EFVS_Runway_Markings:Sensor_Range	2	0.00082	0.00041	0.05509	0.94642
Residuals	133	0.99493	0.00748	NA	NA

B.1.2 Glideslope Max Value

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
EFVS_Runway_Markings	2	0.22774	0.11387	2.30192	0.10384
Sensor_Range	2	0.29260	0.14630	2.95748	0.05520
EFVS_Runway_Markings:Sensor_Range	2	0.06708	0.03354	0.67806	0.50926
Residuals	140	6.92546	0.04947	NA	NA

B.1.3 Localizer RMS

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
EFVS_Runway_Markings	2	0.01016	0.00508	1.32951	0.26821
Sensor_Range	2	0.06603	0.03301	8.64071	0.00030
EFVS_Runway_Markings:Sensor_Range	2	0.00290	0.00145	0.37964	0.68487
Residuals	129	0.49286	0.00382	NA	NA

B.1.4   Localizer Max Value

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
EFVS_Runway_Markings	2	0.02752	0.01376	0.80804	0.44791
Sensor_Range	2	0.31605	0.15802	9.28073	0.00017
EFVS_Runway_Markings:Sensor_Range	2	0.05035	0.02517	1.47852	0.23170
Residuals	133	2.26459	0.01703	NA	NA

B.1.5   Vertical Speed at Touchdown

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
EFVS_Runway_Markings	2	44764.794	22382.397	2.564	0.081
Sensor_Range	2	47783.251	23891.626	2.737	0.068
EFVS_Runway_Markings:Sensor_Range	2	4009.703	2004.851	0.230	0.795
Residuals	132	1152383.943	8730.181	NA	NA

B.1.6   Distance from Centerline

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
EFVS_Runway_Markings	2	301.618	150.809	0.727	0.485
Sensor_Range	2	368.745	184.373	0.889	0.413
EFVS_Runway_Markings:Sensor_Range	2	82.530	41.265	0.199	0.820
Residuals	136	28201.743	207.366	NA	NA

B.1.7   Distance from Markers

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
EFVS_Runway_Markings	2	187301.0	93650.48	0.549	0.579
Sensor_Range	2	344735.8	172367.89	1.010	0.367
EFVS_Runway_Markings:Sensor_Range	2	161354.7	80677.37	0.473	0.624
Residuals	129	22006298.7	170591.46	NA	NA

B.2   Likelihood Test Examining Participants as a Source of Variance

	Glideslope RMS	Glideslope Max Value	Localizer RMS	Localizer Max Value	VSI Touchdown	Distance Centerline	Distance Markers
Runway Markings	0.00011	0.00147	0.00094	0.01965	0.00172	7e-05	0
Sensor Range	0.00005	0.00152	0.00001	0.00192	0.00109	9e-05	0

B.3   Mixed-Effect ANOVA Tables

B.3.1   *Glideslope RMS vs EFVS Portrayal of Runway Markings*

	numDF	denDF	F-value	p-value
(Intercept)	1	117	450.77676	0.00000
EFVS_Runway_Markings	2	117	2.42286	0.09311

B.3.2   *Glideslope RMS vs EFVS Sensor Range*

	numDF	denDF	F-value	p-value
(Intercept)	1	117	450.13968	0.00000
Sensor_Range	2	117	5.11467	0.00742

B.3.3   *Glideslope Max Value vs EFVS Portrayal of Runway Markings*

	numDF	denDF	F-value	p-value
(Intercept)	1	124	456.54322	0.00000
EFVS_Runway_Markings	2	124	2.76243	0.06703

B.3.4   *Glideslope Max Value vs EFVS Sensor Range*

	numDF	denDF	F-value	p-value
(Intercept)	1	124	456.54318	0.00000
Sensor_Range	2	124	2.57706	0.08006

B.3.5 Localizer RMS vs EFVS Portrayal of Runway Markings

	numDF	denDF	F-value	p-value
(Intercept)	1	113	242.41687	0.00000
EFVS_Runway_Markings	2	113	1.42724	0.24426

B.3.6 Localizer RMS vs EFVS Sensor Range

	numDF	denDF	F-value	p-value
(Intercept)	1	113	218.84068	0
Sensor_Range	2	113	16.78468	0

B.3.7 Localizer Max vs EFVS Portrayal of Runway Markings

	numDF	denDF	F-value	p-value
(Intercept)	1	117	157.68133	0.00000
EFVS_Runway_Markings	2	117	0.80468	0.44969

B.3.8 Localizer Max Value vs EFVS Sensor Range

	numDF	denDF	F-value	p-value
(Intercept)	1	117	153.00857	0e+00
Sensor_Range	2	117	12.78198	1e-05

B.3.9 Vertical Speed vs EFVS Portrayal of Runway Markings

	numDF	denDF	F-value	p-value
(Intercept)	1	116	227.15837	0.00000
EFVS_Runway_Markings	2	116	2.91237	0.05833

B.3.10 Vertical Speed vs EFVS Sensor Range

	numDF	denDF	F-value	p-value
(Intercept)	1	116	220.87381	0.000
Sensor_Range	2	116	3.28379	0.041

B.3.11 Distance from Centerline vs EFVS Portrayal of Runway Markings

	numDF	denDF	F-value	p-value
(Intercept)	1	120	62.29854	0.00000
EFVS_Runway_Markings	2	120	0.98094	0.37795

B.3.12 Distance from Centerline vs EFVS Sensor Range

	numDF	denDF	F-value	p-value
(Intercept)	1	120	62.80038	0.00000
Sensor_Range	2	120	0.60005	0.55042

B.3.13 Distance from Markers vs EFVS Portrayal of Runway Markings

	numDF	denDF	F-value	p-value
(Intercept)	1	113	41.94833	0.00000
EFVS_Runway_Markings	2	113	1.32407	0.27015

B.3.14 Distance from Markers vs EFVS Sensor Range

	numDF	denDF	F-value	p-value
(Intercept)	1	113	43.37535	0.00000
Sensor_Range	2	113	0.95089	0.38947

