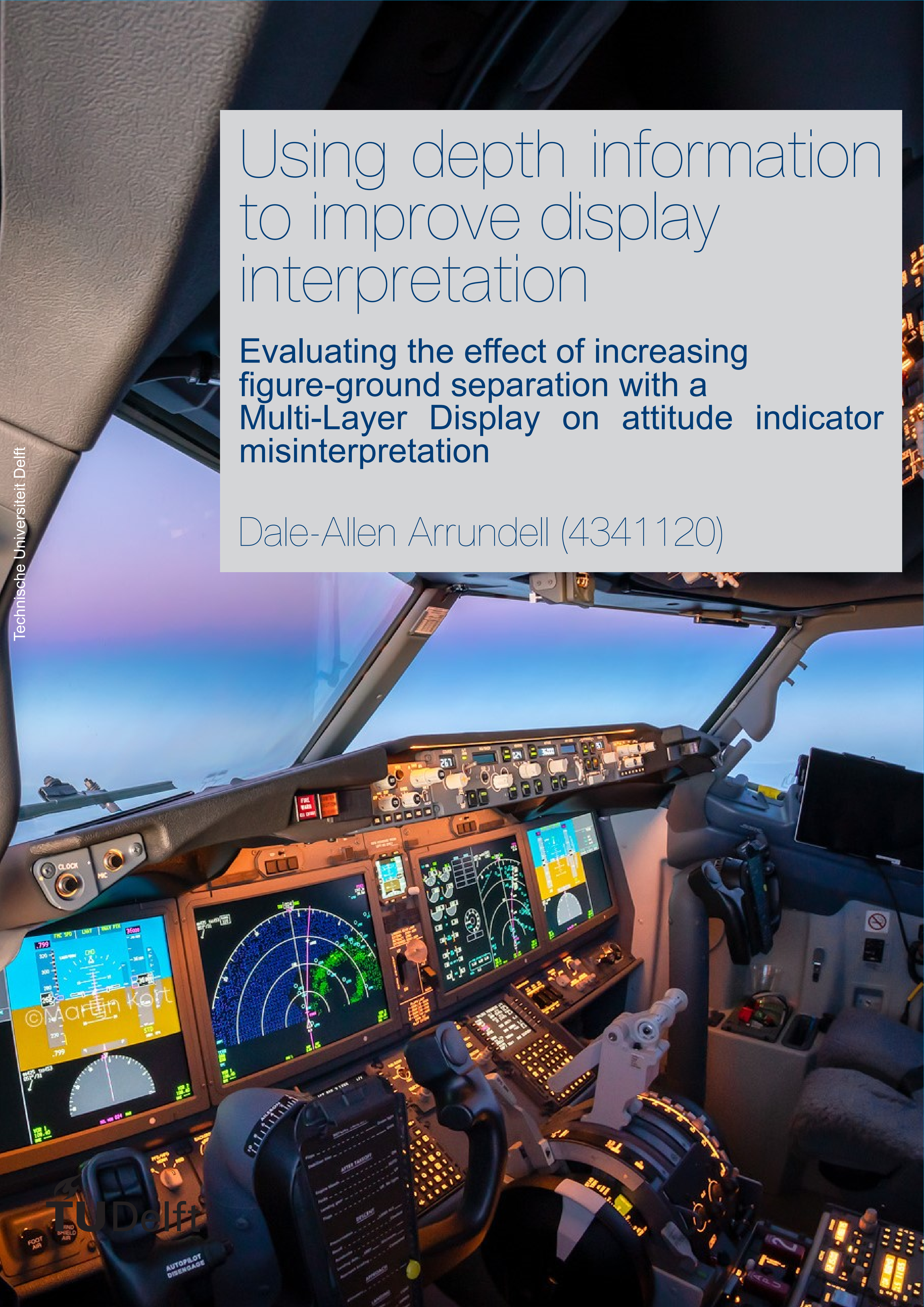
Using depth information to improve display interpretation

Evaluating the effect of increasing figure-ground separation with a Multi-Layer Display on attitude indicator misinterpretation

Dale-Allen Arrundell (4341120)



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by

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to obtain the degree of Master of Science
at the Delft University of Technology,

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This thesis is confidential and cannot be made public until the 1^{st} *of April 2021.*

TU Delft

Preface

This thesis was written to fulfil the final requirement for obtaining a Master of Science degree in Aerospace engineering, and is the last step on my journey as an engineering student.