APPENDIX C. GRAPHS OF PILOT PERFORMANCE AS A

FACTOR OF EFVS SENSOR LIMITATIONS

C.1   Glideslope RMS
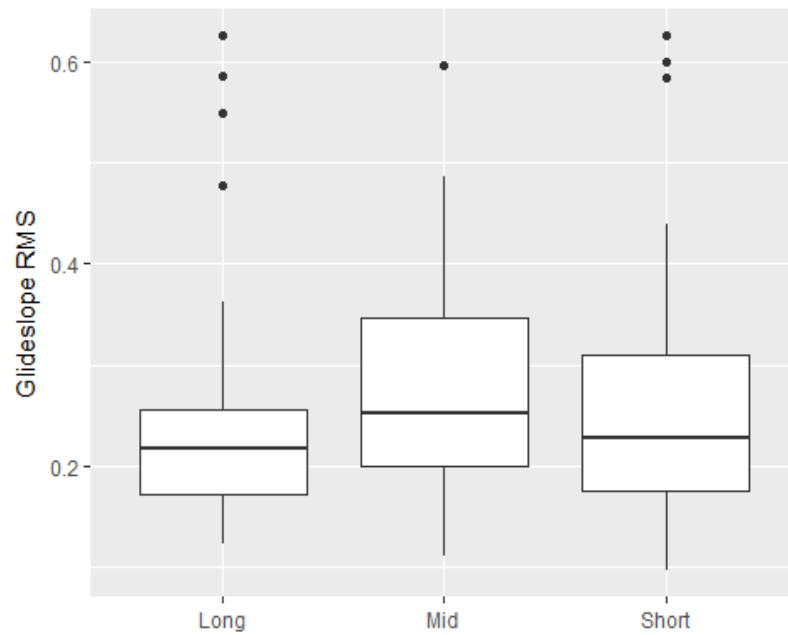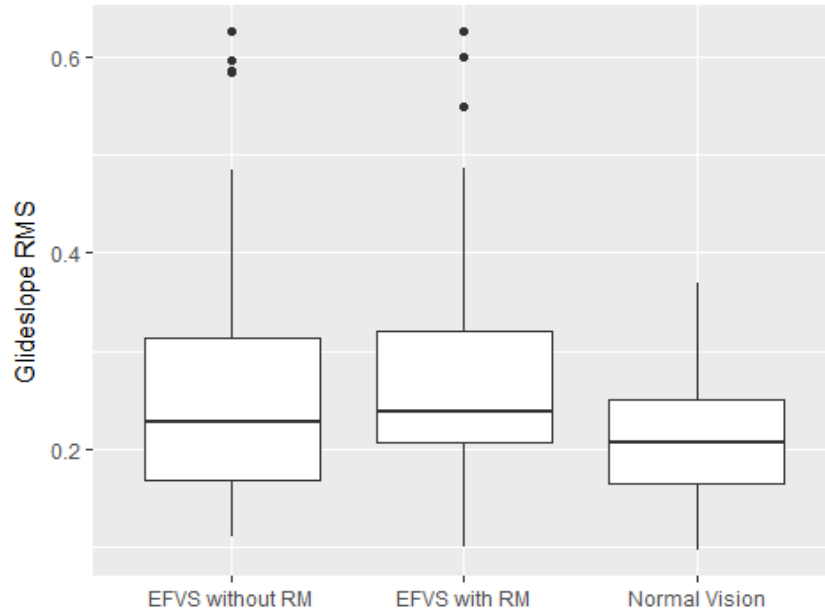
C.2 Glideslope Max Value
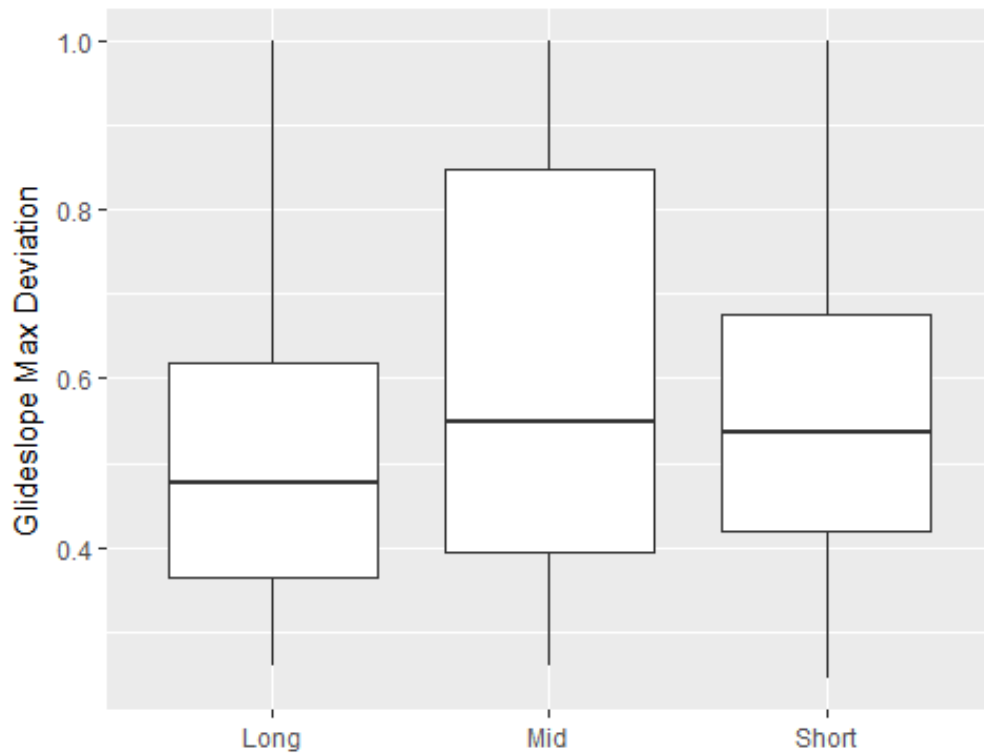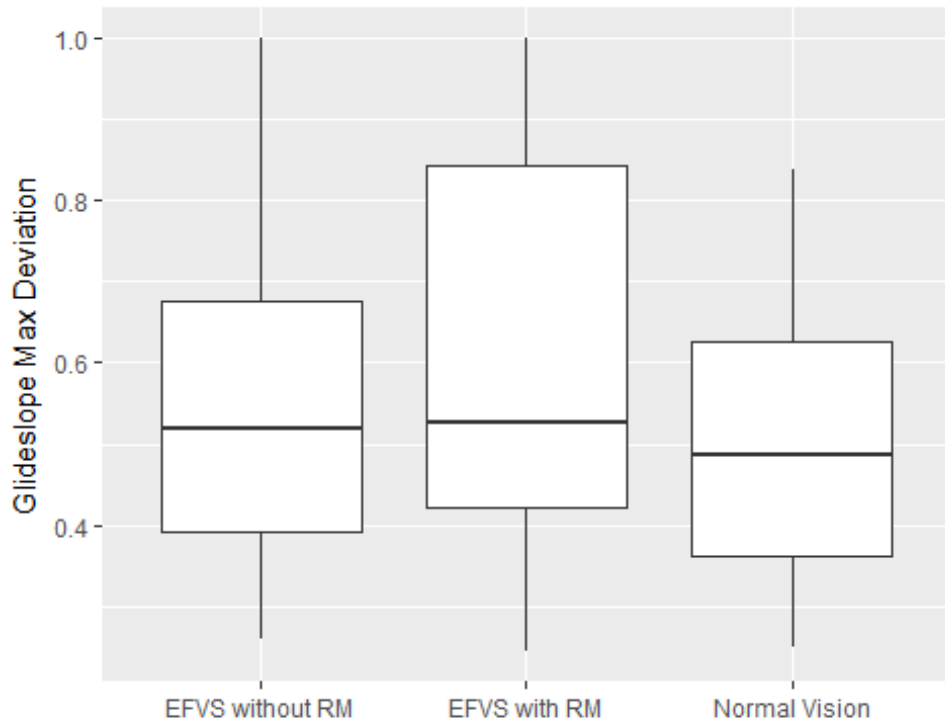
C.3 Glideslope Number of Exceedances
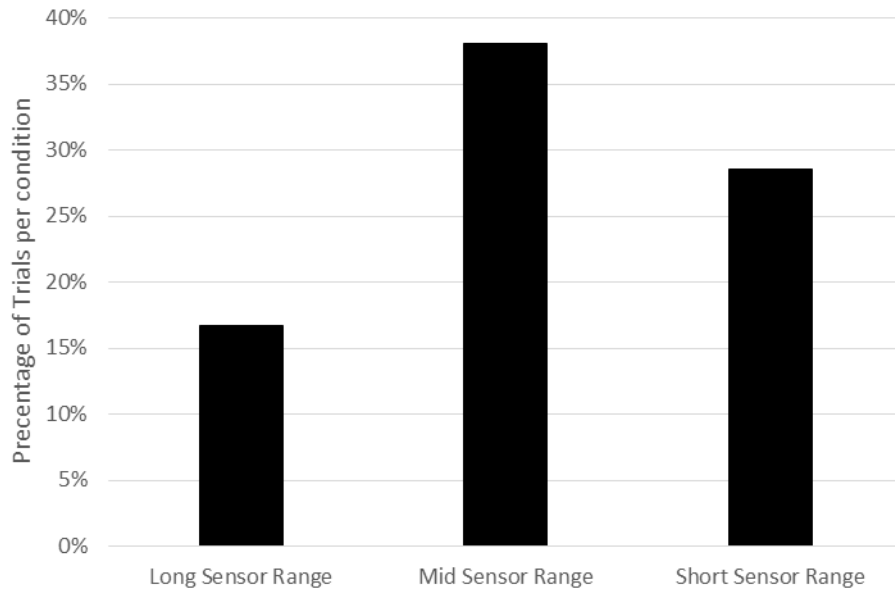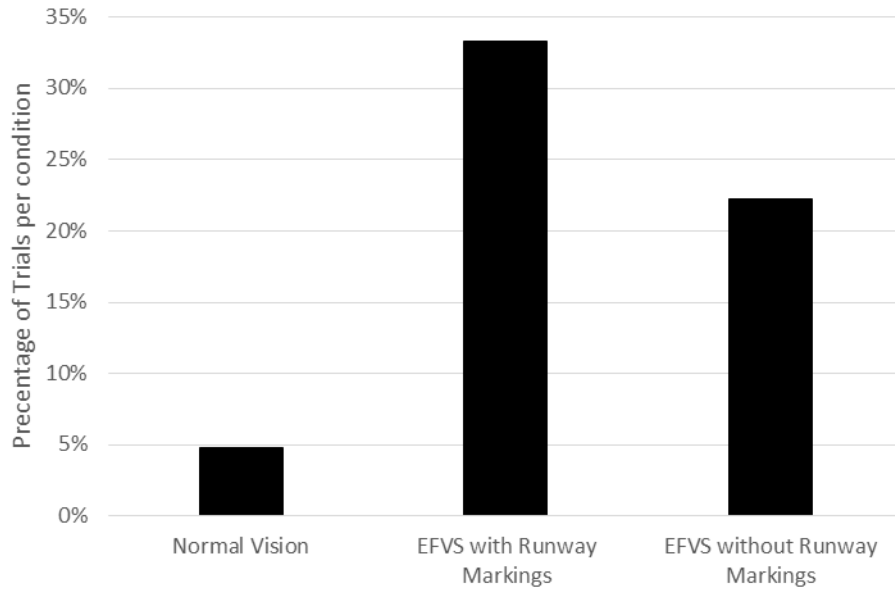
C.4 Localizer RMS
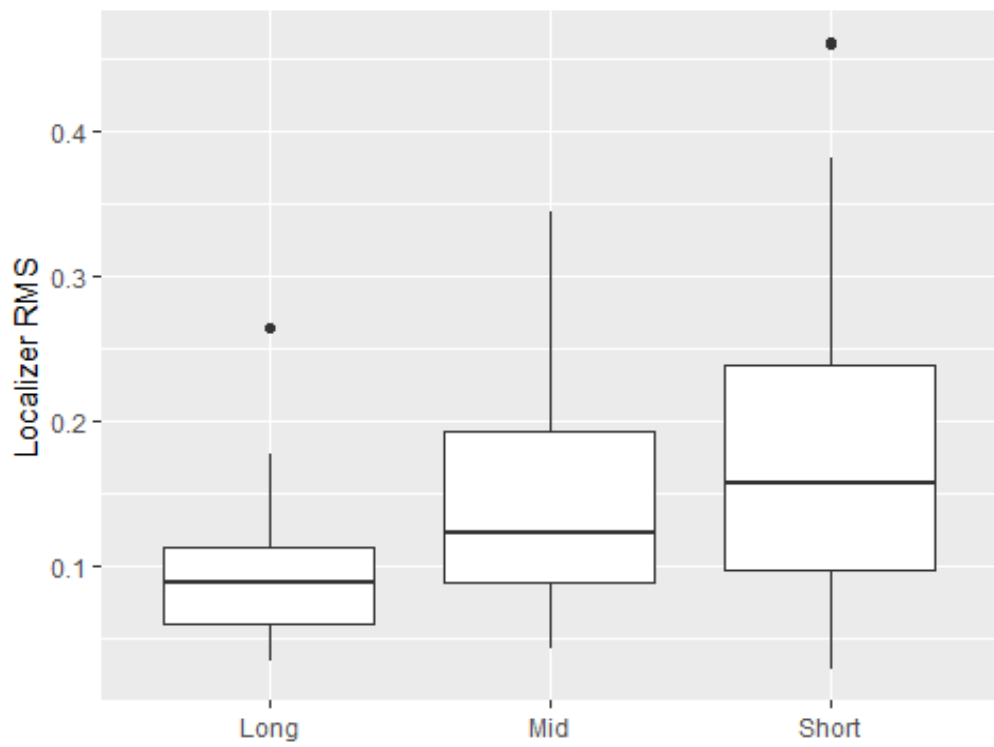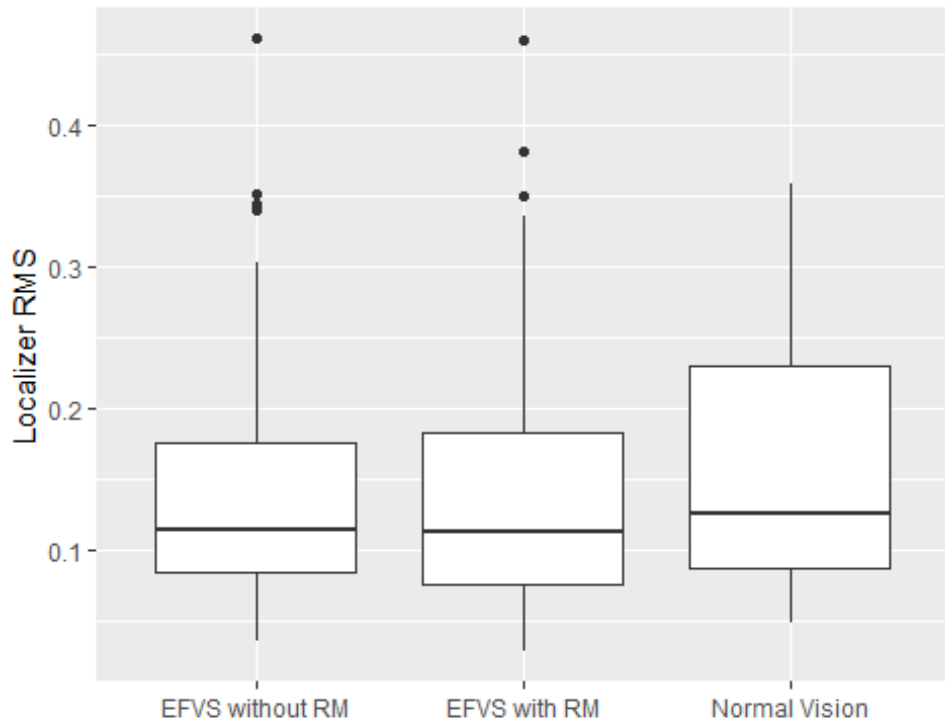
C.5 Localizer Max Value
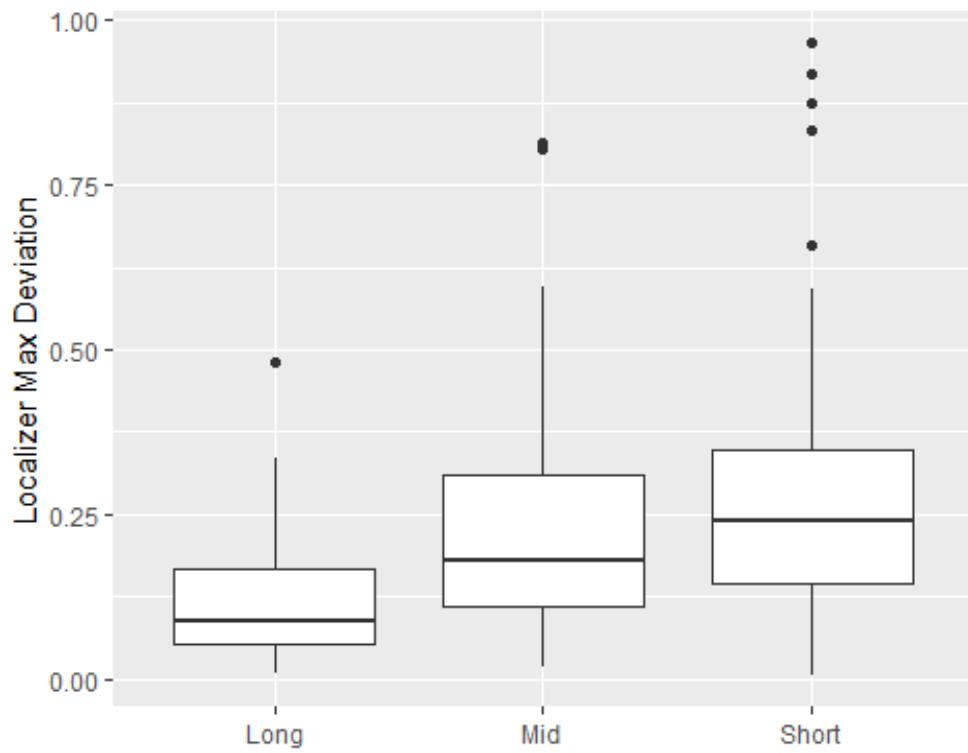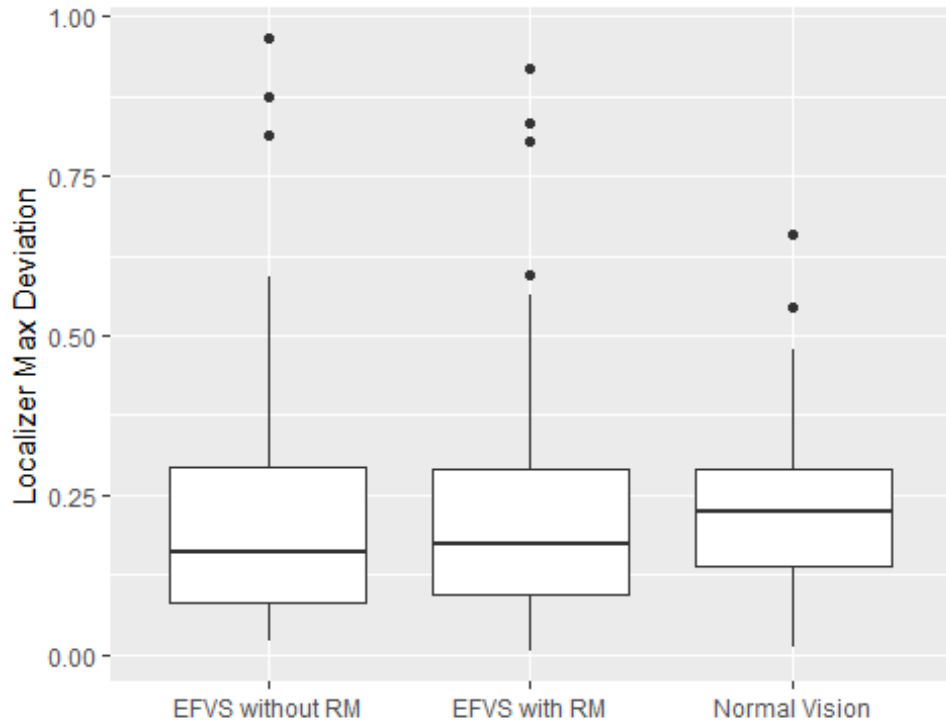
C.6 Localizer Number of Exceedances
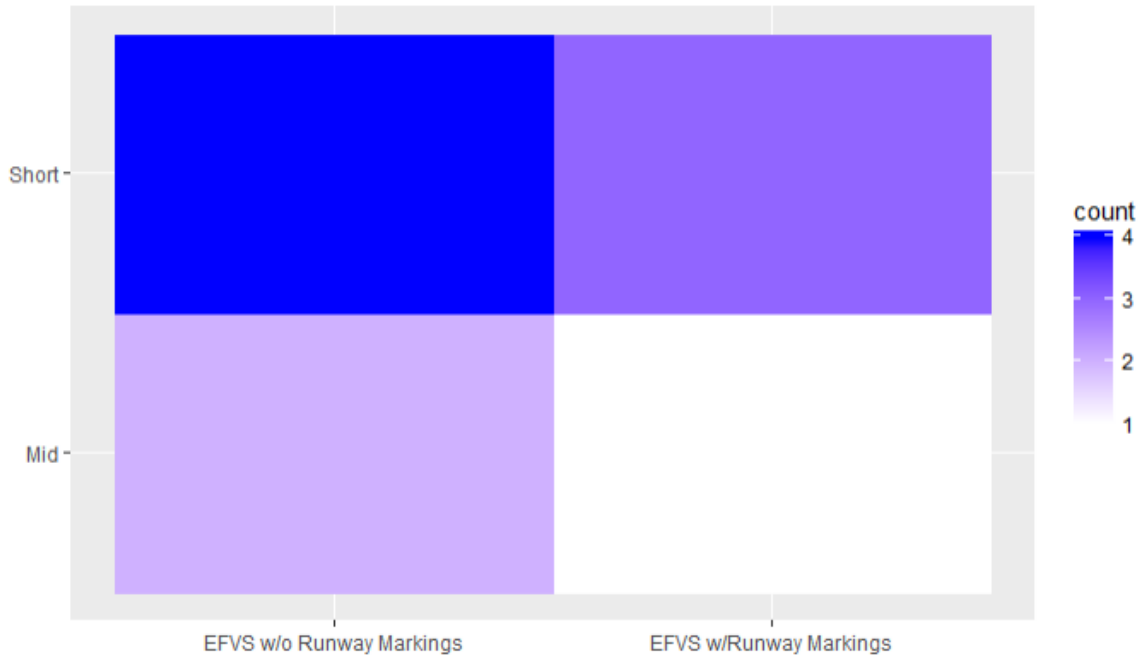
C.7 Vertical Speed at Touchdown
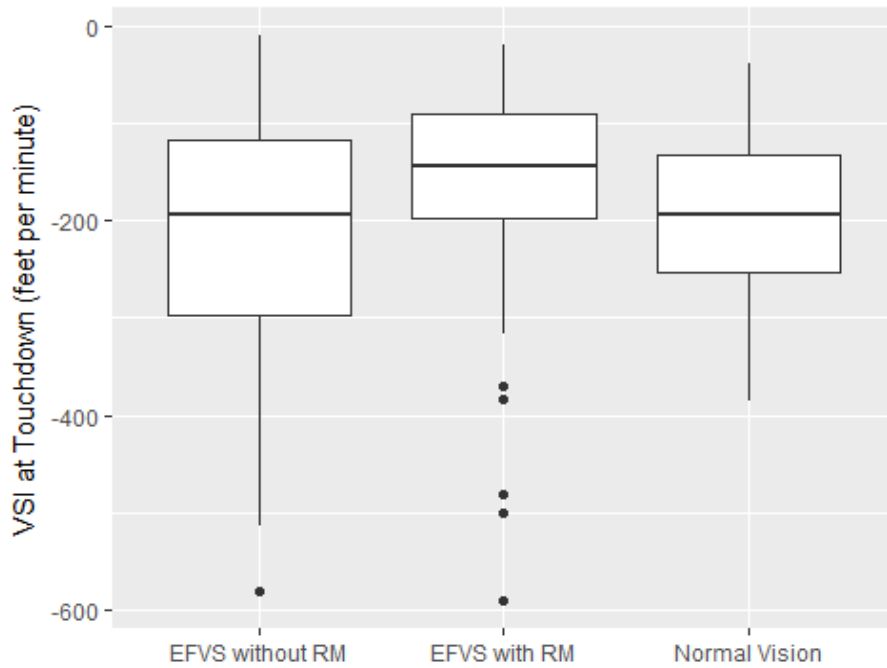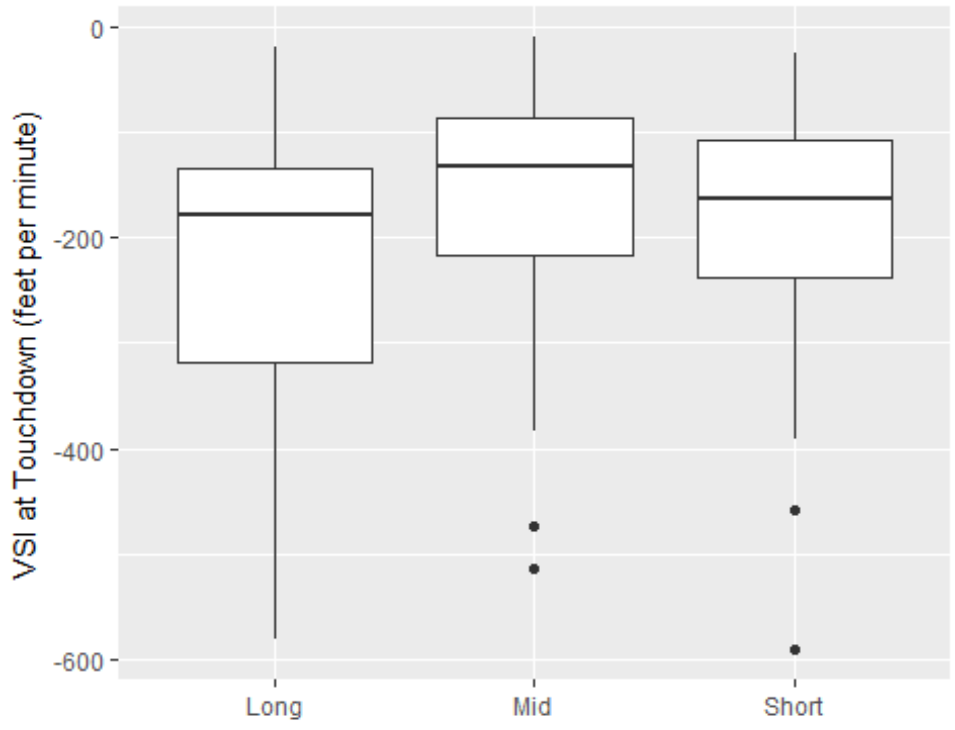
C.8   Distance from Centerline
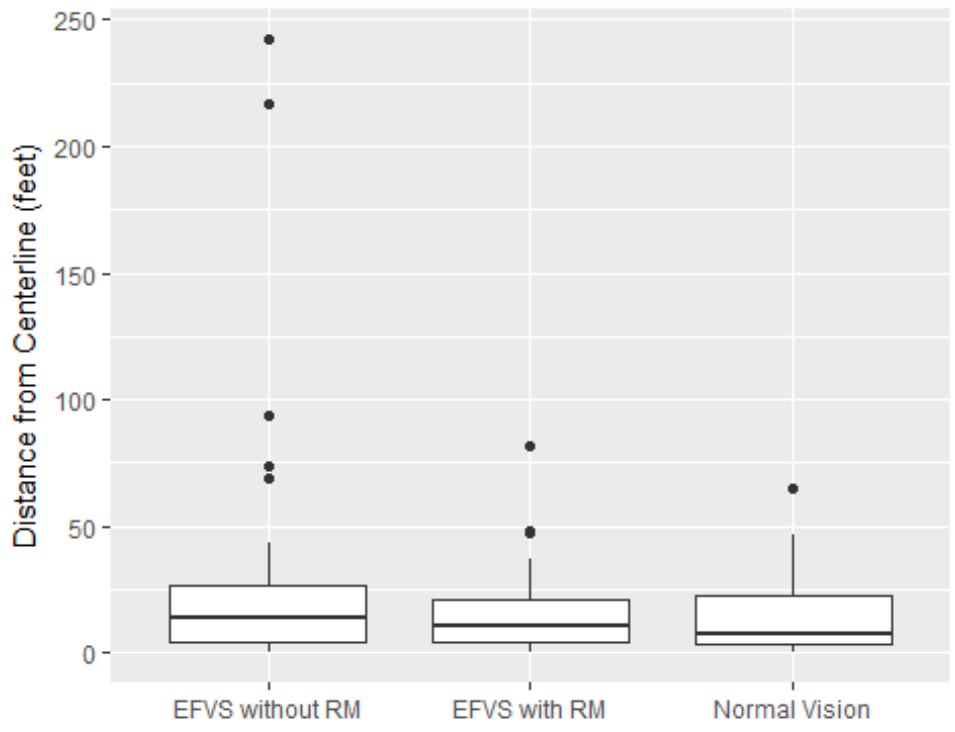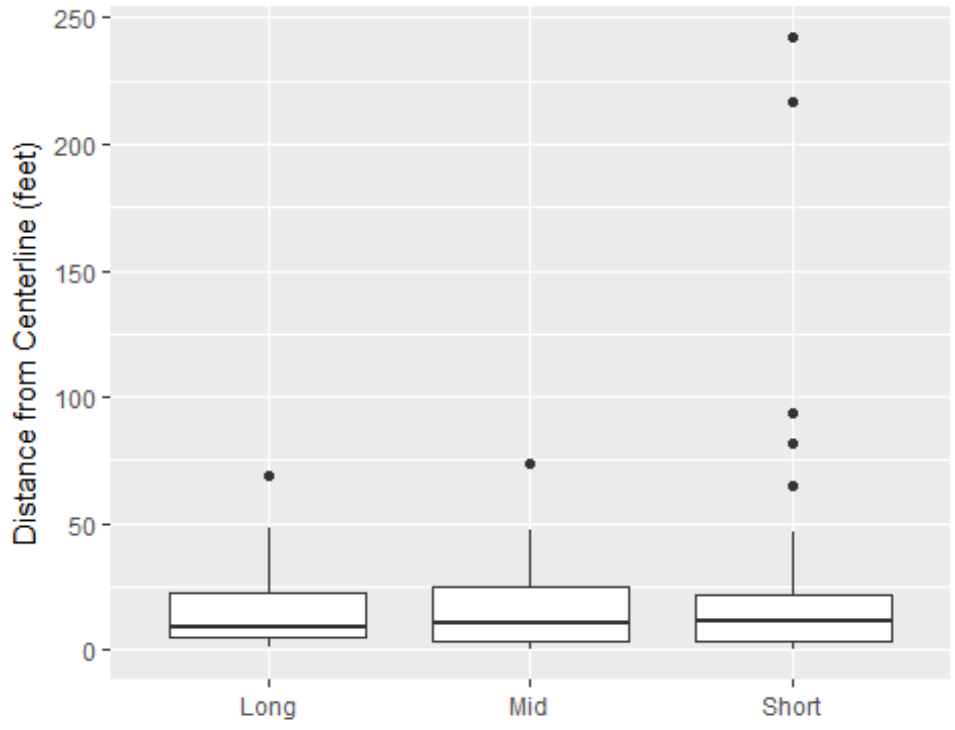
C.9 Distance from Markers
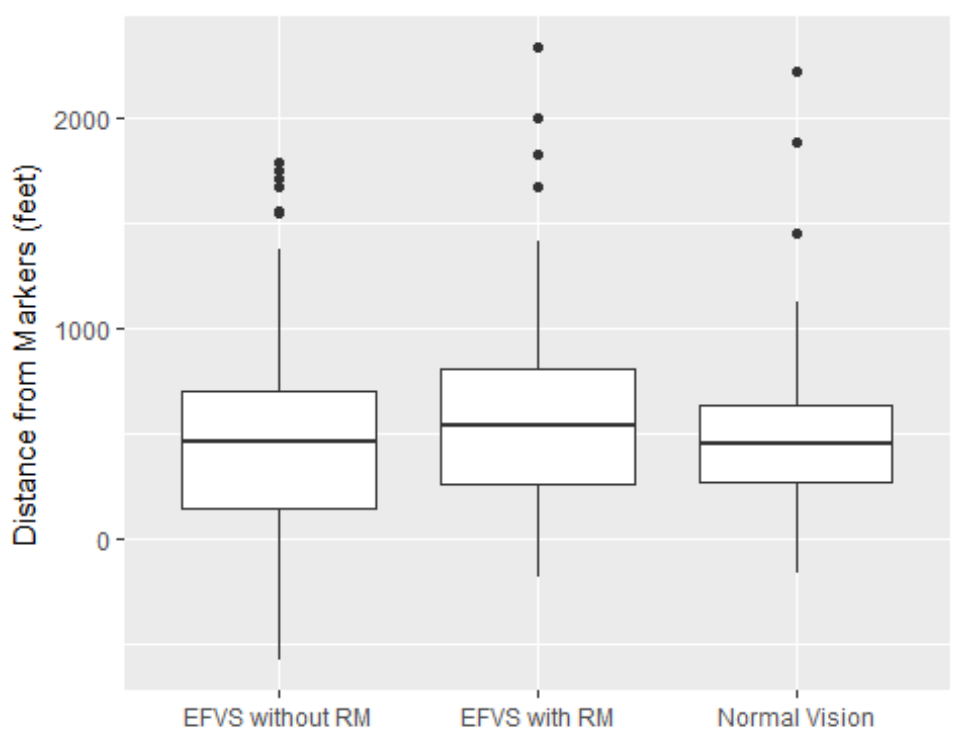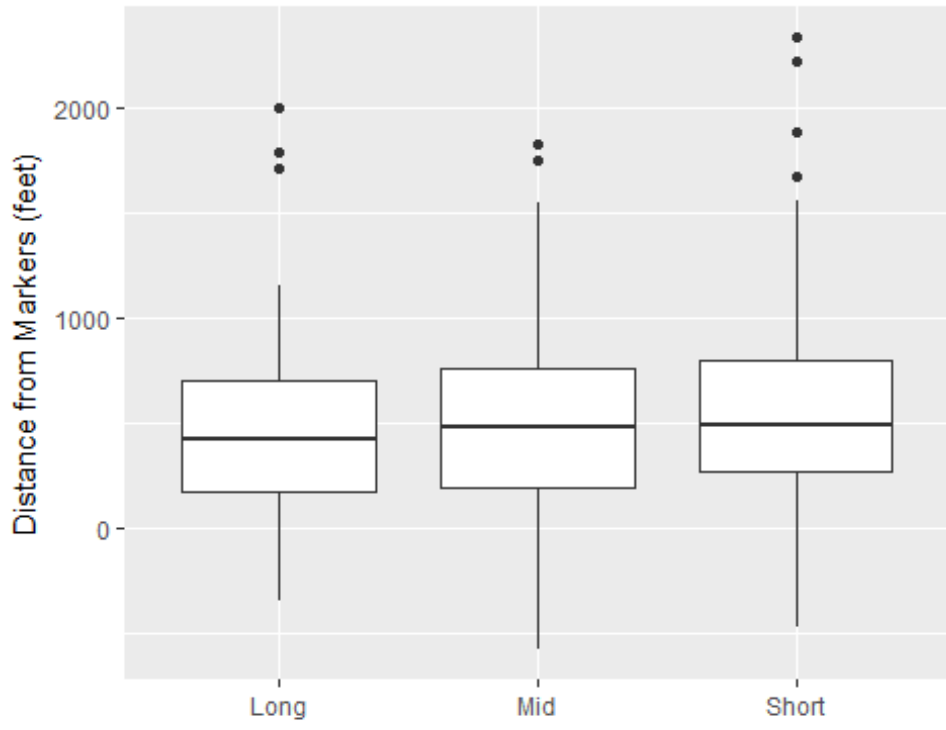
APPENDIX D: NASA TLX AND QUESTIONNAIRE GRAPHS