This journey has been a challenging one where i have gained a lot of invaluable knowledge and experience in the field which i love most, aviation and aerospace.

I would like to thank all of my supervisors for their support and guidance throughout the entire thesis period. Max, thanks for being such an infinite source of knowledge and advice, and for helping me find this project which was an ideal match for me. Annmarie, your help in analysing the data combined with your knowledge with statistics was really appreciated. Olaf, your help and guidance with all my DUECA blunders was really appreciated, thanks for giving me that push in the back to keep me going. René, your valuable insights have helped me a lot in maintaining the big picture of the project which has been really helpful. I would also like to thank Eric Groen and TNO for providing the equipment used for this thesis. I would also like to thank all the participants without which I would be unable to conduct this experiment. Lastly i would like to thank my entire support system, friends, housemates, girlfriend, family and especially my parents. Without you, mom and dad, i would not have made it half as far. Your support and wise words are extremely appreciated and helped shaped me into the person I am today.

Dale-Allen Arrundell (4341120)
Delft, 03-03-2021

Contents

List of Figures

List of Tables

List Of Abbreviations

AI	Attitude Indicator
DERP	Design Eye Reference Point
DUECA	Delft University Environment for Communication and Activation
HCR	Horizon Control Reversal
ICAO	International Civil Aviation Organization
IMC	Instrument Meteorological Conditions
LOC-I	Loss of Control - In flight
MLD	Multi-Layered Display
PFD	Primary Flight Display
RRE	Roll Reversal Errors
SA	Situational Awareness
SD	Spatial Disorientation
SLD	Single Layer Display

I

Paper

Using a Multi-Layer Display to prevent interpretation errors of the attitude indicator

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***Abstract*—In previous studies it was shown that both pilots and non-pilots sometimes make roll reversal errors (RREs) when the aircraft bank angle is presented on a moving horizon type attitude indicator. This incorrect input has been shown to be caused by a misinterpretation of the horizon symbol on such an attitude indicator. The figure-ground relation of the aircraft symbol and horizon symbol on the attitude indicator has been cited as being a contributing factor to this misinterpretation. A Multi-Layer Display (MLD) is tested as a possible intervention tool for these interpretation errors. With this display type, the horizon symbol is presented on a physically deeper layer, making it possibly more easily interpreted as being in the background, and the aircraft symbol is presented on a second layer on the foreground.**

A group of 23 non-pilots and 18 pilots were asked to perform a recovery task on a desktop-based simulator without outside visuals and only an Attitude indicator on both a MLD as well as a conventional Single Layer Display for repeated-measures. Although roll reversal errors were observed at a comparable level to previous research, no significant difference were observed on the error rate between the two display types. A possible explanation is that the stereoscopic depth of the MLD is not effective when the subjects sit still and remain exactly in front of the display. This leaves open the possibility that other types of depth cues, such as monocular cues, can be added and used to enhance the figure-ground relation in displays.

I. INTRODUCTION

Loss of Control in flight (LOC-I) has for a long time been the leading major cause of many fatal aviation accidents. LOC-I is the situation in which the flight crew is not able to maintain control of the flight path of the aircraft which results in an unrecoverable situation [1].