D.1 Overall Workloads for Each Participant for Each Scenario
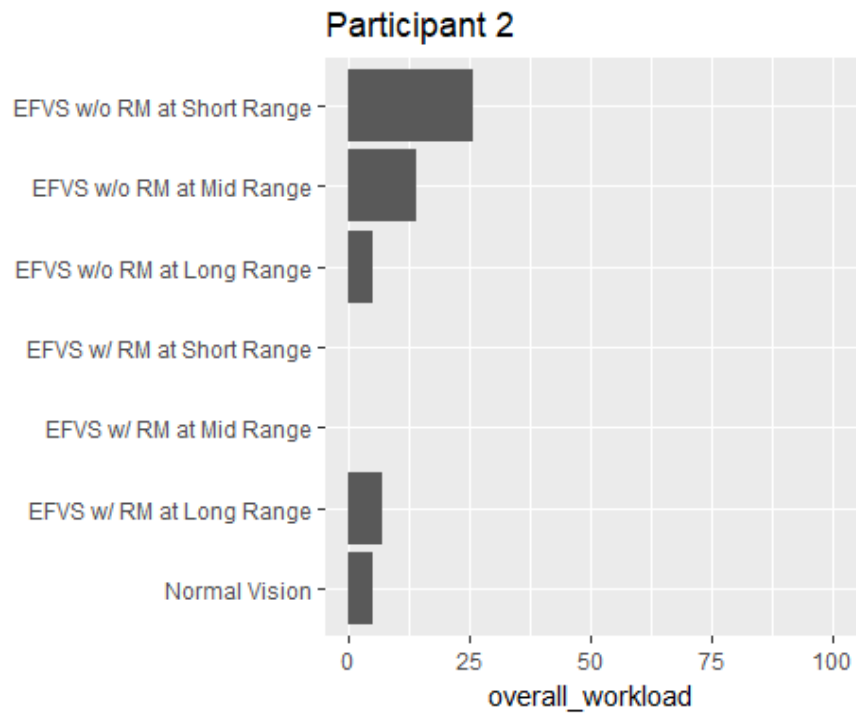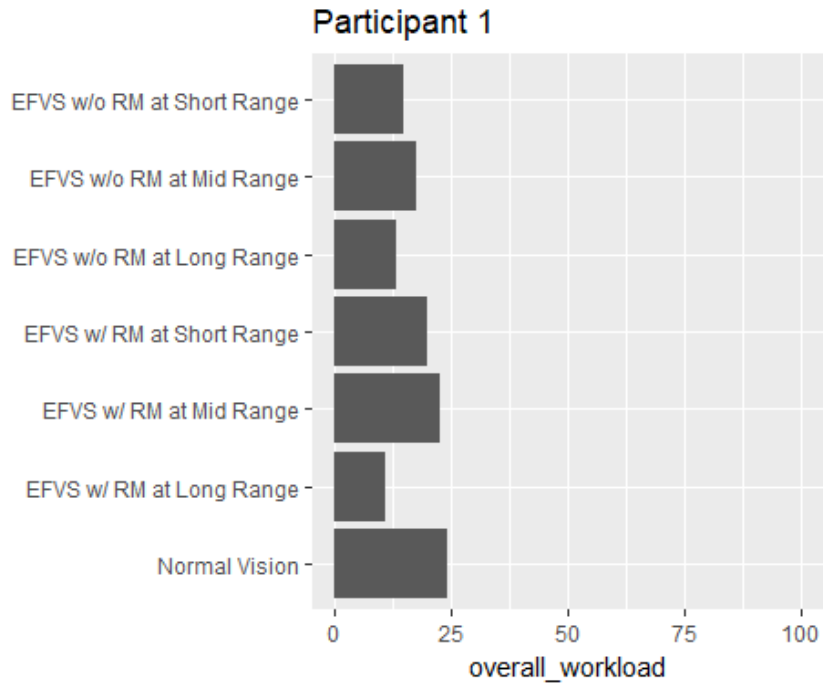
Participant 3
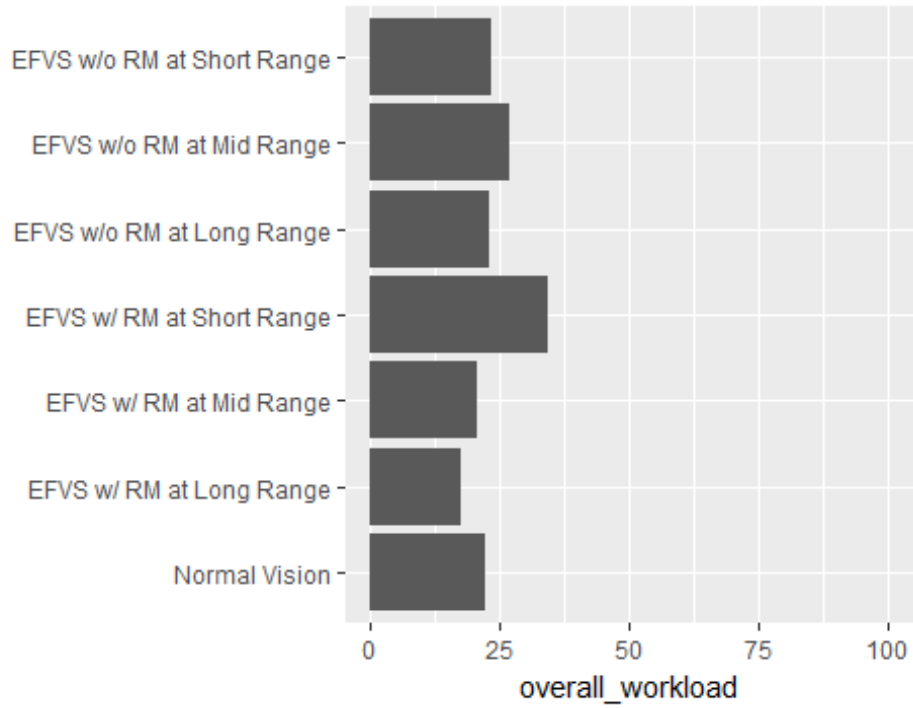
Participant 4
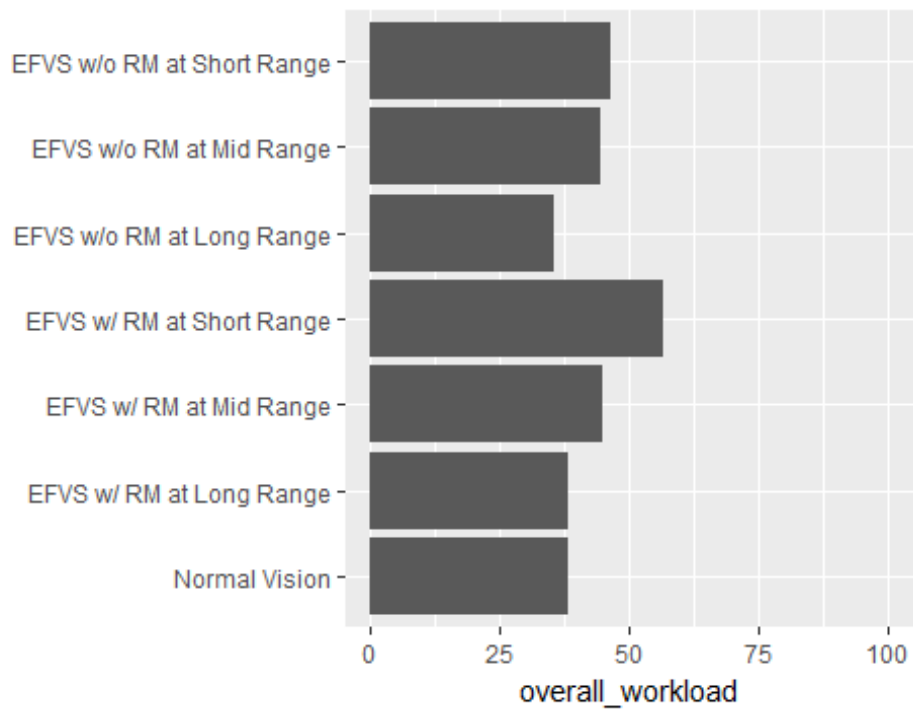
Participant 5
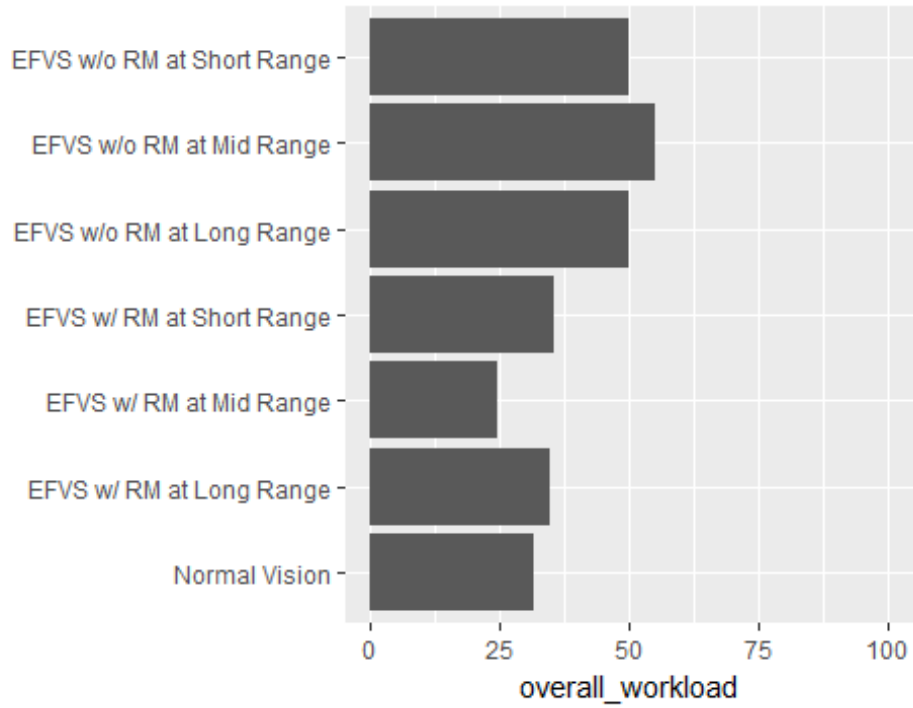
Participant 6
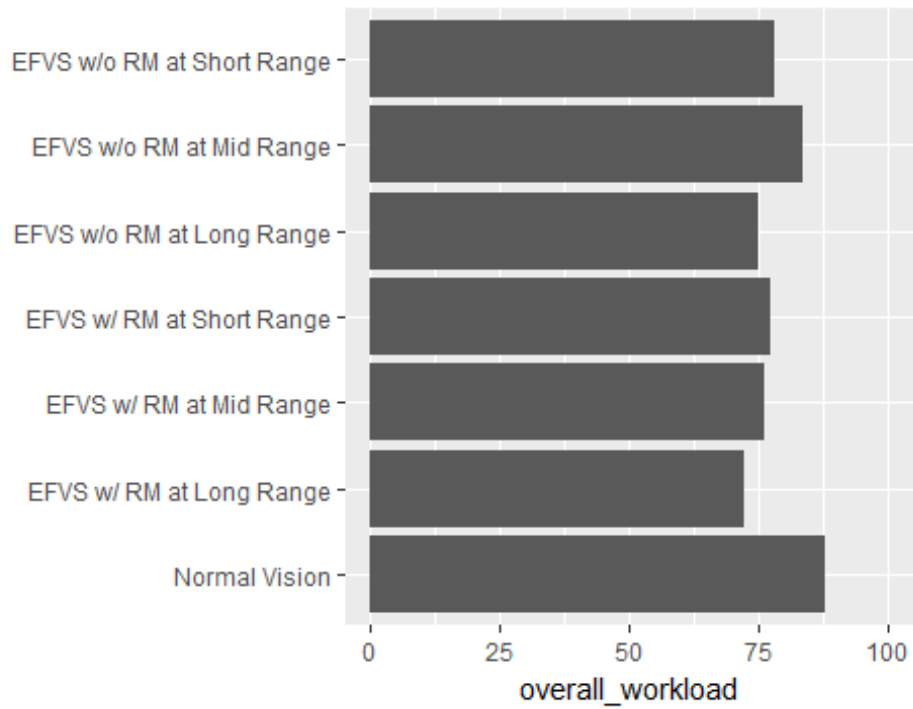
Participant 7
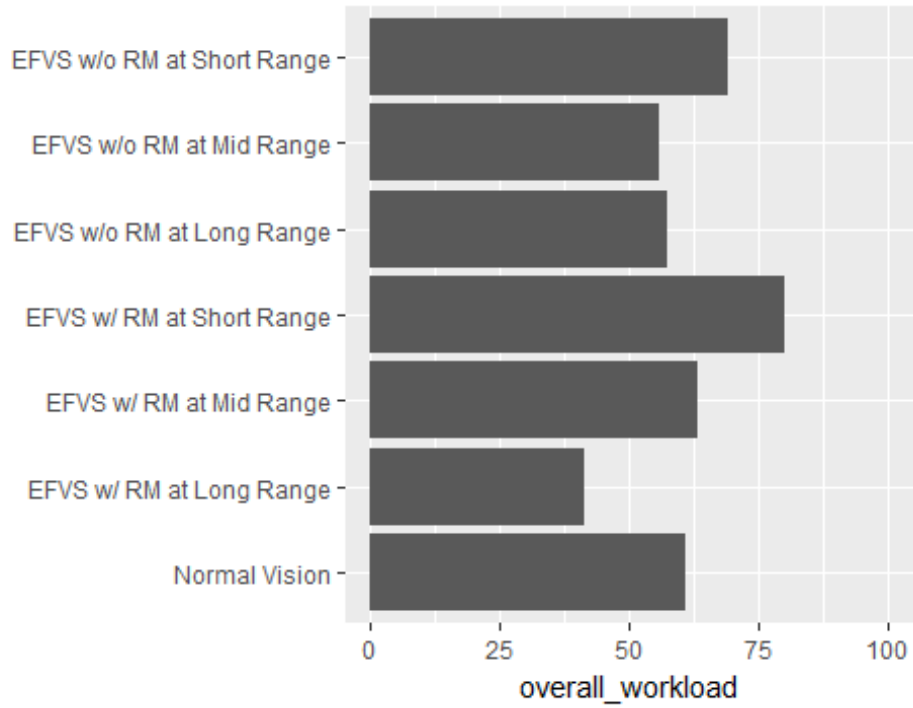
Participant 8
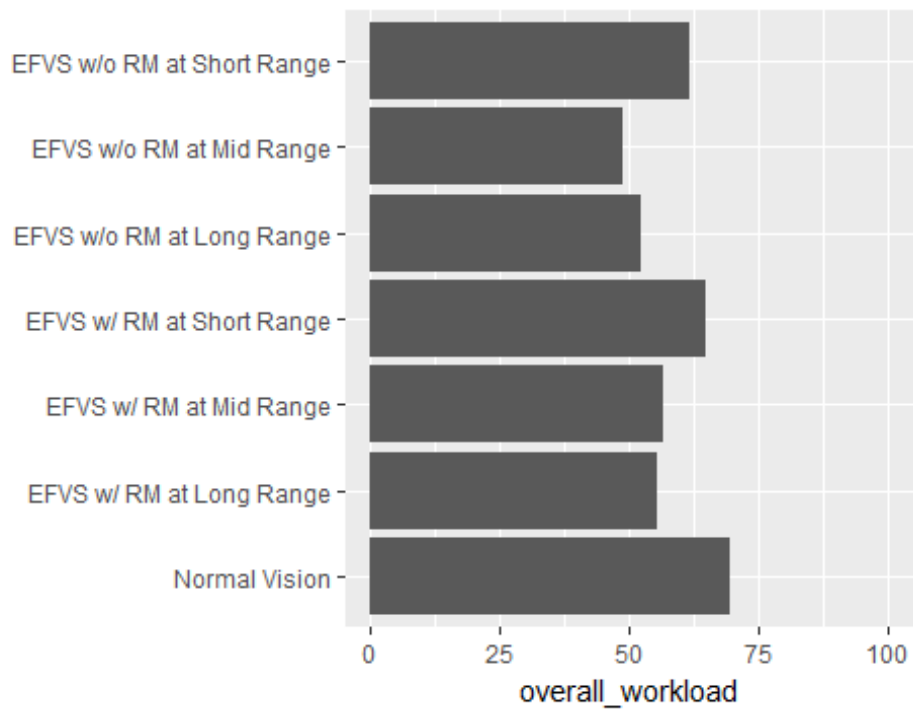
Participant 9
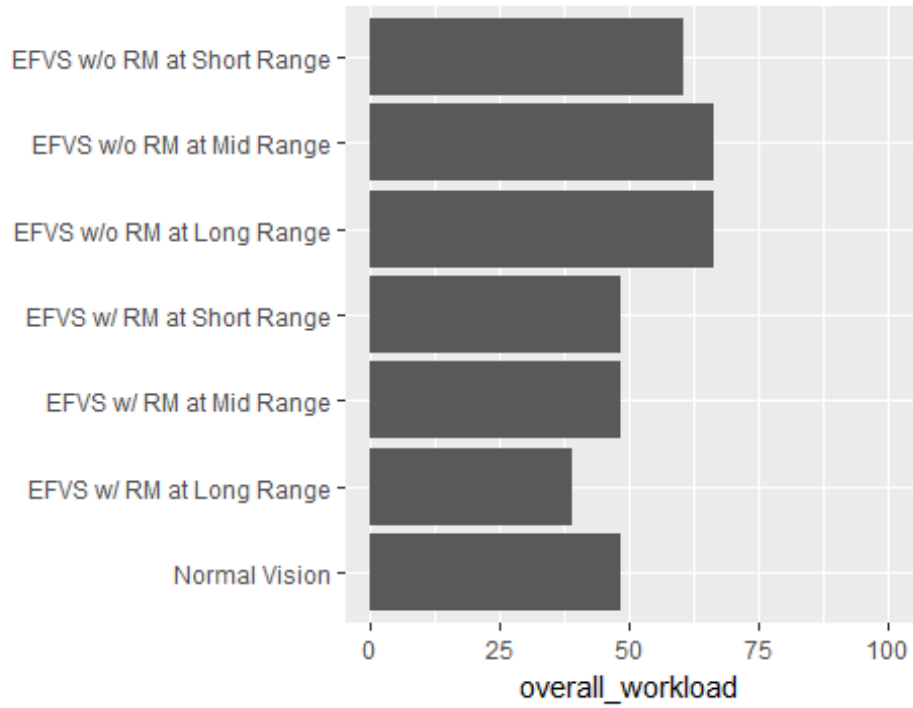
Participant 10
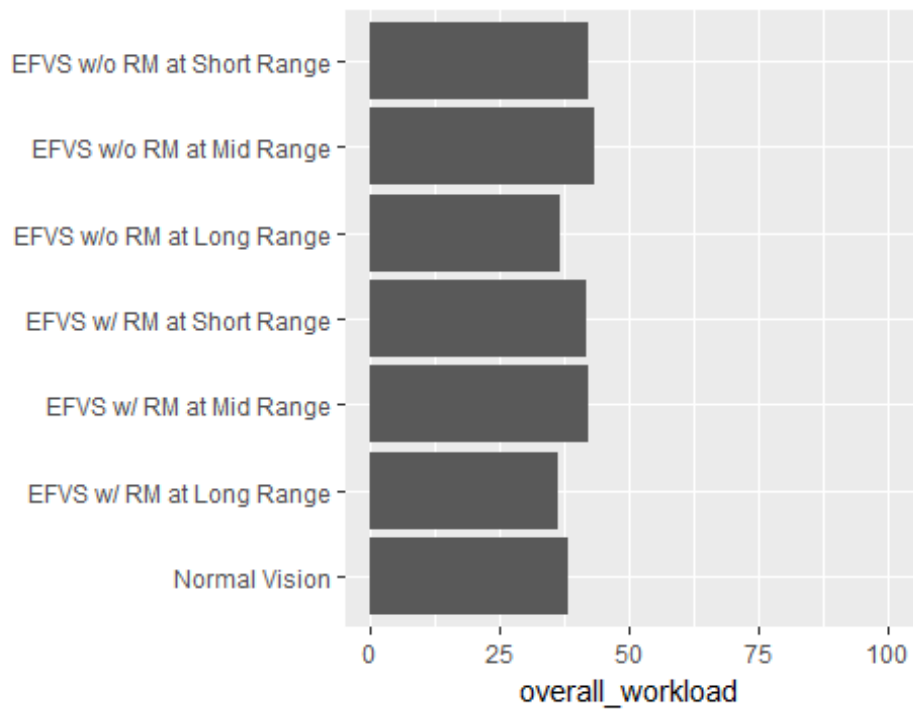
Participant 11
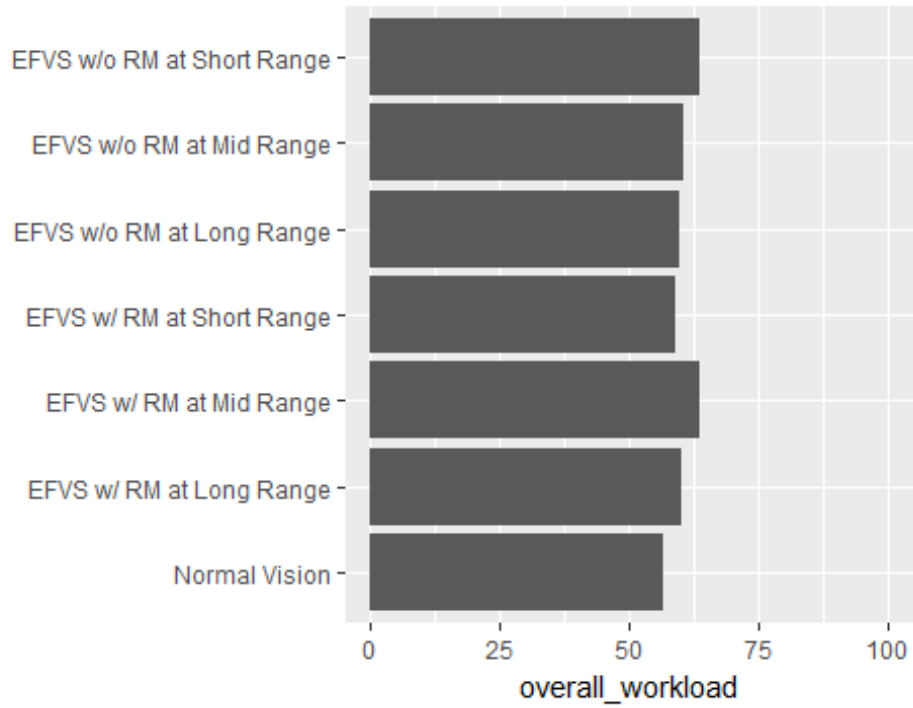
Participant 12
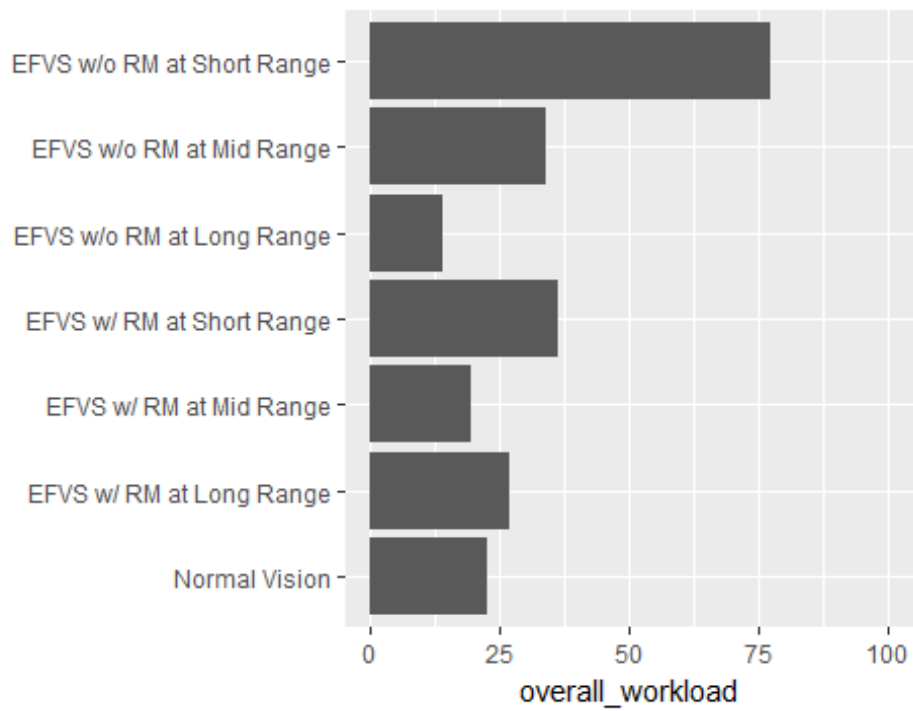
Participant 13
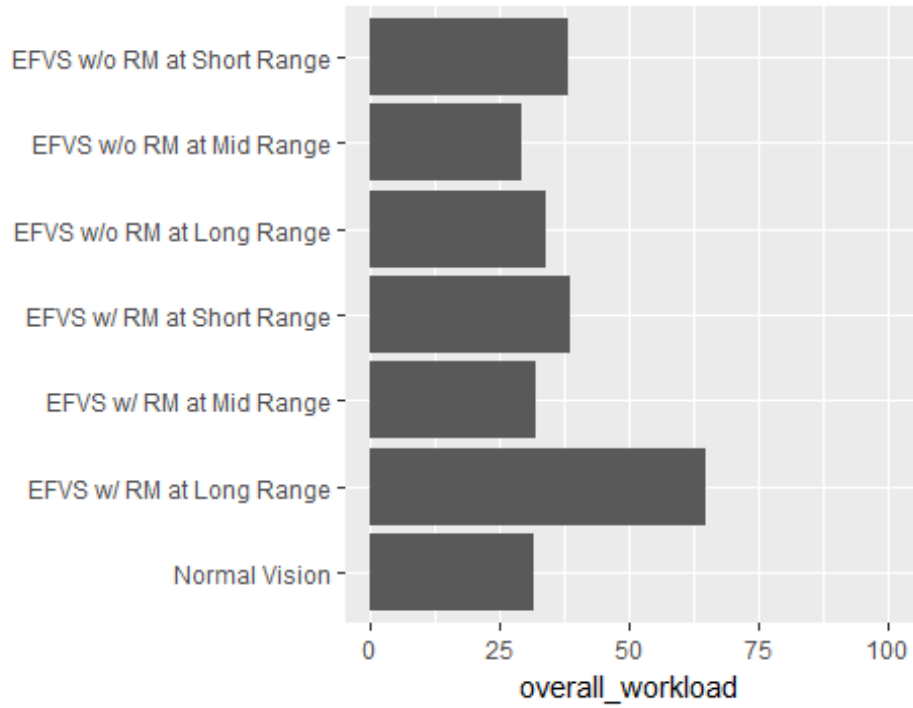
Participant 14
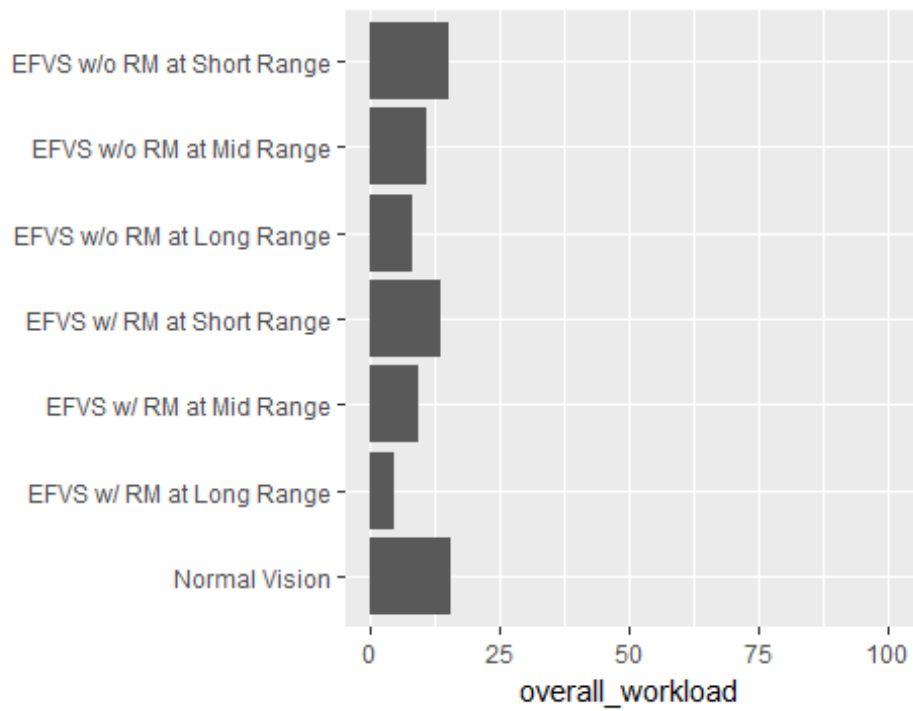
Participant 15
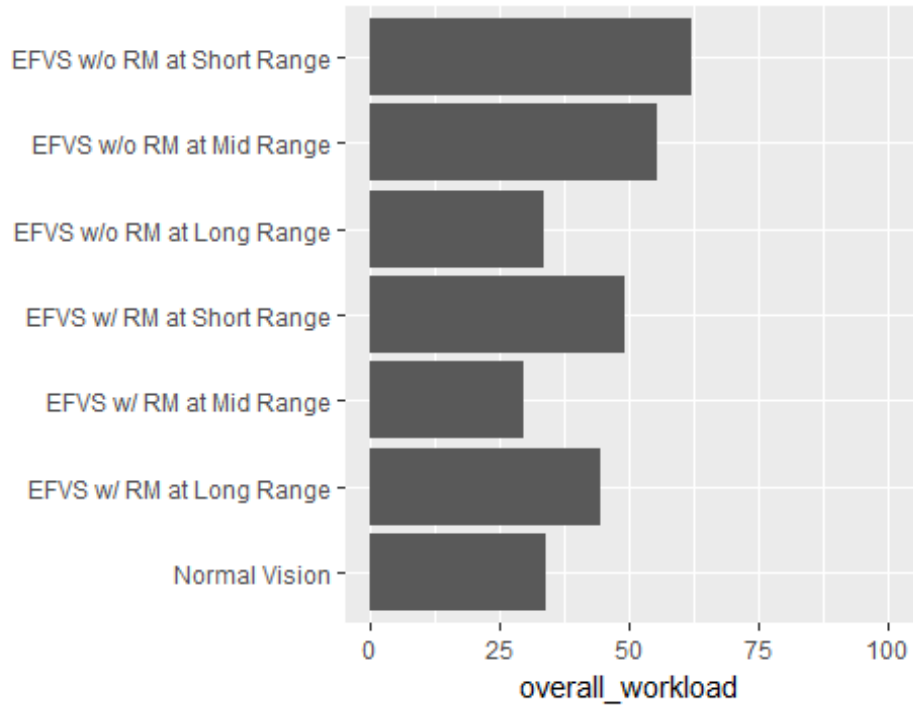
Participant 16
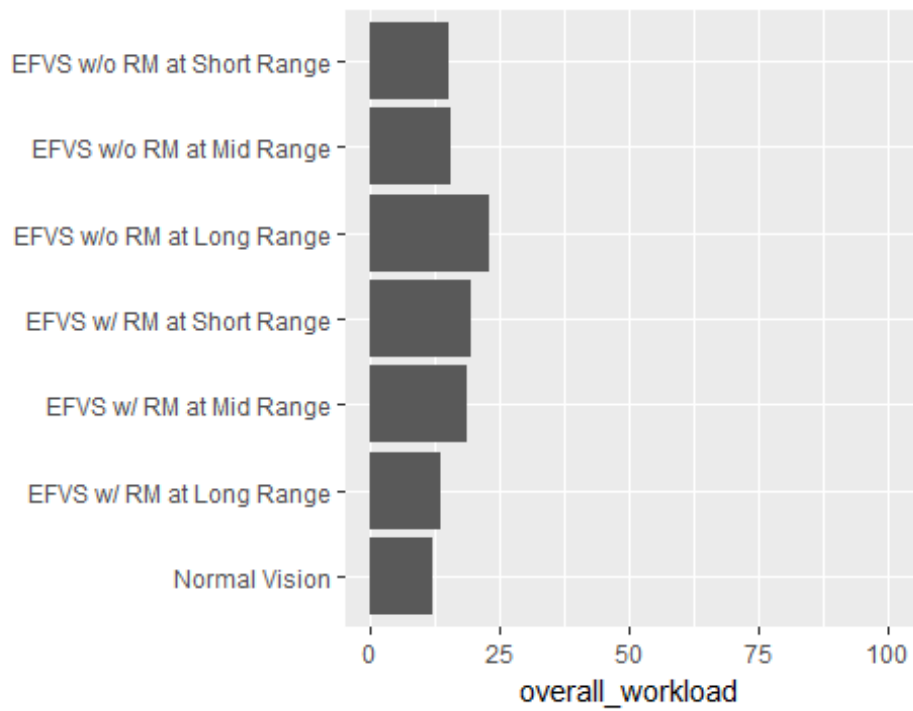
Participant 17
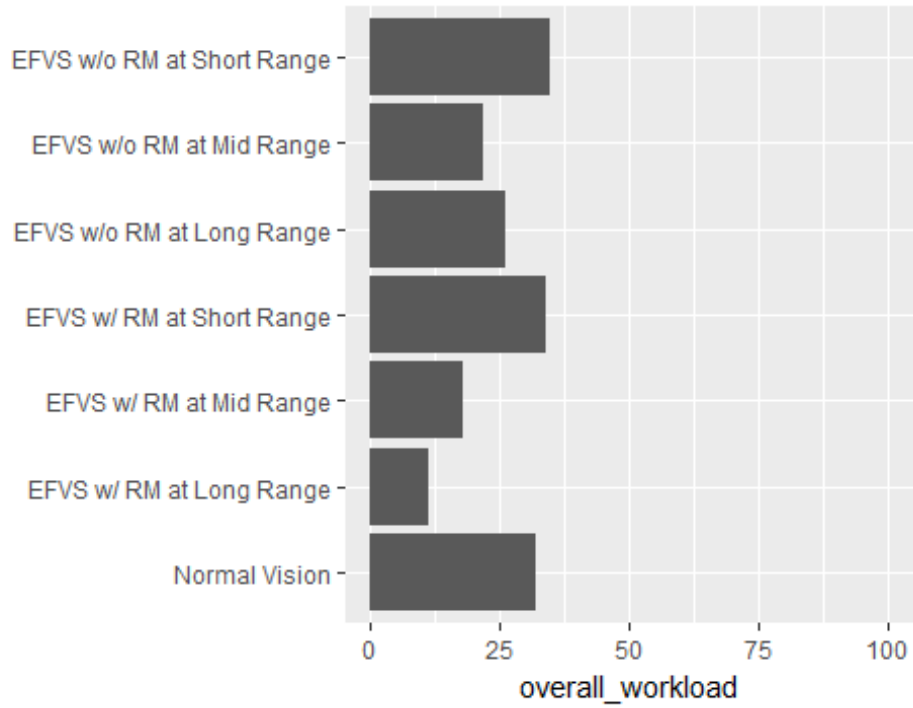
Participant 18
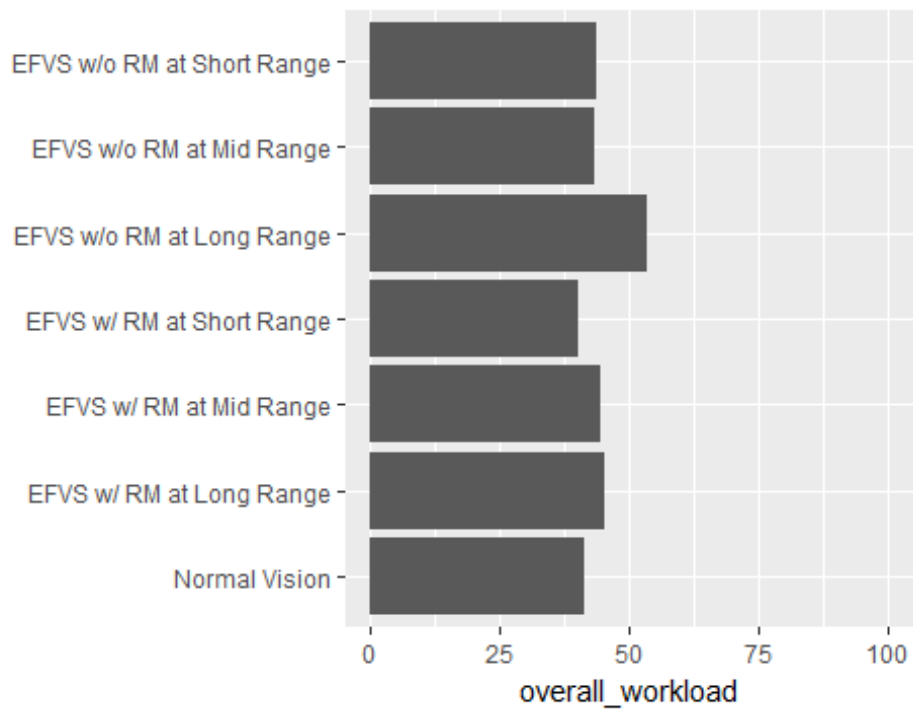
Participant 19
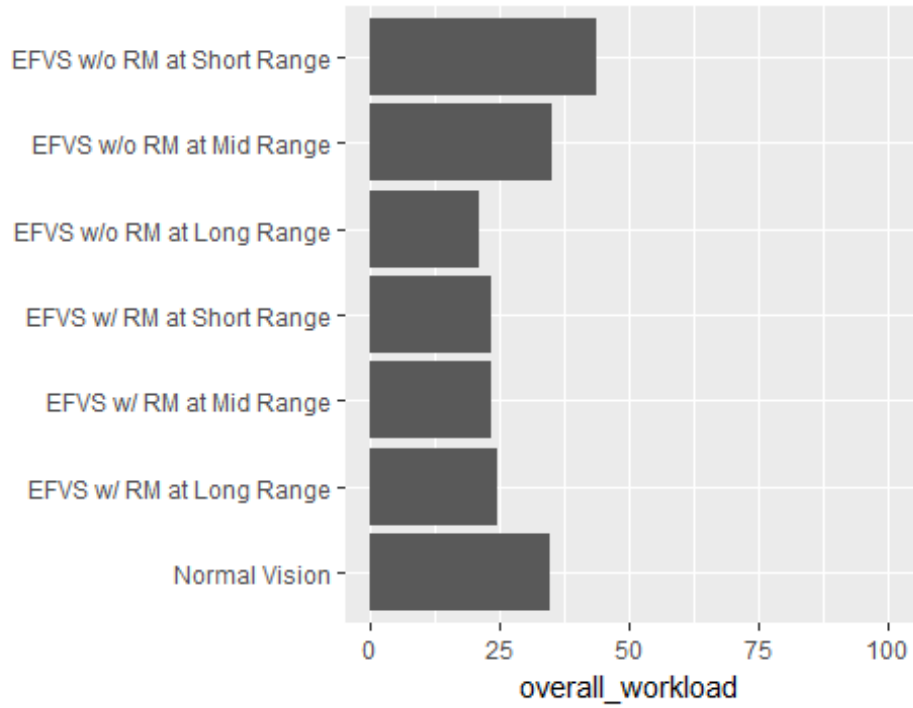
Participant 20
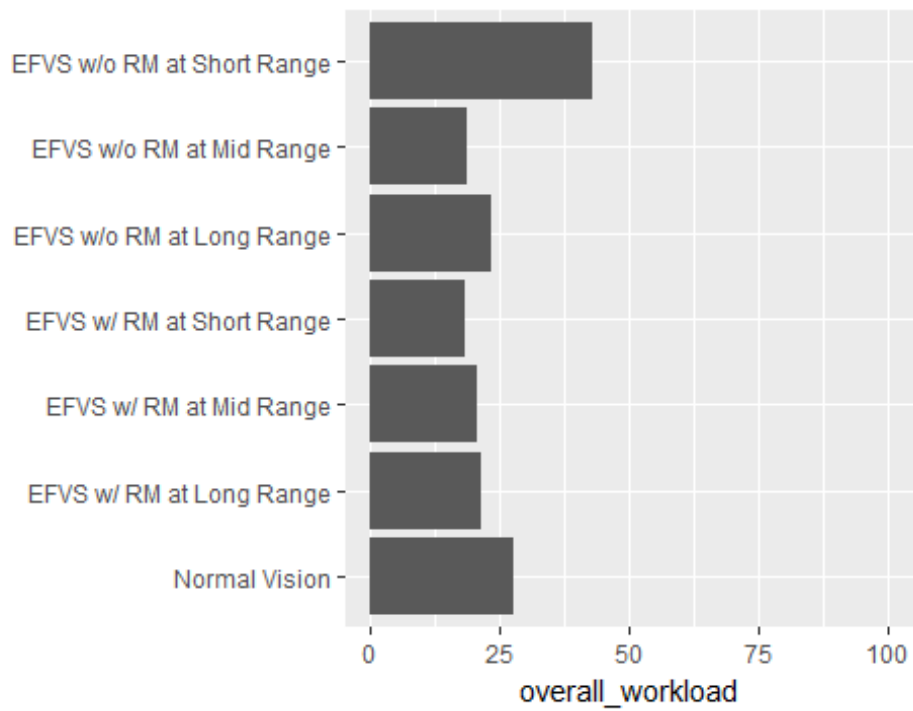
Participant 21
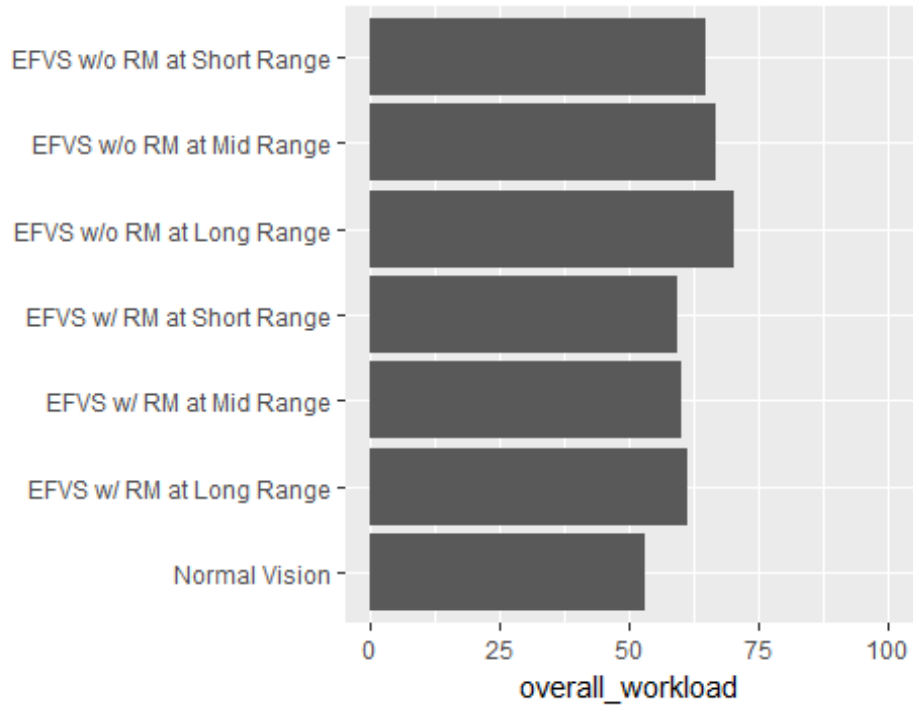
Average Overall Workload
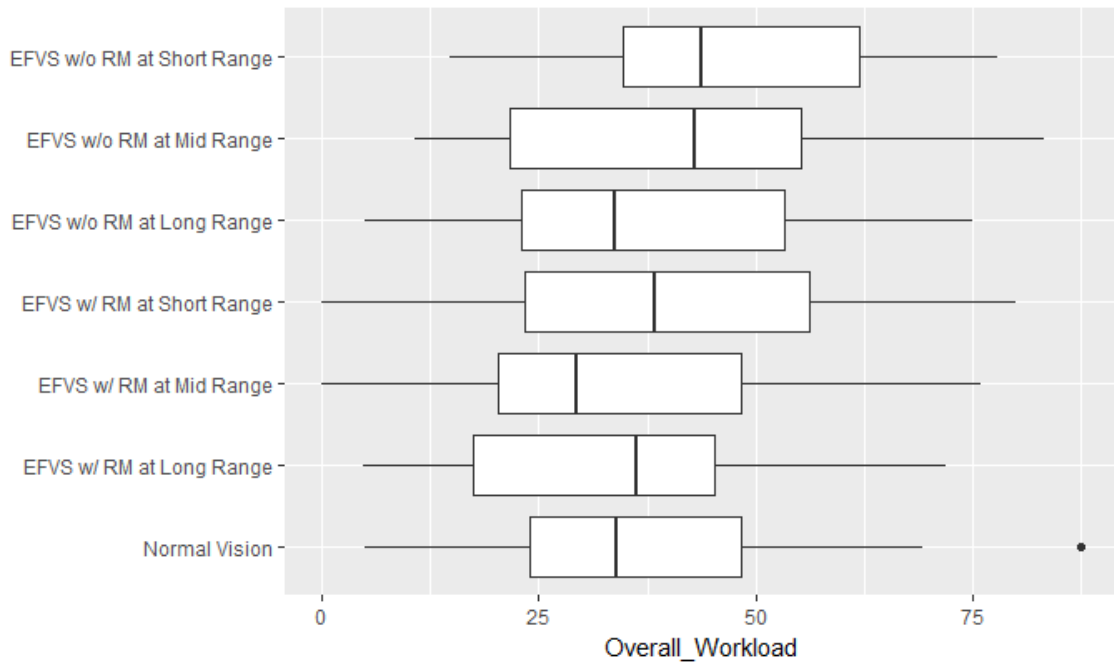
D.2 Workload Breakdowns for Each Scenario for Each Participant

D.2.1 Participant 1
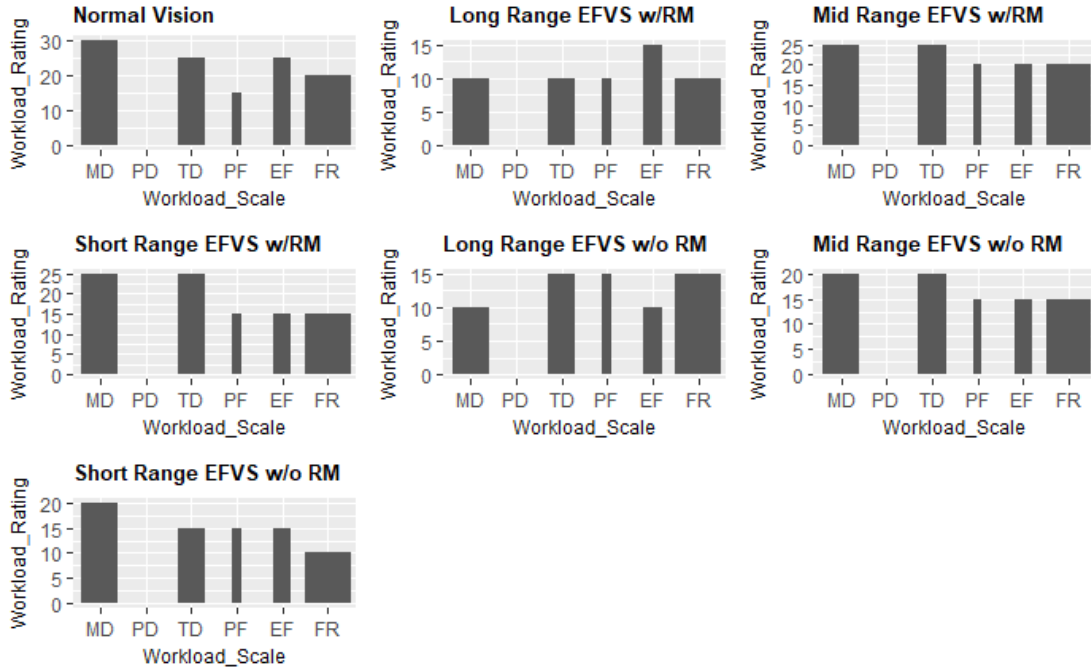
D.2.2 Participant 2
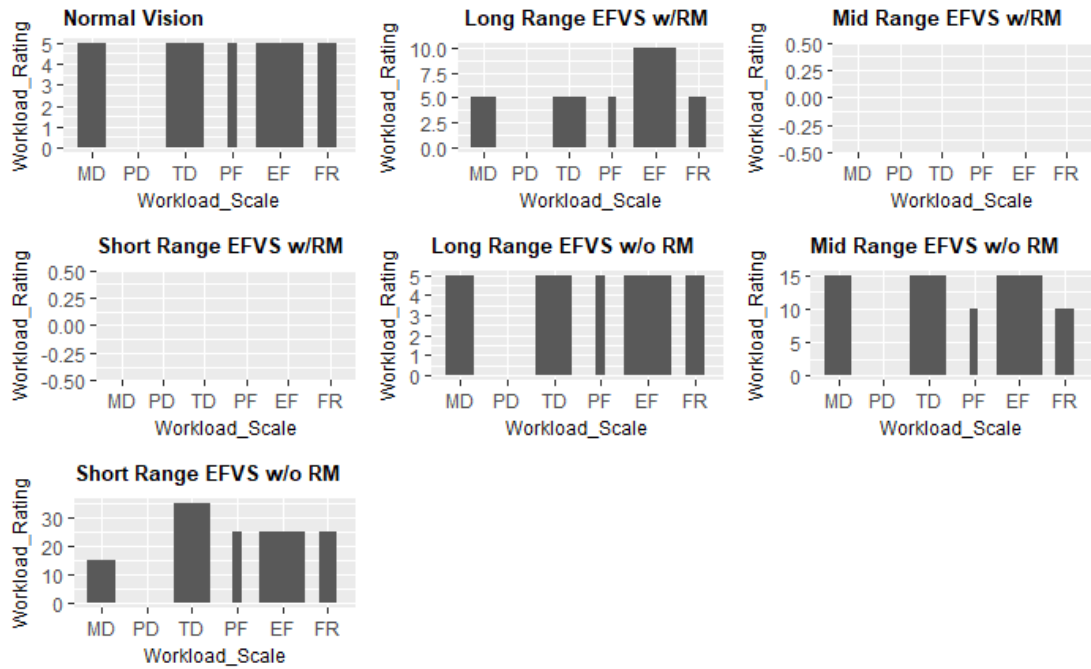
D.2.3   Participant 3
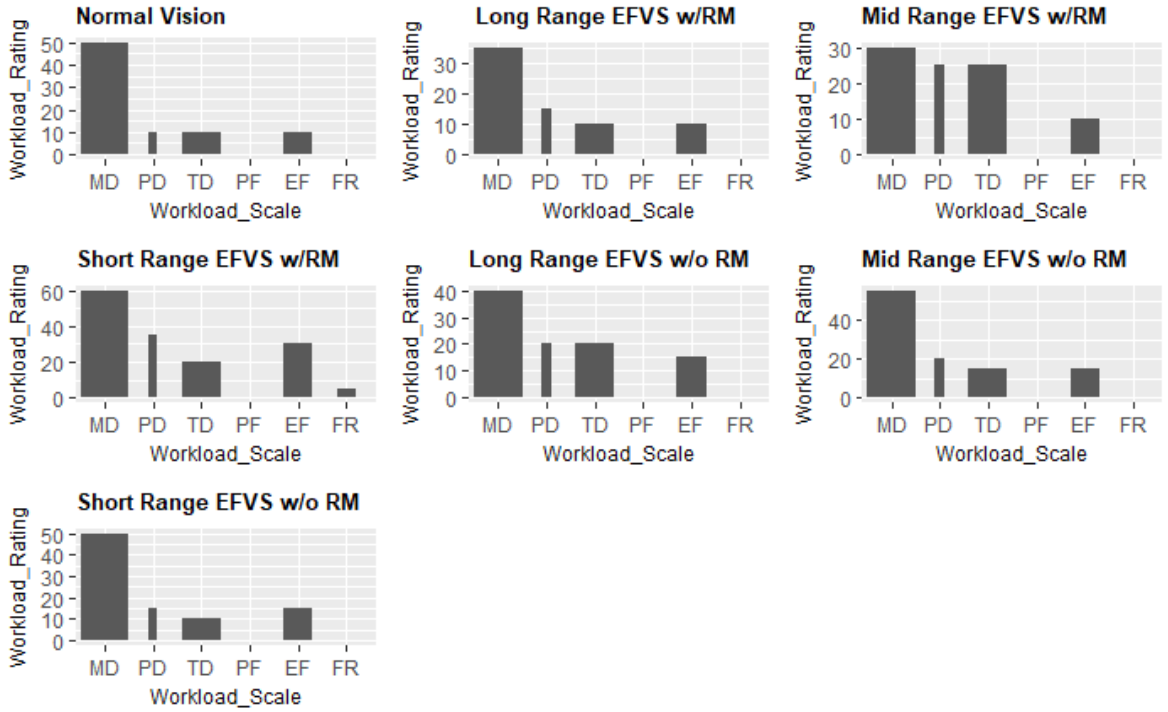
D.2.4   Participant 4
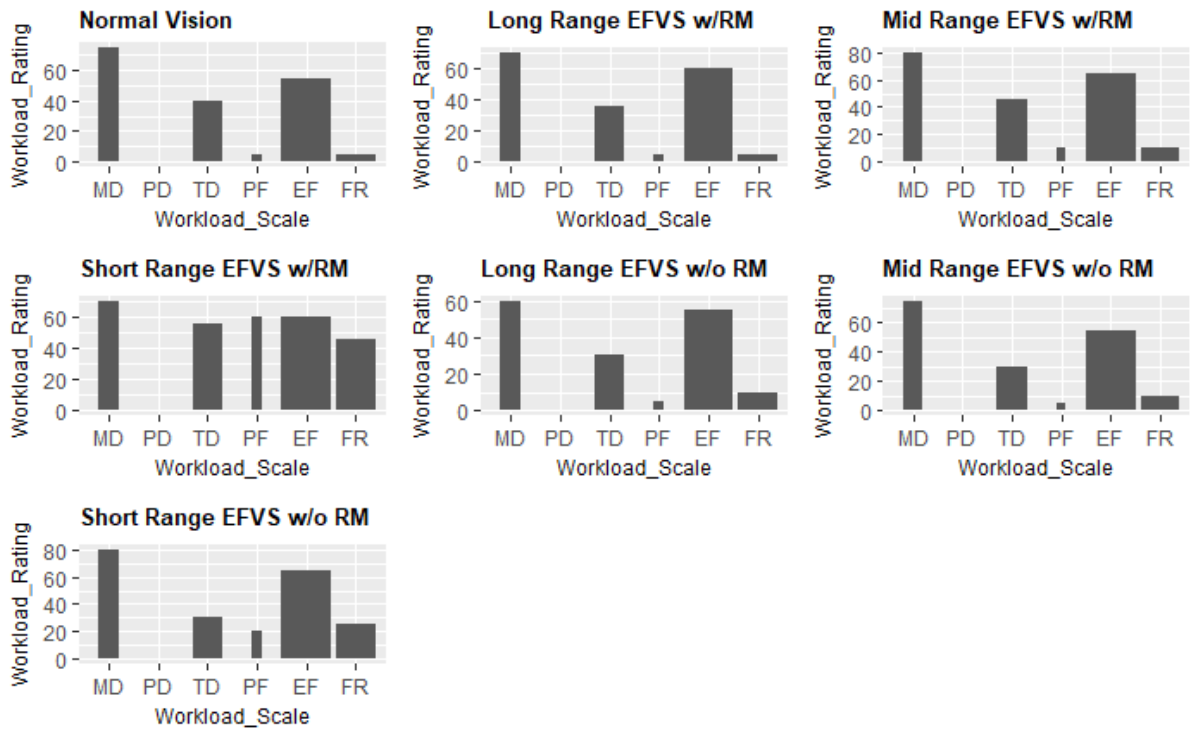
D.2.5 Participant 5
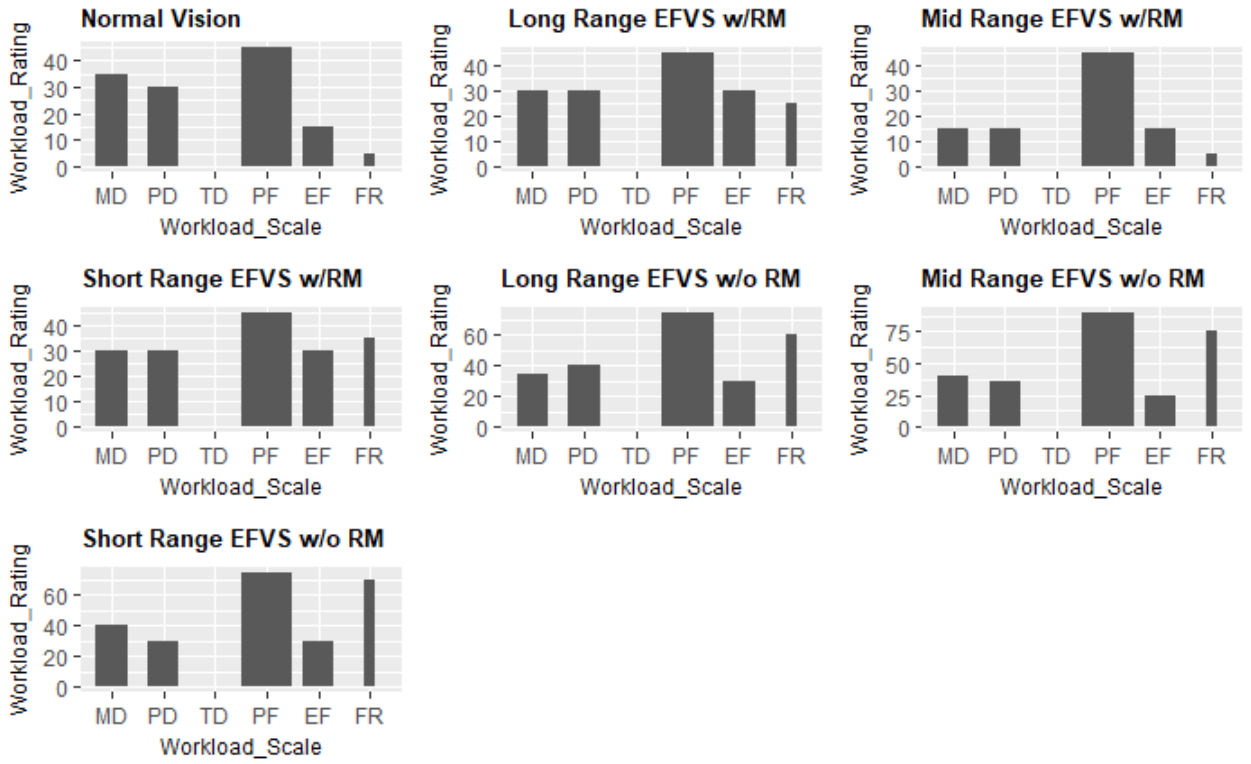
D.2.6 Participant 6
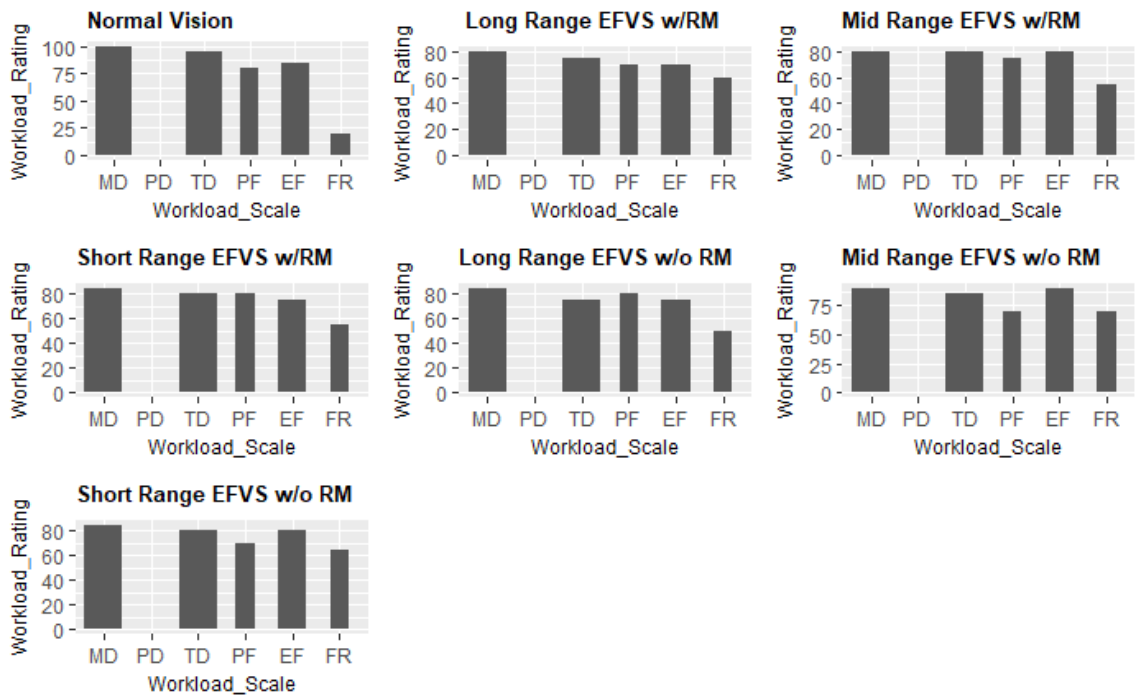
D.2.7 Participant 7
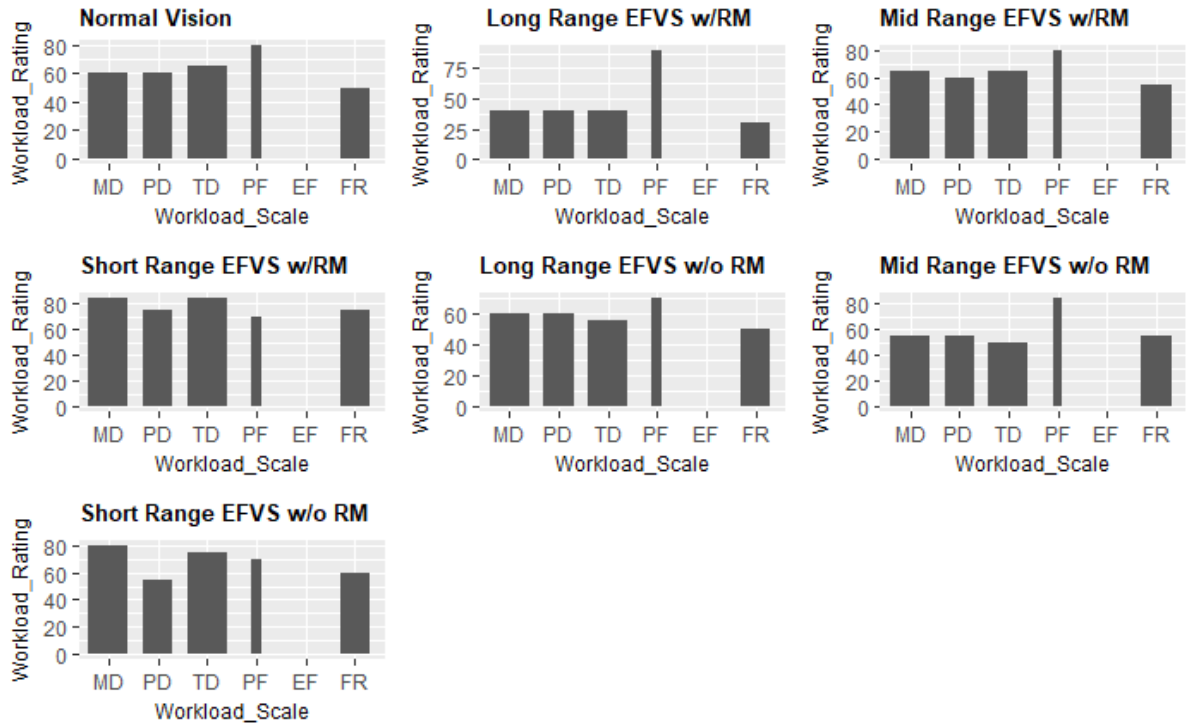
D.2.8 Participant 8