Due to this accident type long being a leading cause in many fatal aviation accidents, industry sees a need to apply any and all means necessary to mitigate this risk, from implementing design/ manufacturing fixes to pilot awareness and training [1]. LOC-I covers such a broad category of aviation related accidents which involves too many contributing factors to all be considered in one study. One of these contributing factors has been identified as attitude indicator misinterpretation, in which a pilot fails to correctly interpret the attitude information being presented by the attitude indicator [2]. This results in the pilot making an erroneous input to the flight controls which leads to departed flight from the intended flight path. The situation in which a pilot makes a response during recovery that is opposite of the intended response is known as a Roll Reversal Error (RRE).

The Attitude indicator is the primary source for self orientation in the cockpit in situations where the natural horizon is not present. It has previously been established that erroneous interpretation of the attitude indicator bank angle information can be caused by a misleading motion stimuli [3] or by an incorrect expectation of bank angle [4], both of which can give pilots an incorrect assumption of the aircraft bank angle leading to the occurrence of RREs. The situation in which the pilot has an incorrect interpretation of the total aircraft state, including altitude, attitude and airspeed is defined as spatial disorientation [5]. One of most well known forms of this incorrect interpretation of aircraft state, when the bank angle of the aircraft is considered, is known as "the leans". Here, a false perception of the orientation of the horizon exists in the pilots perception. In the aforementioned incorrect interpretation of the aircraft state and attitude indicator, the tilt angle of the horizon on the attitude indicator is then incorrectly interpreted as the bank angle of the aircraft leading to an incorrect control input, a RRE. This phenomenon is therefore also known as the horizon error and is displayed in Figure 1

Figure 1. Horizon Errors in which the horizon symbol on the AI (left) is mistaken for the bank angle of the aircraft from a rear view (right)

These RREs have been investigated both in Pilots and in Non-pilots where these RREs have been induced in-flight [2] [6], as well as in fixed-based [7] and motion based simulators

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[3]. These studies have had a range of objectives, mainly focusing on the ambiguity of the attitude indicator. In all of these studies, the gestalt principle of the figure-ground relation is cited as being a leading cause of the horizon control errors. These studies also propose different methods to reduce the occurrence of these RREs or investigating the effect of different design elements of the attitude indicator on the occurrence of RREs [6]. For example the effects of using a certain type of sky-pointer, either military, commercial or general aviation type, on RREs have been clearly demonstrated [8] where it has been shown that the usage of the General Aviation sky pointer leads to least amount of errors. Also the effect of extending the horizon symbol has been shown to have beneficiary effects on the occurrence of roll reversal errors [7], where extending the horizon symbol has shown to lead to fewer RREs. Furthermore, the effect of the type of attitude indicator, being either of the Moving Aircraft (MA) or Moving Horizon (MH) type of attitude indicator on the occurrence of RRE, where this research found a clear advantage of the MA type display over the MH type [7] [9] [10].

The gestalt principle of the figure-ground relation is central in all the aforementioned studies on the attitude indicator. This principle is the means of the brain to distinguish a foreground and a background in an image, even when such a distinction does not clearly exist [11]. The argument of figure-ground separation states that in current display technologies the aircraft symbol, which is intended to be perceived as the figure, is not being correctly distinguished from the horizon symbol, which is intended to be perceived as the background, leading to RREs. This argument has been put forth since 1947 [12] and has been well supported [3] [7] [13] [14]. The current study aims to investigate the possibility to conceptually separate these two elements in the pilots frame of reference, by using physical depth in the attitude indicator display to improve the perceived figure-ground relations in the attitude indicator.

A multi-layer display (MLD) may be an effective way to create this conceptual separation of figure and ground or of the "self" and "world" and thus making it easier for the pilots to distinguish the tilt of the angle of the horizon ("world") from the bank angle of the aircraft ("self"). This MLD system was found to have significant benefits in search and detection tasks [15], as well as preventing clutter on displays [16] however this layering has never been investigated with respect to the self orientation capabilities of humans, and also in this case pilots. The primary goal of the current study is to investigate if using physical depth cues leads to fewer or less severe forms of RREs. If successful, this method will be an effective tool in the toolkit of display designers to improve figure-ground separation, and especially when creating attitude indicators that reduce the occurrence of Roll Reversal errors which have LOC-I accident as a result.