D.2.9 Participant 9

Normal Vision

Long Range EFVS w/RM

Mid Range EFVS w/RM

Short Range EFVS w/RM

Long Range EFVS w/o RM

Mid Range EFVS w/o RM

Short Range EFVS w/o RM

D.2.10 Participant 10

Normal Vision

Long Range EFVS w/RM

Mid Range EFVS w/RM

Short Range EFVS w/RM

Long Range EFVS w/o RM

Mid Range EFVS w/o RM

Short Range EFVS w/o RM
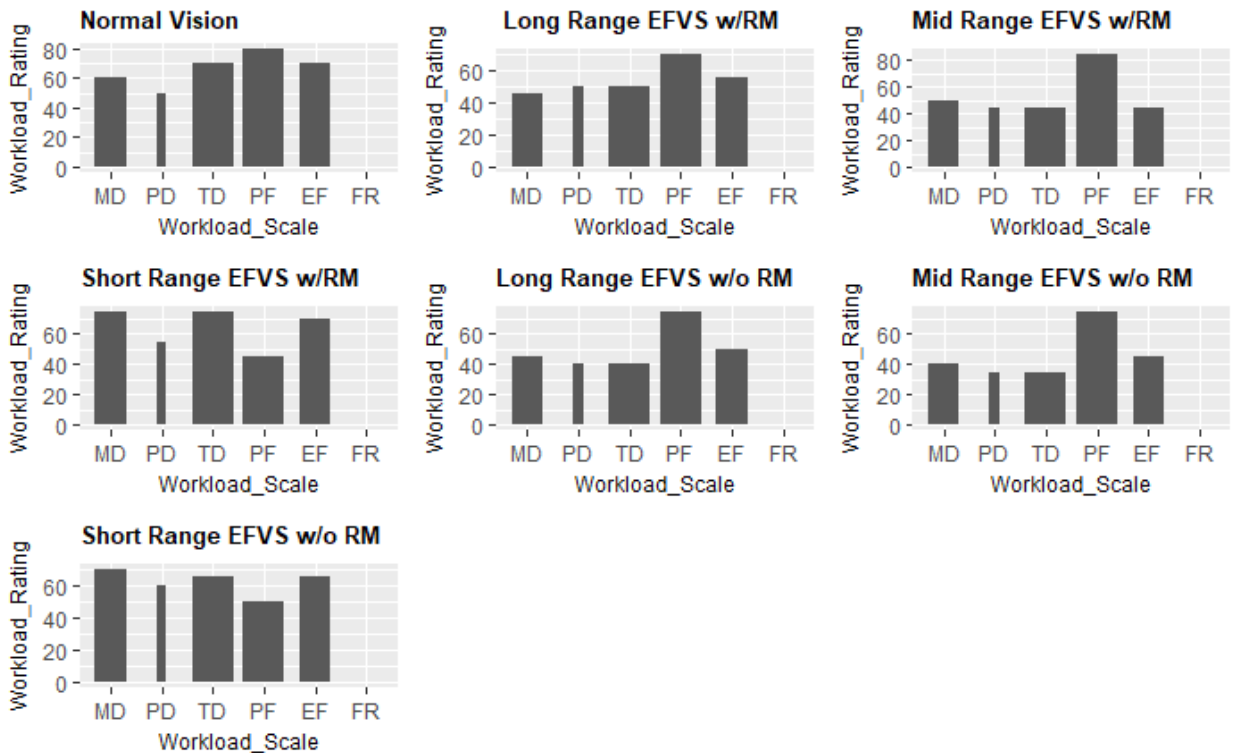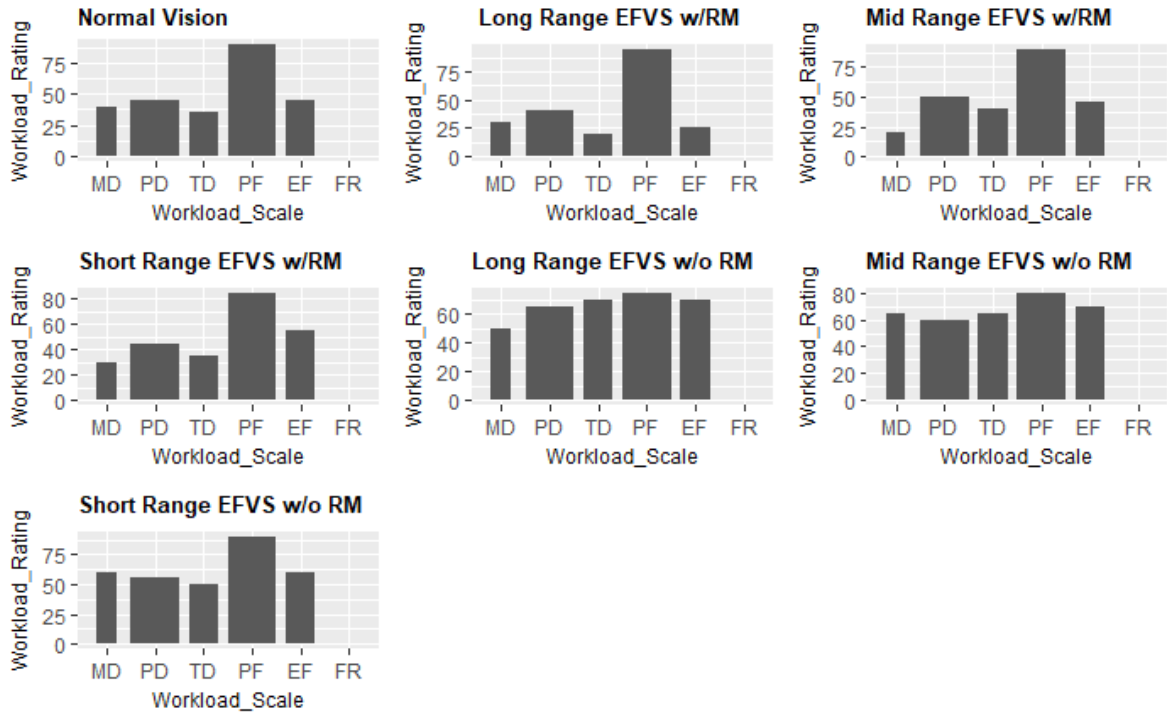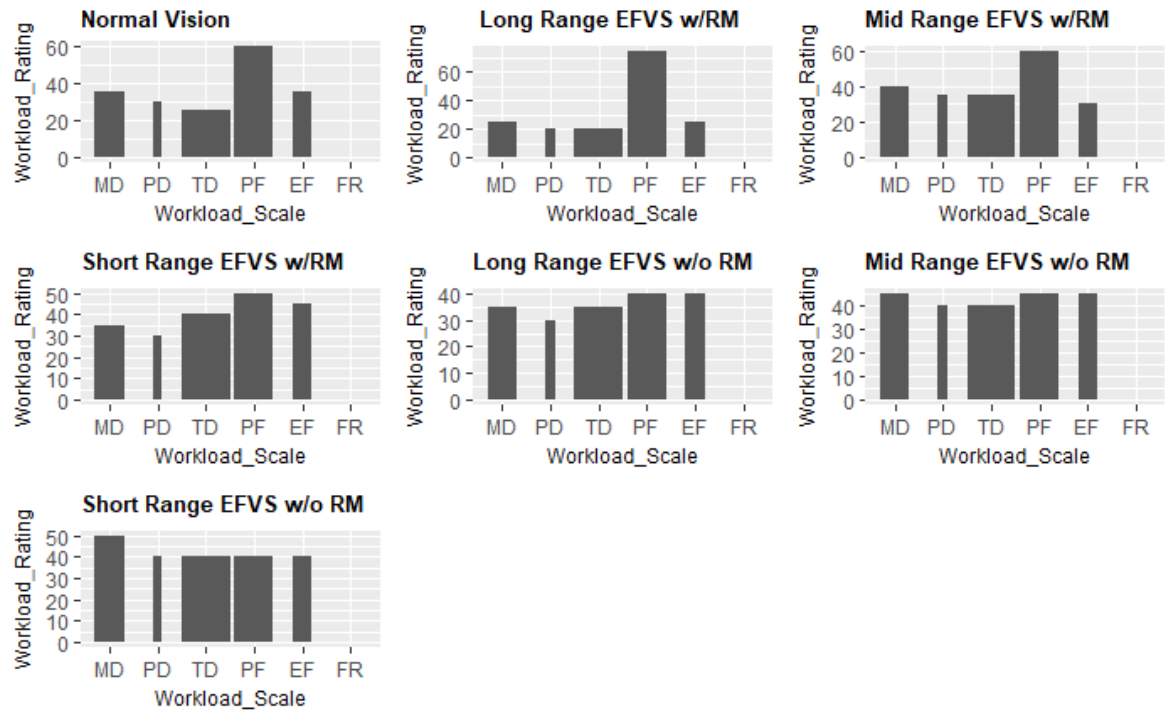
D.2.11 Participant 11
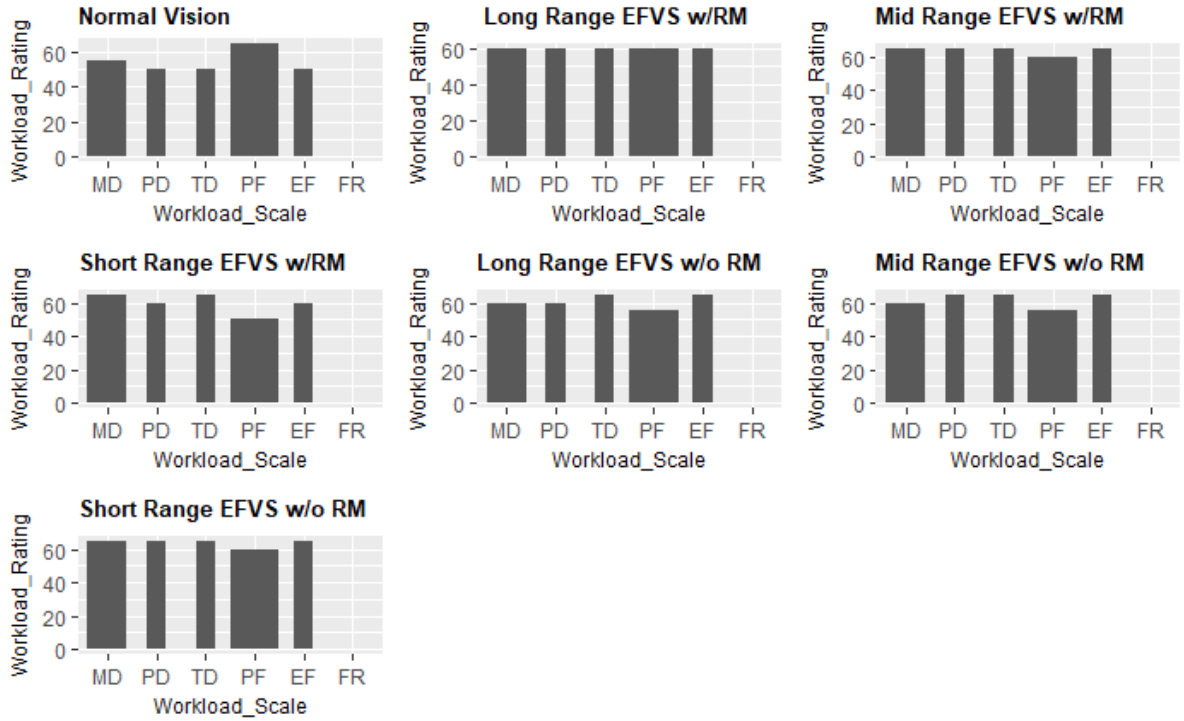
D.2.12 Participant 12
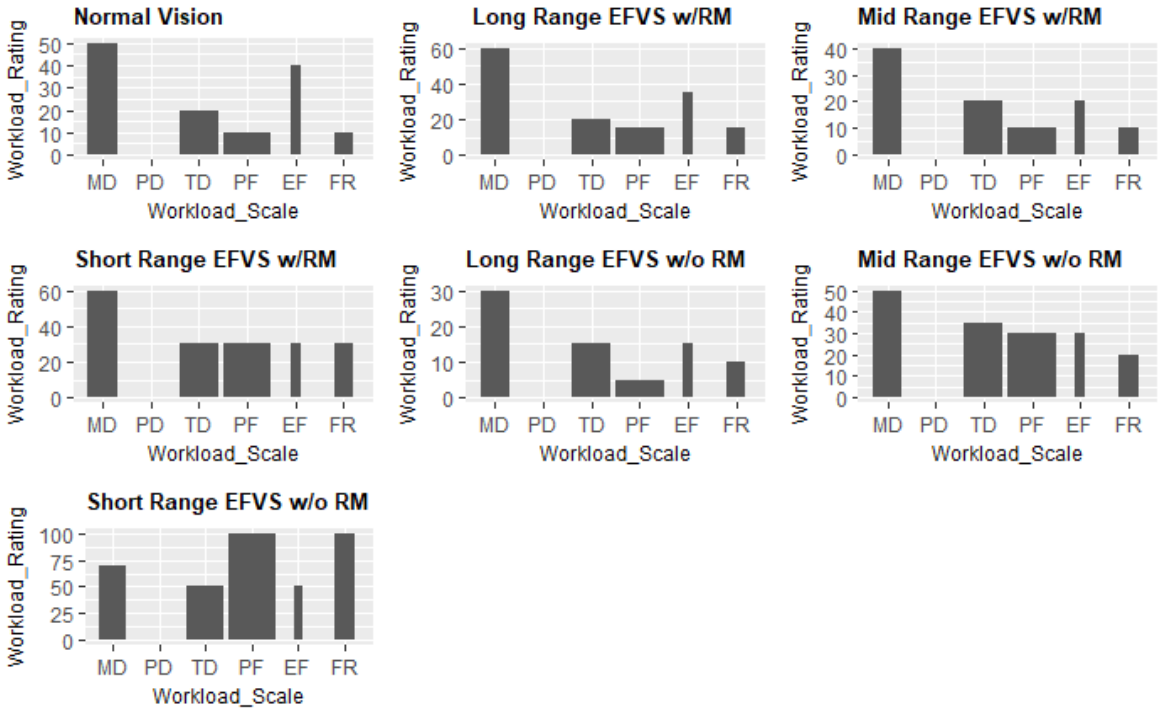
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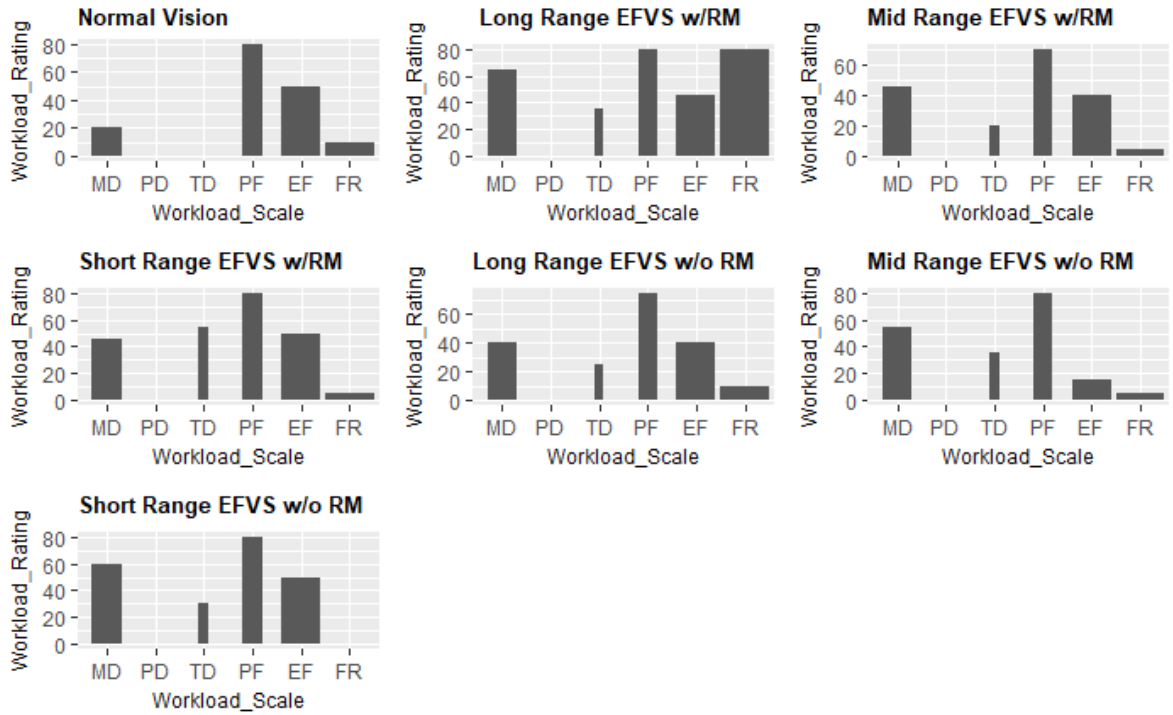