II. BACKGROUND

In the current study, the effect of using physical depth to separate the aircraft symbol from the horizon symbol in the attitude indicator is examined. An MLD will be used to create this physical depth. Exactly what an MLD is, why it has been used previously and the reasons why it is hypothesised to improve self orientation capabilities will now be elaborated upon.

A. *Multi-layer display*

An MLD is a type of display consisting of multiple semi-transparent layers onto which information can be projected. In general there exist two main ways of creating multiple layers to display information on, namely using the half silvered mirror-approach and the conventional multiple LCD displays separated by a perspex layer [17]. It should be noted that with both these type of MLD displays, multiple discrete layers are created onto which information can be presented. In the current study, the half silvered mirror type MLD is used. A schematic of which can be seen in Figure 2. This display option was chosen due to its availability.

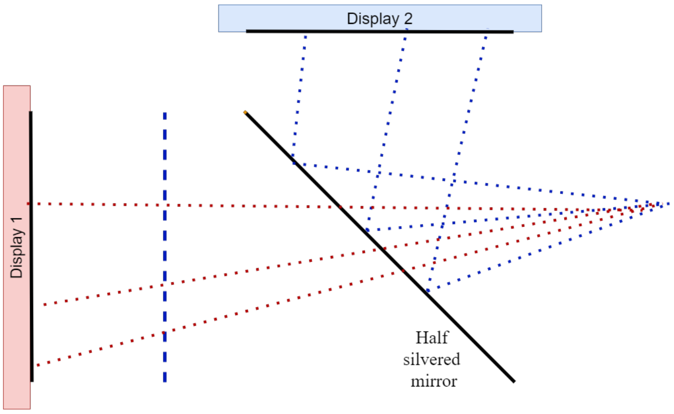

Figure 2. Schematic on how the second layer is observed as a virtual image in front of the first display

MLDs have previously been used in studies to asses their ability to increase users' search performance, as well as improving information uptake [15]. In that study, different stimuli were placed on the two discrete layers of the MLD and it was found that the MLD significantly improved search performance if care is taken to design the correct placement of stimuli. Furthermore, the MLD was also shown to increase the information uptake capabilities of users, where transparency, colour and form of data presentation was investigated, however this was only the case for increased task difficulty [18].

Furthermore, MLDs have been used in a study for clutter prevention, in which it is reasoned that by designing the correct placement of stimuli on each of the discrete screens, it is possible to prevent the screens from being too cluttered. This was shown experimentally in a study where an MLD was used for emergency ambulance dispatchers [16], where it was shown that for scenarios with high clutter this display was effective in increasing the subject performance on their task. This display has also previously been used for the area of clutter prevention in the aviation sector where an MLD was used as a Multi-Function Display (MFD) of a combat simulator to present an overview of the combat scenarios and information from the radar of the aircraft to military pilot participants [19]. Here it was found to increase overall pilot performance measured by overall mission effectivity and it was found to decrease mission workload.

B. Orientation with Display Depth

The attitude indicator is the primary source of self-orientation. Depth perception plays an important role in human self orientation. Humans perform self-orientation through a combination of inputs of the visual, vestibular and proprioceptive systems which combine their information in the brain to create self awareness of ones position in space. The visual system in most cases dominates this process of self-orientation. This principle is known as visual dominance [20]. Three aspects that result from the workings and flaws of the visual system are of importance for the current study and form the argument of using an MLD in an Attitude indicator to perform self orientation:

1) *Figure-Ground Relationship* The principle of the figure-ground relationships governs which item is perceived as being the focus point (figure) and which items are perceived as being in the background (ground) [10] [6]. By this principle, when this difference is not clear, the brain creates a probabilistic guess of this relation [11]. In the current study, depth in the attitude indicator display is therefore used to physically separate the two stimuli such that there is no confusion possible as to which stimuli are to be perceived on the foreground and which on the background.
2) *Pre-Attentive processing of stimuli* Mostly, when the processing of stimuli is discussed, much attention is paid to how the stimuli is measured by the human sensory system and processed by the brain. However the brain itself plays an important role in which stimuli are processed, and in which order [21]. This causes some stimuli to be processed and interpreted before actual cognition of those stimuli takes place. This phenomenon is known as pre-attentive processing, and is done by the brain on salient stimuli, causing them to "pop-out" during cognitive processing of said stimuli [22]. There are many visual attributes that cause stimuli to be pre-attentively processed. These attributes are mostly subdivided into being as part of either the form or colour of the stimuli [22]. Attributes that allow for a stimulus to be detected within less then 200 to 250 ms on a display with multiple stimuli, are considered to be pre-attentive attributes, Stereoscopic depth is one of the visual attributes that, when used in stimuli, cause these to be pre-attentively processed. In the current study, creating stereoscopic depth in the used attitude indicator display, causes the aircraft symbol to be pre-attentively processed meaning it will be processed before other displayed stimuli.
3) *Focal and Ambient extrapersonal space* In a study on the neuropsychology of 3D space and how it is perceived by the brain for self orientation, an argument was put forth that there are four main brain systems used to interact with the three dimensional world. These four brain systems, the peripersonal, focal extrapersonal, action extrapersonal and ambient extrapersonal brain systems are each responsible for the observation of and the interaction with one of the segments of three dimensional space [23]. Each of these brain systems has its primary function in the corresponding segment of 3D space. This argument has since then been well tested and is well supported [10] [24], and suggests that items placed in the ambient extrapersonal space are used for self orientation in an earth centred coordinate system. When cockpit instruments are to be read and interpreted however, these are all located in the space observed by the focal extrapersonal system, which is responsible for object recognition and interpretation. It has been shown that this system is not used well for self-orientation [25]. In the current study, depth in the attitude indicator display is used to remove the horizon symbol from the focal extrapersonal space to the ambient extrapersonal space, located outside of the arms reach, and to be perceived as being further then 2 m. It has also been previously shown, for circular vection, that self-motion is controlled by the display that is perceived to be in the background [26]

These three elements combined form the basis for using an MLD in the attitude indicator to decrease the RREs

III. METHOD

In the current study two experiments were performed. The display is meant to be useful for pilots, which is why the displays were tested in pilots. However, pilots are already more used to the single-layer AI display, which possibly decreases positive effects of the MLD AI. Therefore, the display was first tested in a group of non-pilots. In this group, we also determined what would be the optimal depth of the MLD layers. Furthermore, the two proposed experiments have the same procedure and method. This experiment was approved by the research ethics committee of the Delft University of Technology.

A. Participants

1) Experiment 1: A total of twenty three non-pilot participants (18 male, 5 female) participated in the experiment. The mean age of participants was 24.8 years (SD = 6.9). Of these participants, 5 have never seen nor used an Attitude indicator before, 4 knew what an attitude indicator is but have never used it, 10 had some experience with flight simulators at different fidelity levels, such as PC based flight simulator, and 8 had experience with glider flights. None of them had any experience at the control of powered aircraft of any category. The total group rated their experience with an attitude indicator as 2.8 (SD = 1.24) on a 5 point likert scale ranging from 1 (not at all) to 5 (very much). The participants were randomly assigned to two groups, each of which would perform the same task with the same procedure, but with the MLD presented at a different depth level. Therefore, the groups were presented with the MLD in either the "medium depth" configuration or the "large depth" configuration, which corresponded to a physical display depth of 1.6 cm or 2.1 cm respectively. There was no significant age difference between the two groups, t(21)= 1.658, p = 0.112. All participants were right handed.