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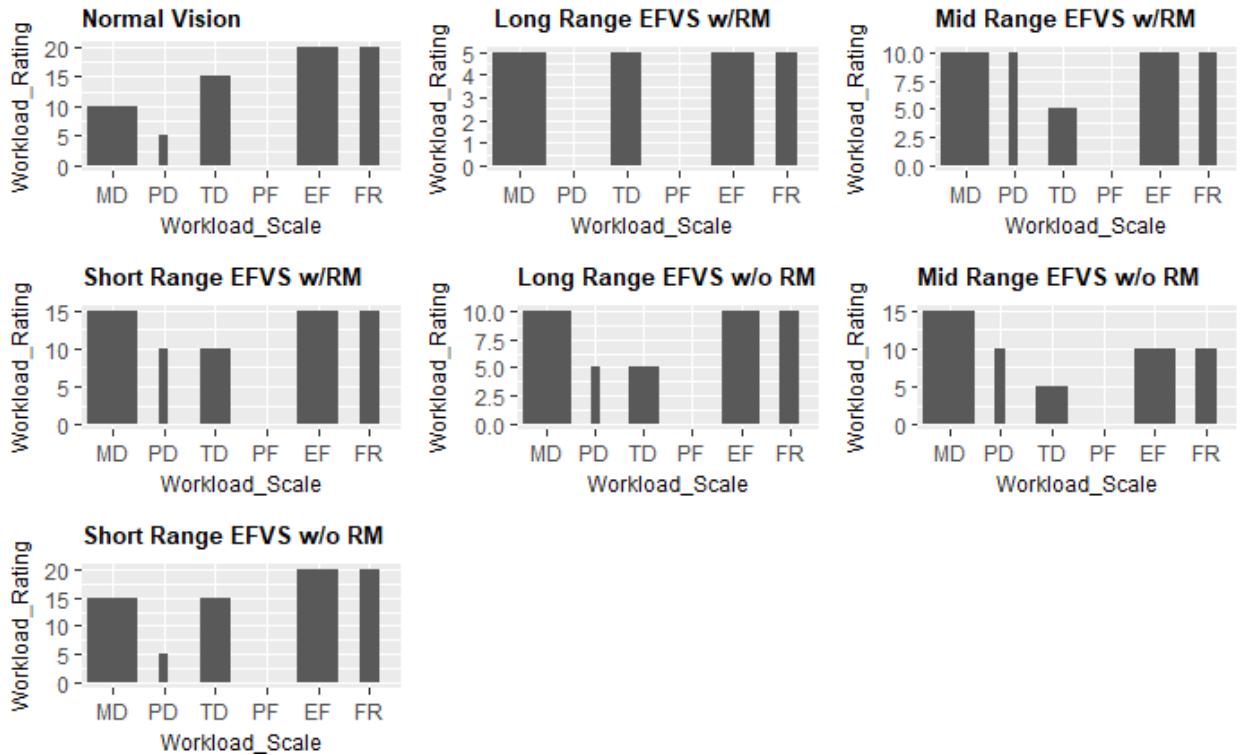
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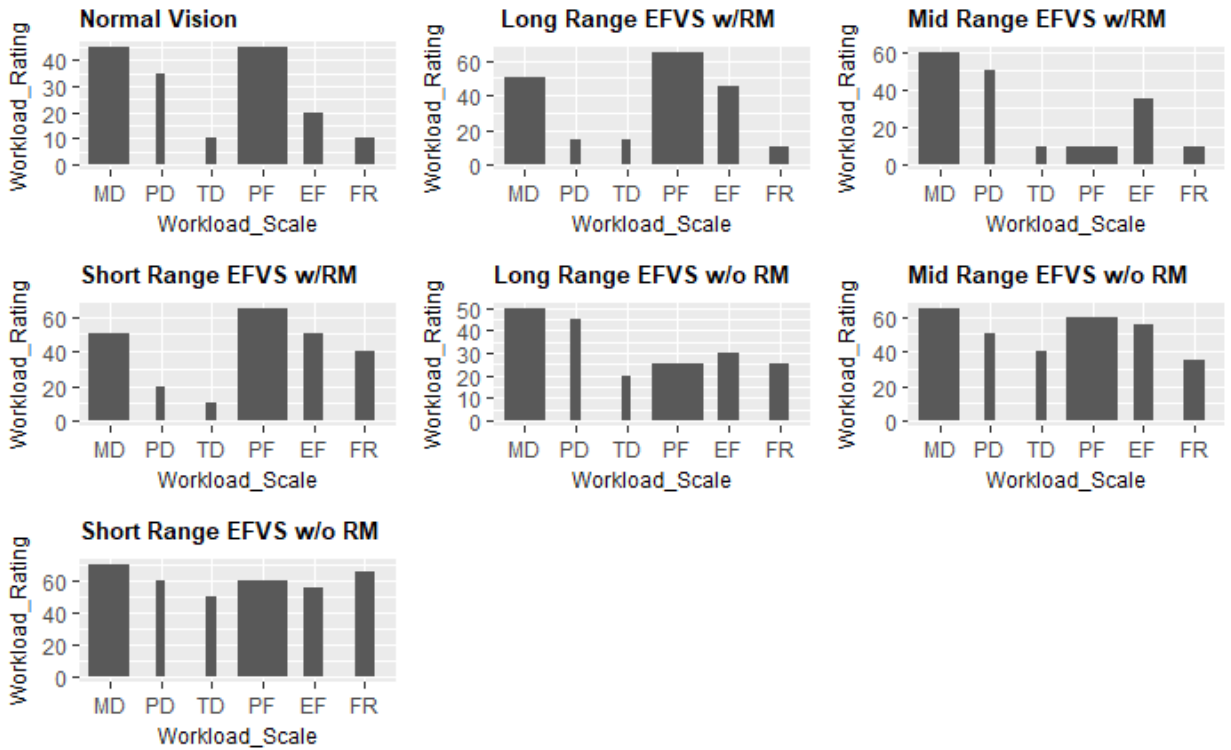
D.2.16 Participant 16
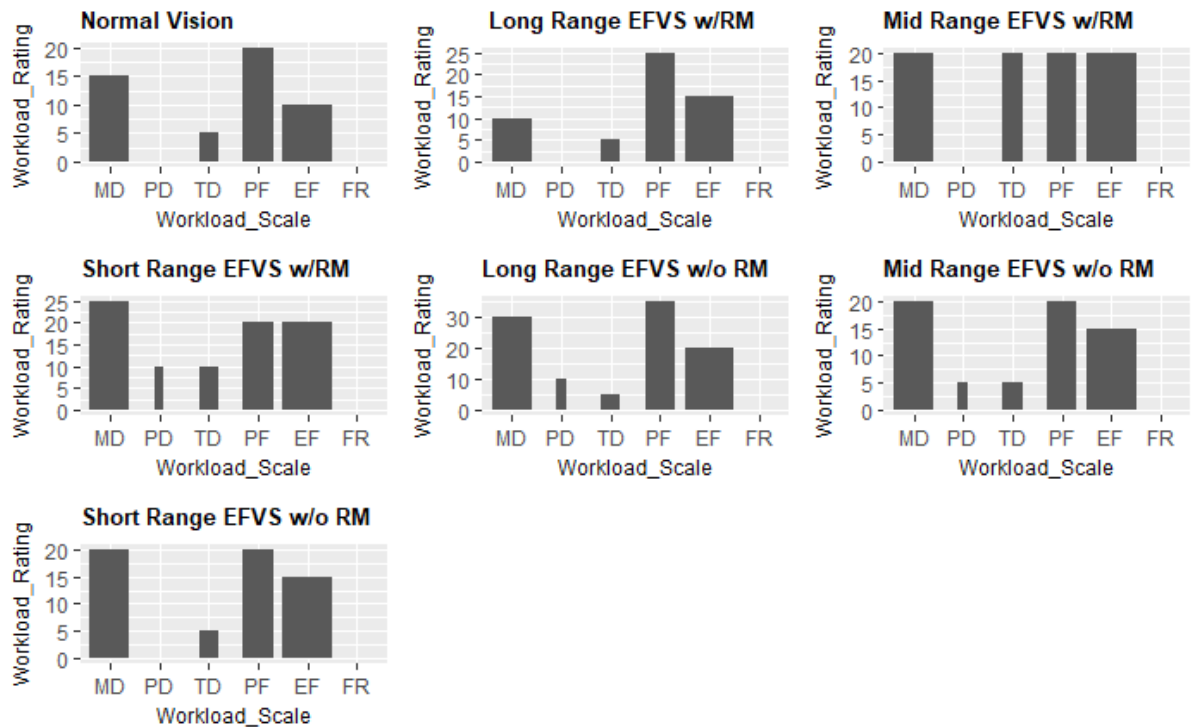
D.2.17 Participant 17
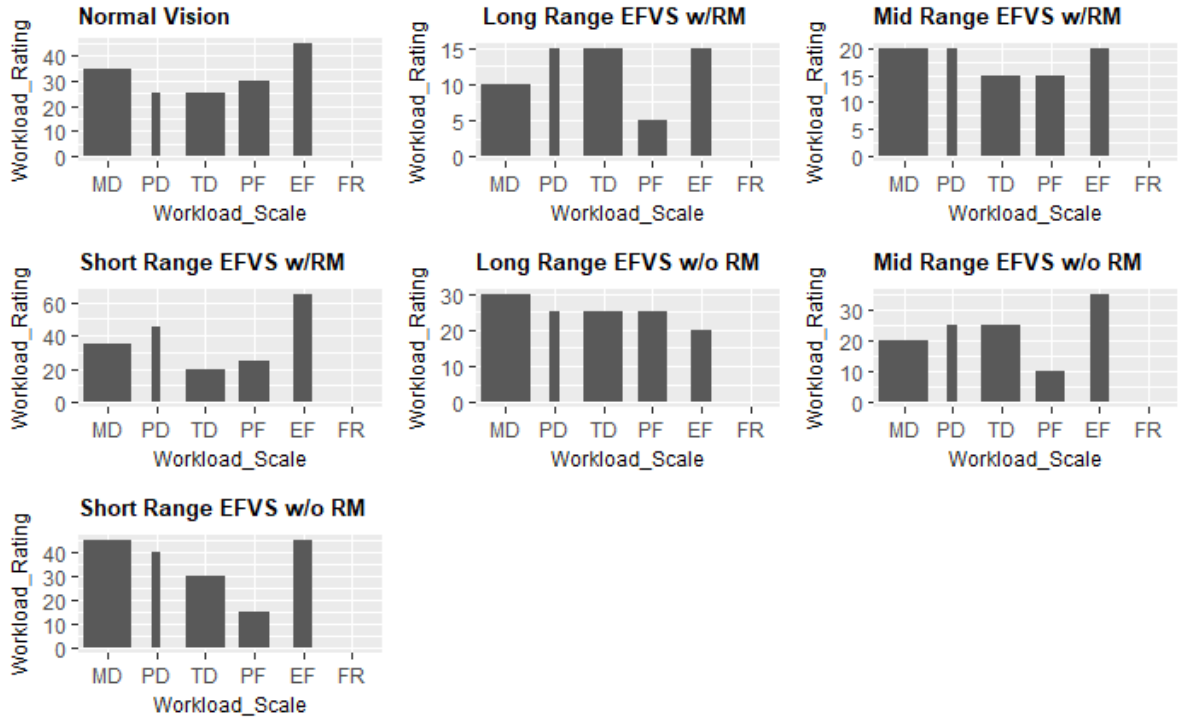
D.2.18 Participant 18
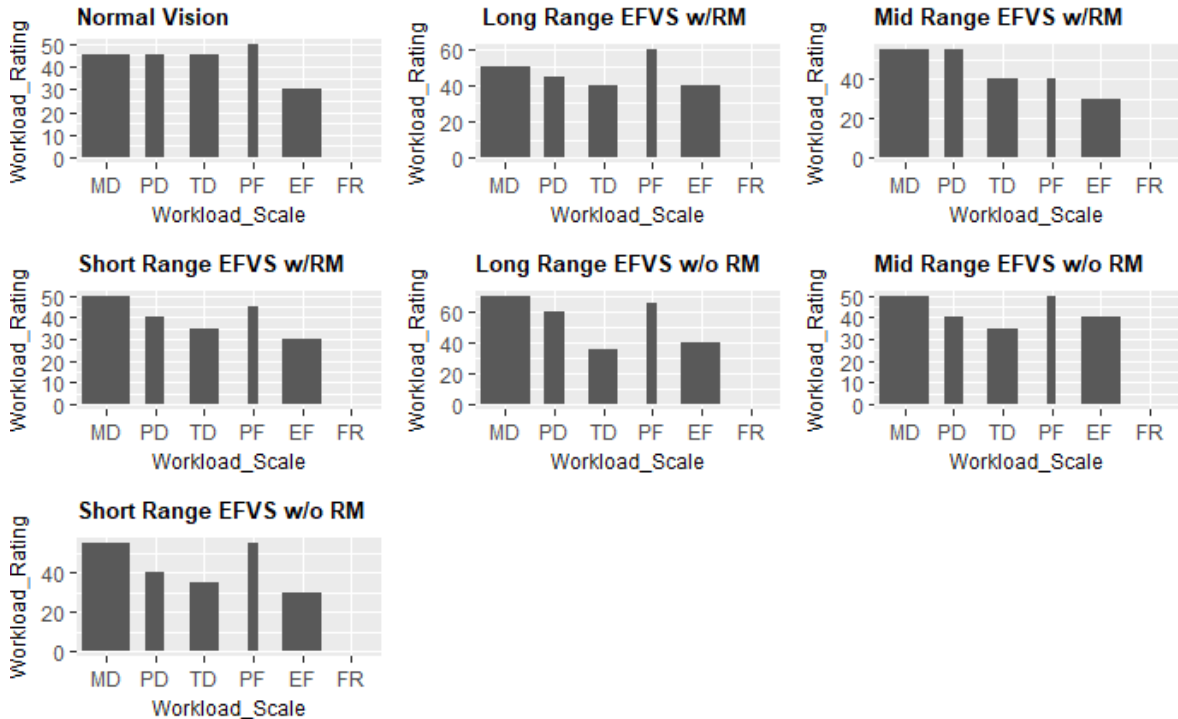
D.2.19 Participant 19
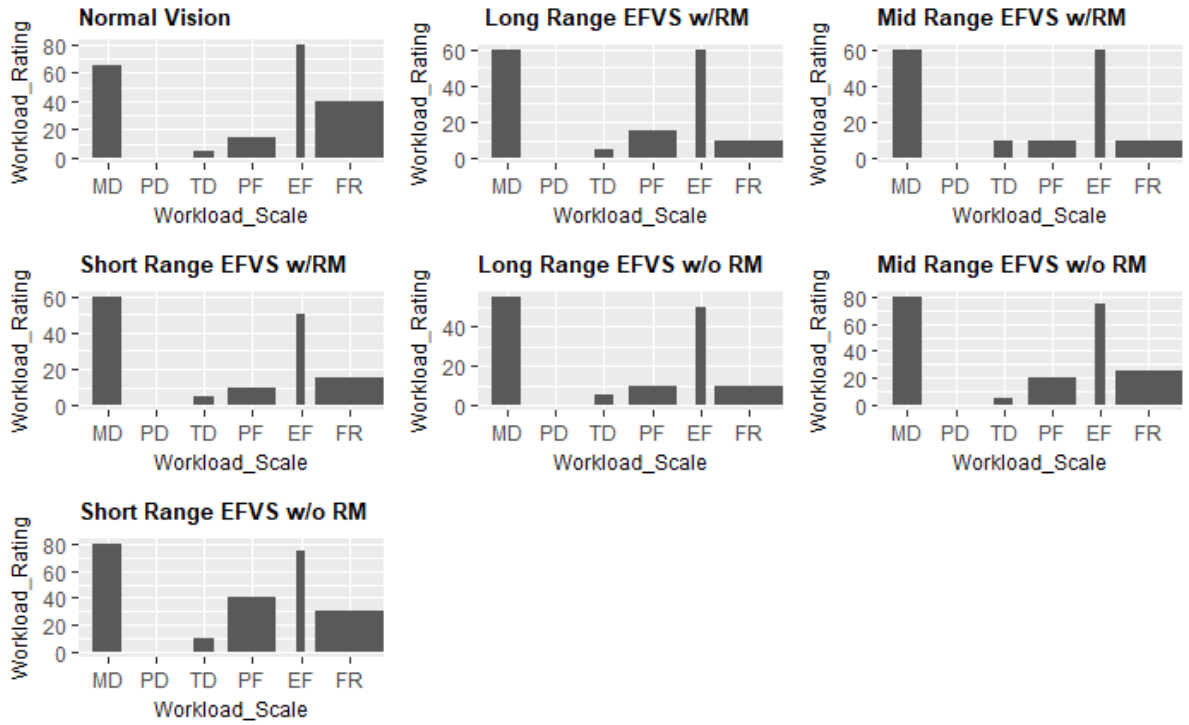
D.2.20 Participant 20
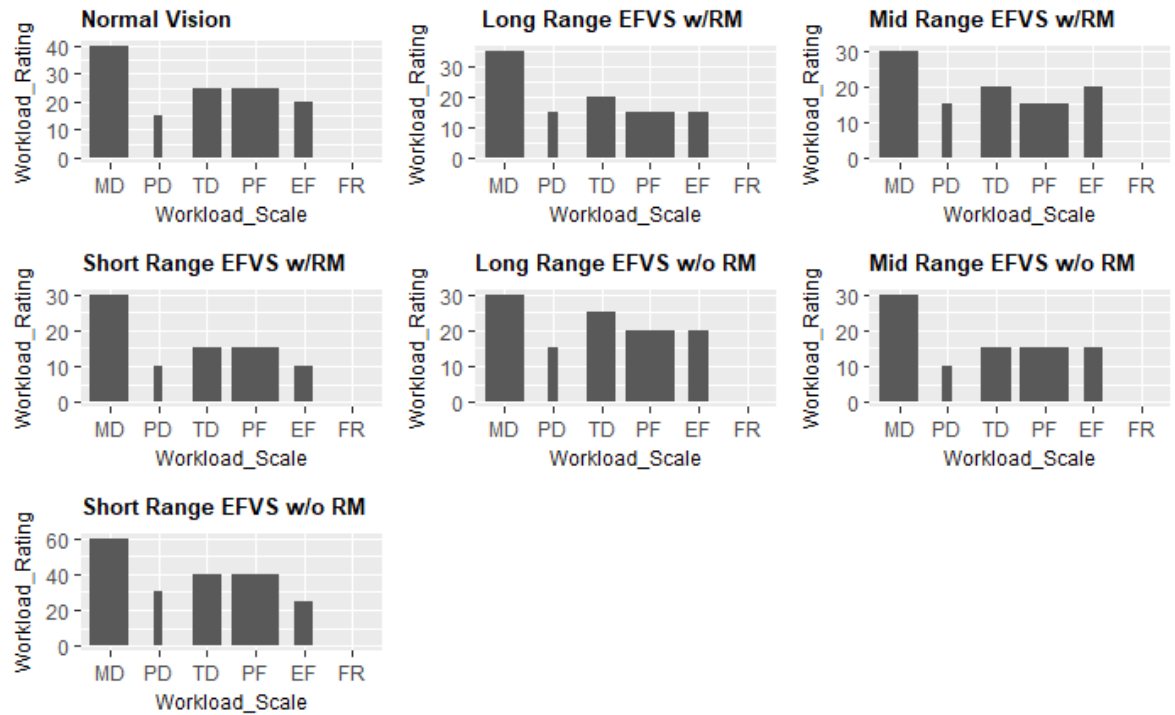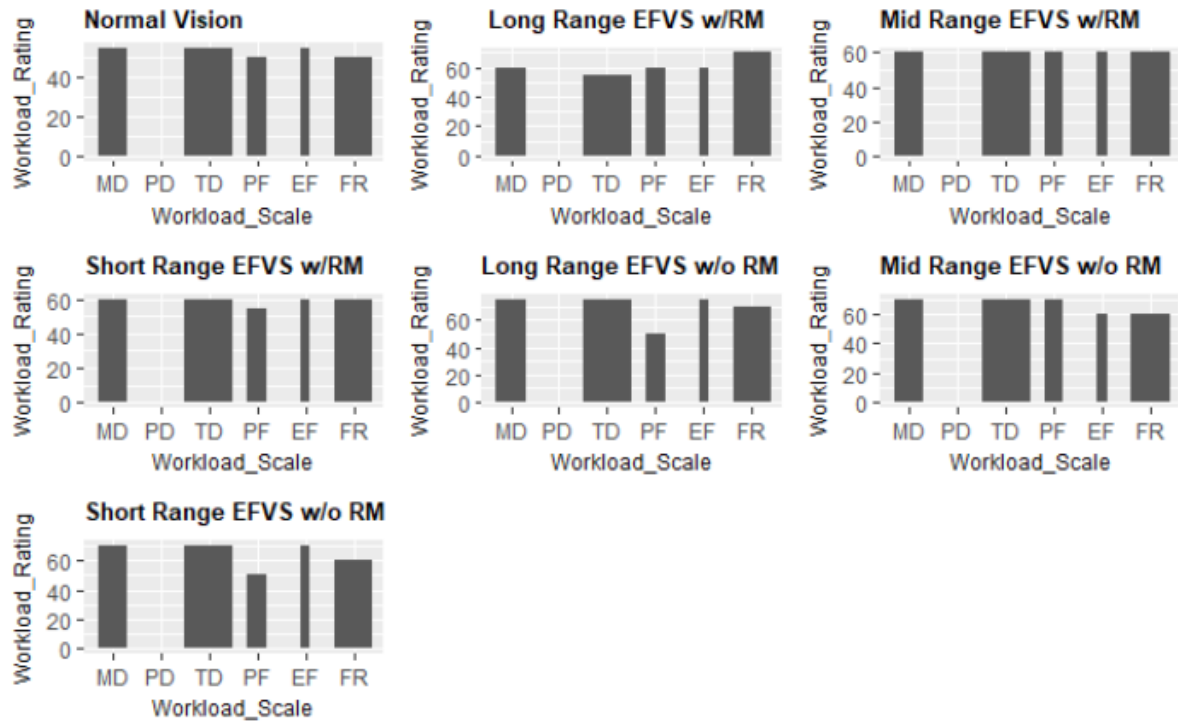
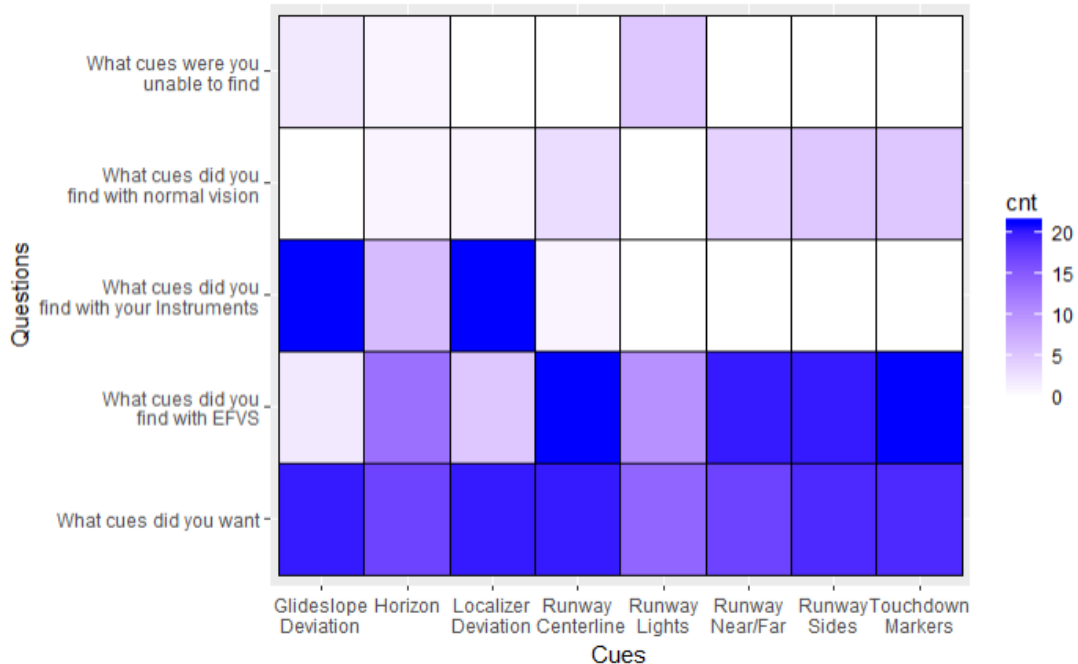## D.3   Average Workload per Scale for Each Scenario
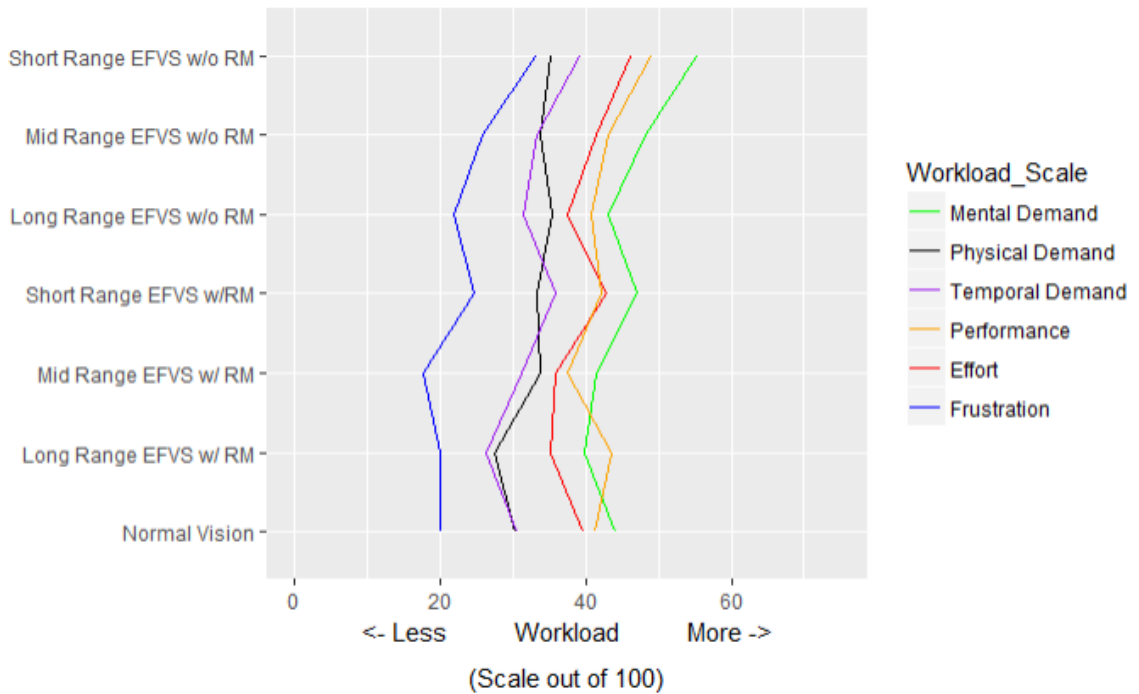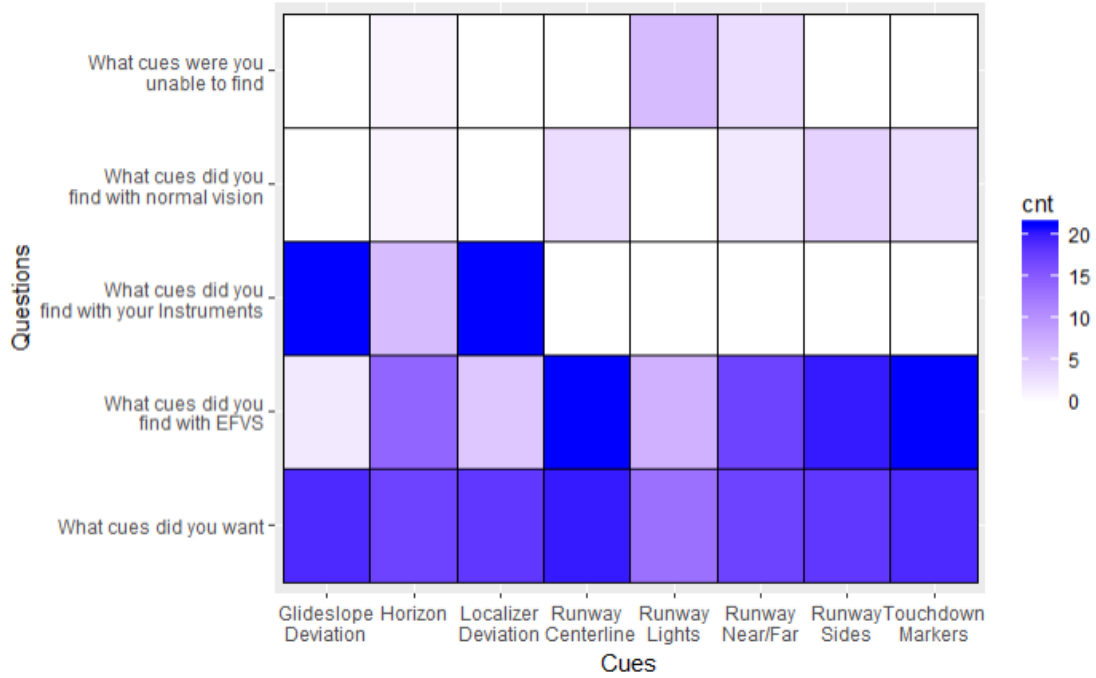
D.4 Visual Cue Question Matrix