2) *Experiment 2:* A total of 18 Dutch private pilots participated in the experiments(18 Male, 0 Female). Only certificated pilots with an EASA PPL were selected. The average age of participants was 43.5 (SD = 16.1), and on average the participants had a total of 324 flight hrs (SD = 245.35) and had 9.8 years of active flying experience (SD = 7.42). These pilots have all completed the minimum Instrument Flying PPL requirements and on average had a total of 9.4 hours flown solely by reference to instrument (SD = 17.96). The group had 6 participants which received UPRT training and 7 participants which received Aerobatic Training. The group in general rated their experience with attitude indicators, in general as well as in flight simulators, as a 3 on a 5 point likert scale (SD = 1.45). Based on the results of experiment 1, presented in the results section, the MLD was set up to be at the medium depth level for all pilots.

B. *Apparatus*

The experiment is conducted as a desktop setup with no outside visuals. In the experiment setup, a half silvered mirror type MLD is used, which can be seen in Figure 3. A schematic of the inner workings of this display can be seen in Figure 2.

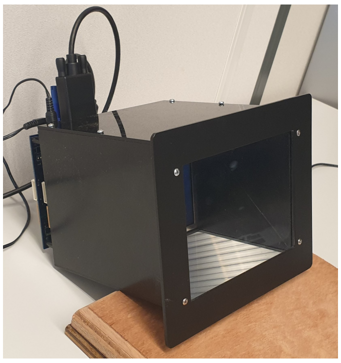

Figure 3. The used MLD, provided by TNO netherlands

The two displays used in this setup were standard LCD type displays with a resolution of 1152 x 864. In Figure 4 it can be seen that the two displays are placed perpendicular to one another, and a half silvered mirror is placed at a 45° to the upper display, which creates a virtual display at some distance X in front of display 1, which is displayed as a dashed blue line in Figure 4. The distance between layers ('X') in the current setup can only be changed by moving display 1, and this distance was not dynamically changeable in the current setup, as there were three discrete slots available to place display 1. In the first slot it was decided by visual inspection that the distance between the two layers was too small. Therefore only the medium and large display depth were used in the experiment. The distance between displays was measured by measuring the distances a, which was the vertical distance between display 2 and the physical starting point of the mirror, and distance b, which is the horizontal distance between display 2 and the physical starting point of the mirror. Distance X is then calculated as being $X = b - a$, and was measured to be 1.6 cm and 2.1 cm for the medium and large depth respectively.

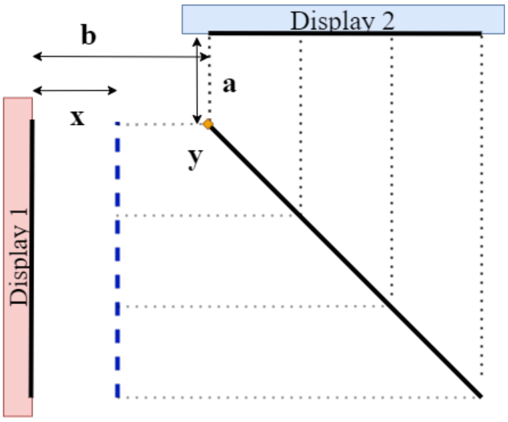

Figure 4. Schematic of inter layer distance within the MLD

To be viewed correctly from an observer in front of the MLD, the information on display 2 is to be mirrored and rotated. With the current MLD it is thus therefore possible to place stimuli on one of two discrete layers. This display is therefore also known as a Dual Layer Display.

During the experiment, a conventional Boeing 747 type PFD was displayed, as this type of instrument is used extensively in operational practice. It is possible to use the MLD setup in a Single Layer Mode, in which display 1 was turned off, and only information was displayed on display 2. This was done because if display 2 is turned off, a dark screen is visible on the virtual layer, which decreases the contrast on images displayed on display 1. In the Multi-Layer Mode, the aircraft symbol and sky pointer and bank angle scale are presented on the virtual display, together with the other airspeed indicator and altimeter. These items were then visible in the foreground. During the experiment these instruments were set to read a fixed value of 10,000 ft and 250 kts, and did not change. On the background, shown on display 2, the horizon symbol and pitch ladder is displayed. This can be seen in Figure 5.