D.4.1 Normal Vision
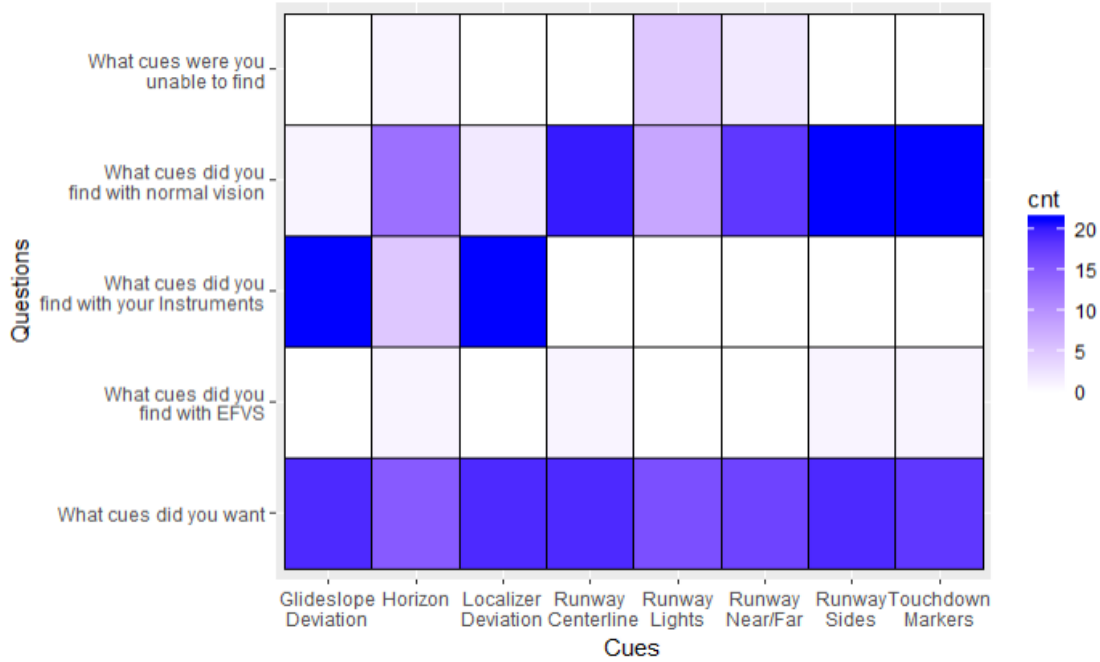
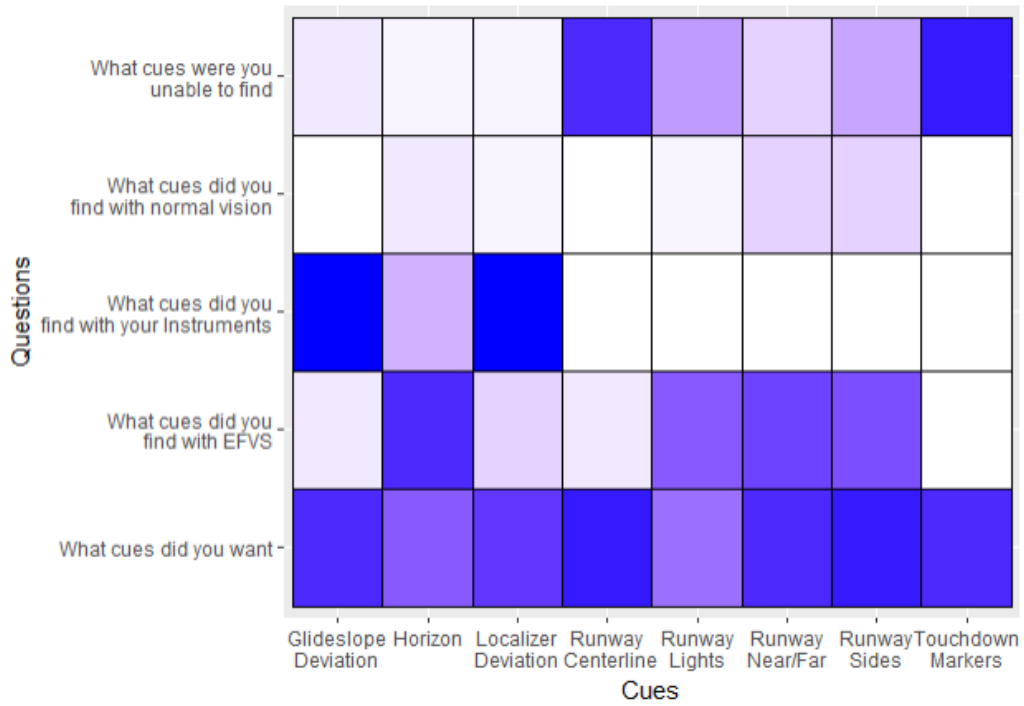### D.4.2 Long-Range EFVS Portraying Runway Markings