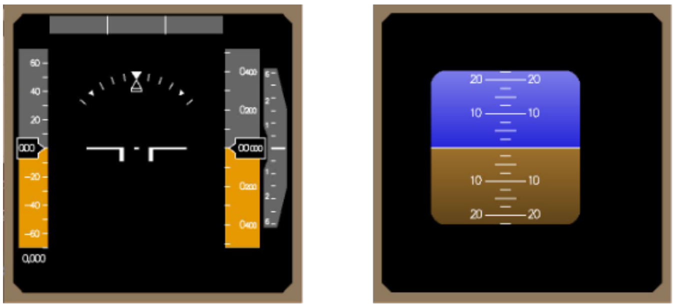

Figure 5. Attitude indicator foreground (L) and background (R) in the Multi-Layer Mode

The alignment of these two displays is of paramount importance as was discovered during initial testing, as the incorrect alignment leads to the creation of false cues, or the illusion that the aircraft state is completely different than what it actually is, such as showing a pitch up while the aircraft is in a pitch down state. Furthermore the MLD is setup to only be viewed from a point perpendicular to display 2 and at a distance comparable to those present in modern cockpit designs.

A standard Logitech Extreme 3D pro joystick was used as input device. The maximum angular deflection on the roll axis of this joystick was measured to be 20°. The stick input to the aircraft model was disabled for the time in which no input was required from the participants. During the actual experiment the pitch of the aircraft was set to be on the horizon, and pitch inputs were ignored, however pitch inputs were possible during the familiarisation phase with the attitude indicator. The aircraft model and stick inputs were logged at a rate of 100 Hz.

C. Experiment Procedure

1) Experiment Task: To investigate the occurrence of roll reversal errors, the participants are to perform a recovery task, thus the primary task of the participant will be to roll the aircraft displayed on the attitude indicator to wings level as directly as possible. This will be the primary task for each run. A timeline of the experiment run can be seen in Figure 6

From Figure 6 it can be seen that each run starts with a five second period in which the display will be completely blank. This is to simulate a period of inattention or not observing the attitude indicator. During this period the aircraft model will be set to display a bank angle with either 30° to the left or right. After the five seconds have passed, a PFD with the Attitude Indicator with a 30° bank angle is displayed in which the participants have to perform their primary task and roll the wings level. They have a total of ten seconds to complete this task. If done correctly the task will not take more then five seconds to get the airplane back to wings level. If a roll reversal error is made, this will take just a bit longer but this will never exceed seven to eight seconds. Ten seconds is therefore more then enough time to complete the task. After this time the screen will again turn blank which signifies the beginning of the next experiment run. This will be done for a total of 30 runs per block. The direction to which the aircraft will be banked, either left or right, is randomised and is set so as to never be more than three times to the same direction to prevent an expectation of bank angle to be created.

In total each participant will perform four blocks of 30 experiment runs. Each block will be with either the display in Single Layer Mode or in the Multi-Layer mode. The runs in both these modes will be exactly the same. The order, however, in which the displays mode will be presented is randomised per participant. These modes will always be alternating, therefore a participant will either have the blocks as Single - Dual - Single - Dual Mode or Dual - Single - Dual - Single Mode. The order of the conditions was therefore counterbalanced between participants. After the second block of experiment runs, there was time for a 10 min break.

2) Briefing: The experiment started with a written experiment briefing in combination with a short oral description of the main goals of the experiment, the experiment task, and the experiment runs.