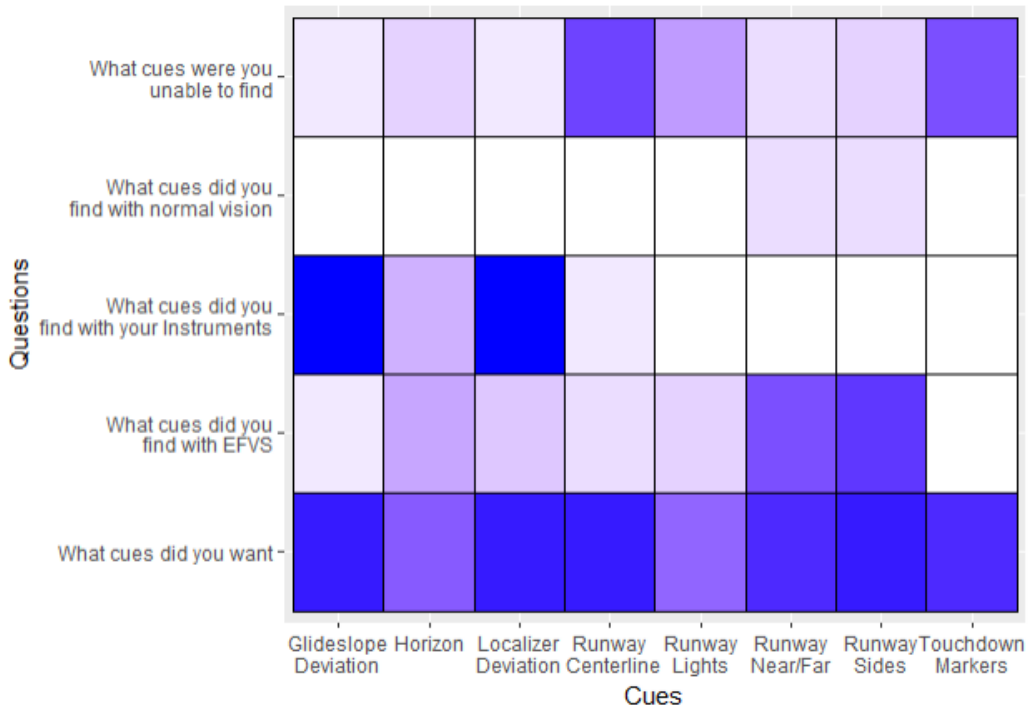## D.4.3   Mid-Range EFVS Portraying Runway Markings

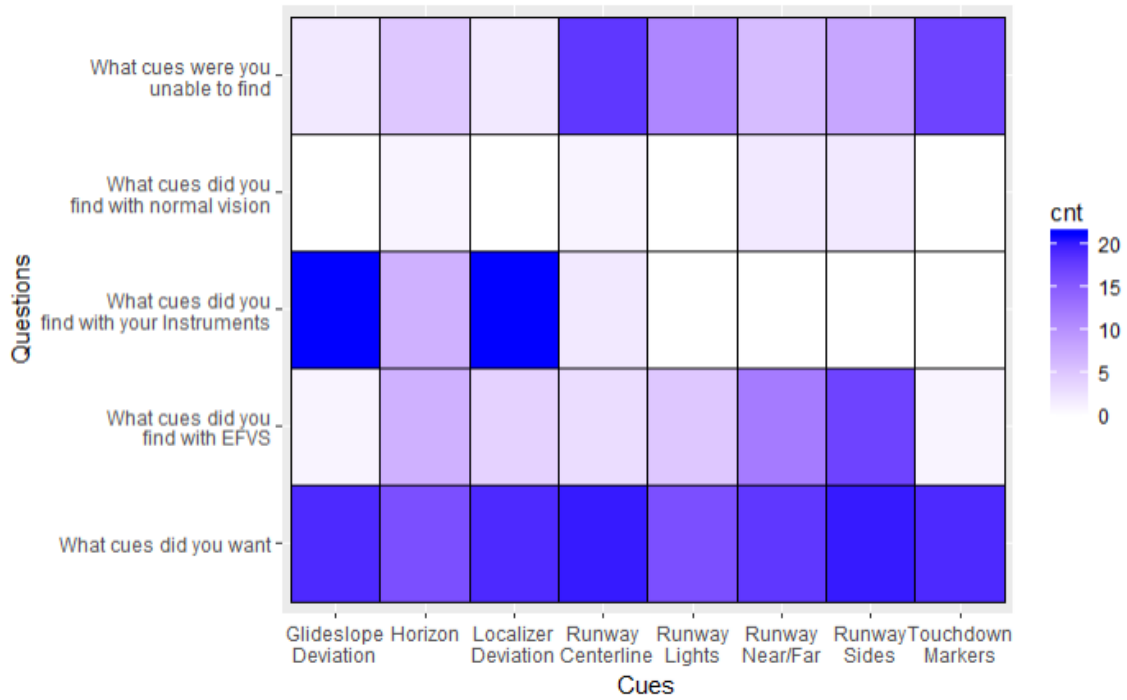## D.4.4   Short-Range EFVS Portraying Runway Markings
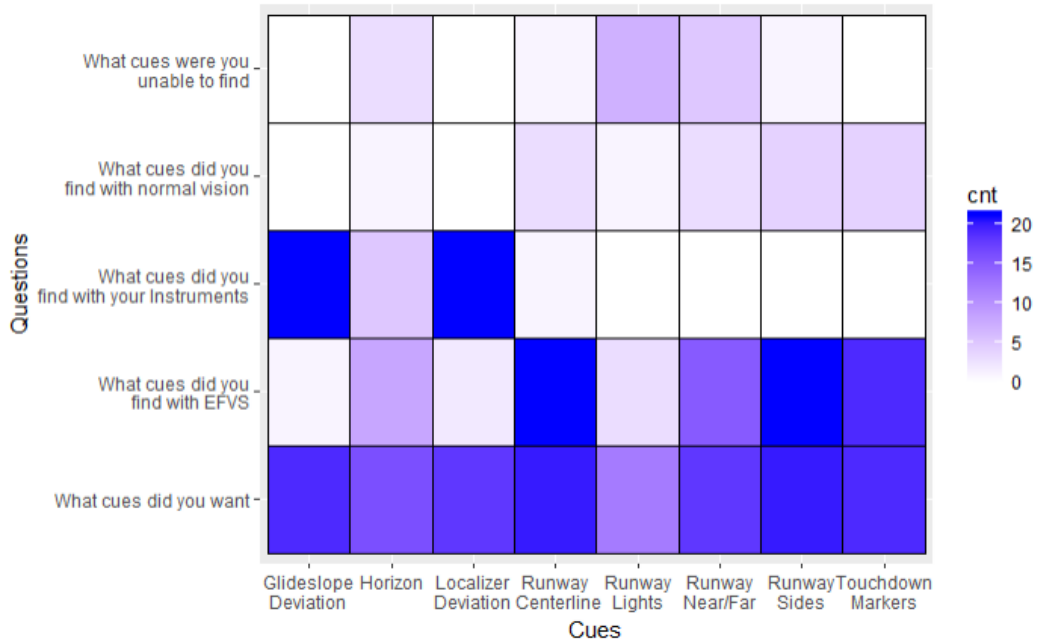
D.4.5 Long-Range EFVS Not Portraying Runway Markings

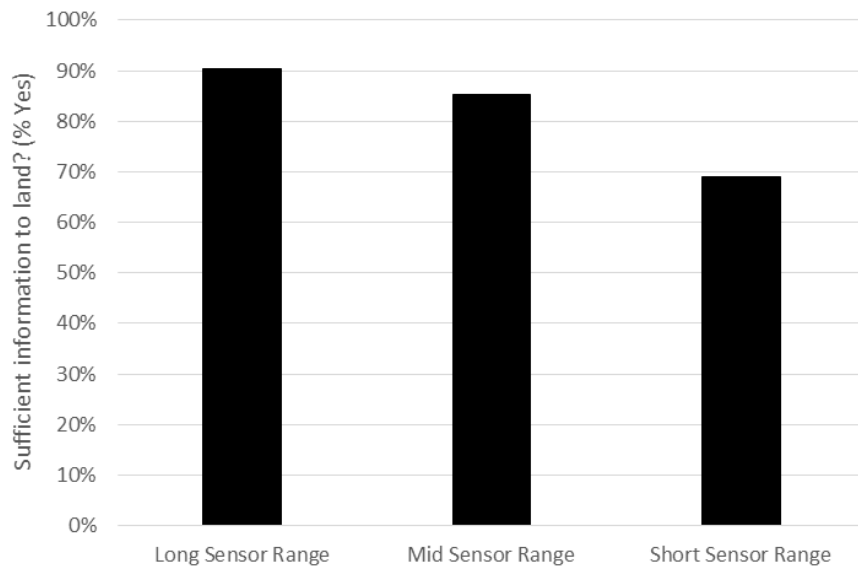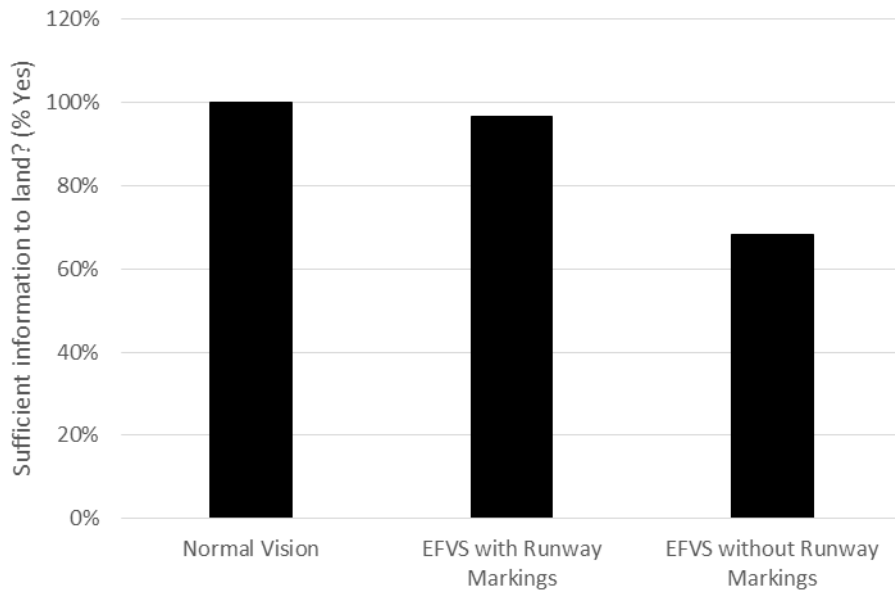## D.4.6 Mid-Range EFVS Not Portraying Runway Markings
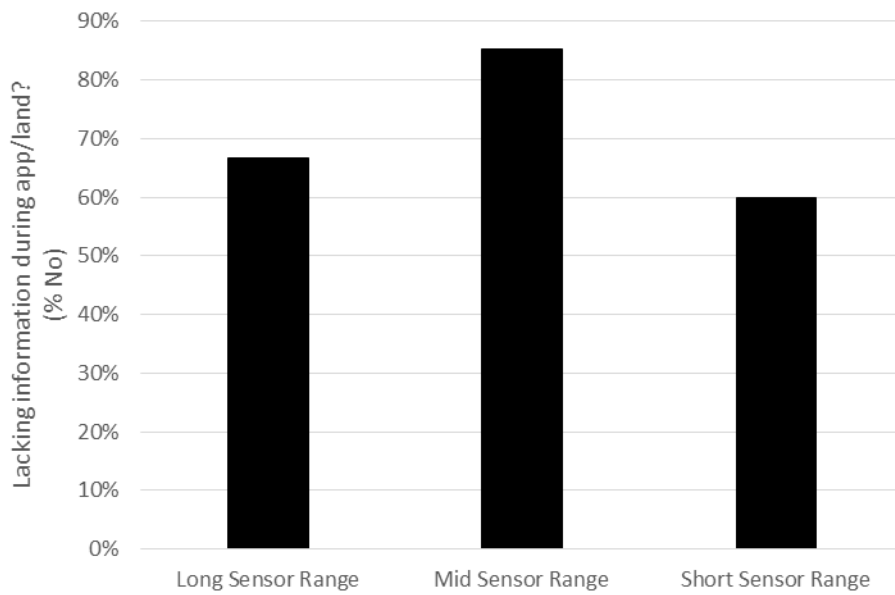
D.4.7 Short-Range EFVS Not Portraying Runway Markings
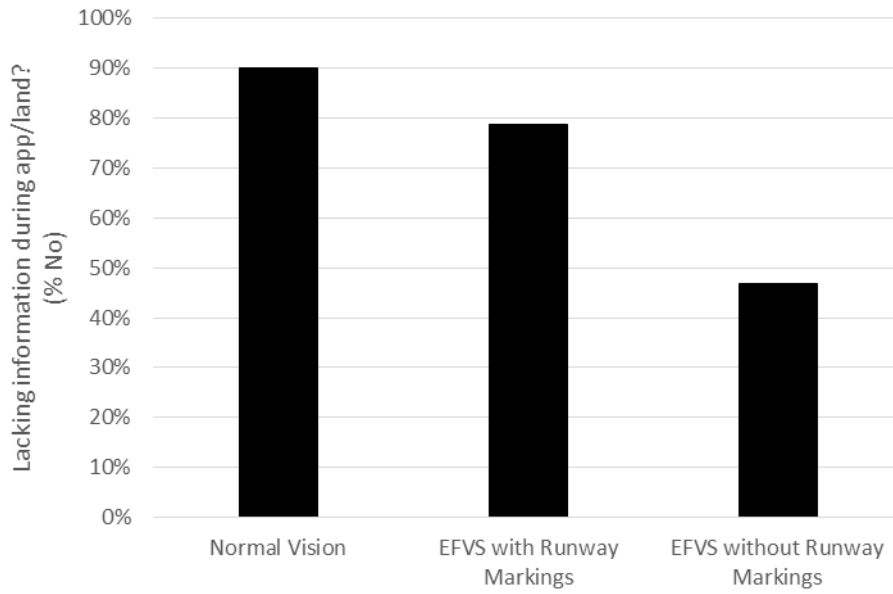

D.5 Scenario Questions

D.5.1 Did you have sufficient information to land?
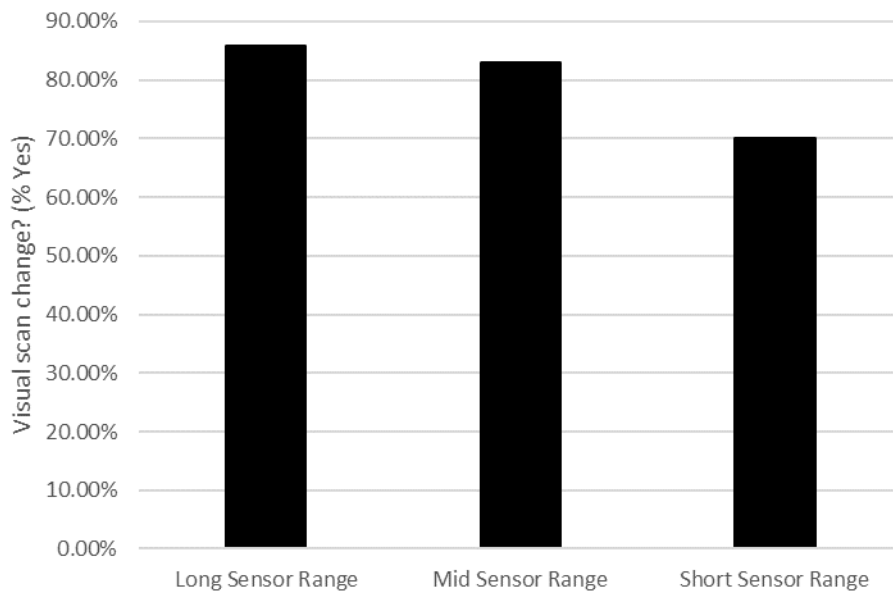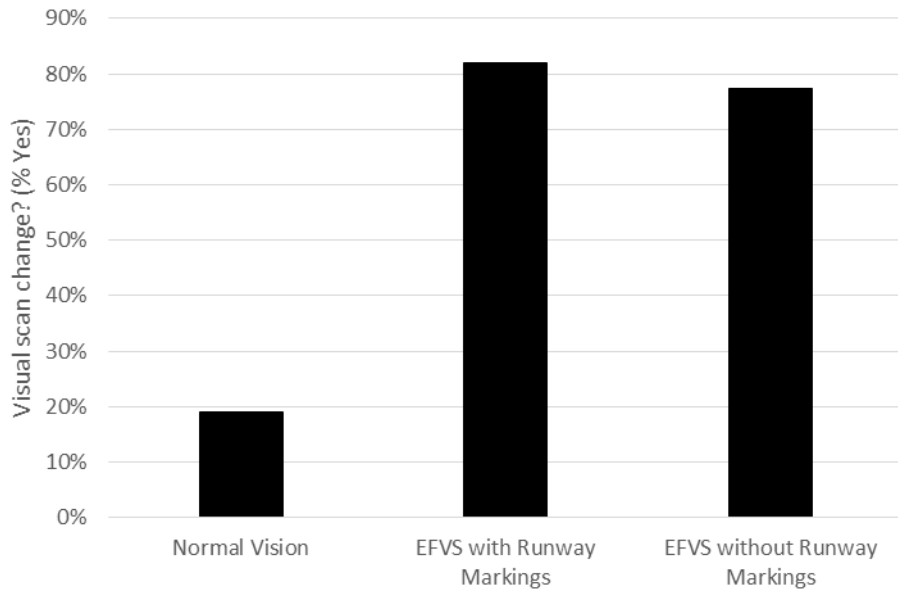
D.5.2   Were you lacking information during approach/landing?

D.5.3   Did your visual scan change?

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