During this briefing, participants are told that the current study is intended to measure reaction time of participants/ pilots with a novel display. This is also verbally briefed to the participants and it is reiterated that a direct and natural response is required. This is done to elicit a natural response to the displayed attitude indicator and prevents participants from taking more time to observe the attitude indicator. Also, it is verbally briefed that the main task of the participant is to roll the wings level.

After this briefing, the attitude indicator is displayed in both the Single Layer Mode and Multi-Layer mode, and the features of the AI are explained. During this time, the participants are allowed to practice with the aircraft model and develop an understanding of the working of the used attitude indicator in free flight. Here both the pitch and bank inputs are used and displayed. When the workings of the attitude indicator on both display configurations is clear, the participants are given ten practice runs both in the Single Layer Mode and the Multi-Layer Mode. These practice runs are used to show the actual experiment run and to allow for the participants to get used to the timing and the required task.

3) Conditions: Before the actual experiment starts, the general timeline of the experiment is explained, in which participants are informed that the experiment contains in total 4 blocks, each of which have 30 runs which are exactly the same as the 20 practice runs that they have just completed, and that there will be time for a break between the second and third block. After the first and second block the participants are asked to rate their mental effort during the last block on a Rating Scale Mental Effort [27], which will give an indication of their mental effort in both types of displays.

After the four experiment blocks, the participants are asked to fill in a questionnaire with their experience with the displays and other subjective questions.

D. Dependent Measures

All data is gathered by a logger module which receives all data from the stick input as well as the resulting model

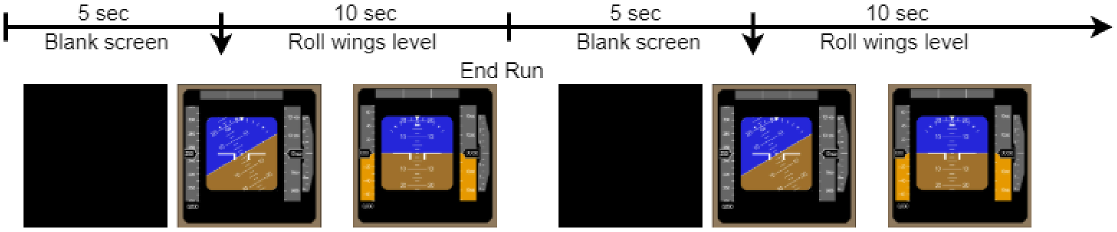

Figure 6. Timeline of Two experiment Runs

state displayed on the PFD. All this information is stored and written to a single Matlab file containing the parameter value for each simulation step. This was stored for each participant per block of the experiment.

In this logger file the model parameters for pitch and bank are stored, also the control inputs for pitch and bank are stored. Furthermore it is also recorded when the PFD display receives an "on" or "off" trigger.

This data is used to create the following dependant measures:

- *Error Rate*: A roll reversal error is recorded when a control input is received to the opposite side of the displayed bank angle. The error rate is percentage of the total amount of runs in which an error is recorded.
- *Reaction Time*: this is the time since when the display is turned on, until the time at which the first control input is made. This "display on time" is defined as the time at which an "on" trigger was recorded.
- *Error Duration*: When an error is recorded, this is the total time in which the incorrect control input was given, based on the displayed bank angle. This is the time it takes for the participant to correct their error and deflect the stick to the correct side.
- *Error Severity*: This is measured by Maximum Stick Deflection in the wrong direction. Maximum Bank Angle is also recorded, but this is a direct result of the maximum stick deflection, and the error duration.
- *Subjective Workload*; this subjective workload assessment was conducted using the Rating Scale Mental Effort, in which participants are to indicate how much effort it took them to complete the previous block on a scale from 0 to 150.

E. Data Analysis

All model parameters, and pilot input is processed using a Mathworks Matlab script from which the aforementioned dependent measures are extracted. A few important steps in this script are described below:

Error determination - It is of importance to check that all the runs that were considered to have a RRE did in fact contain an error. It was noticed that if the control stick was not centred during the beginning of the run and this deflection was to the incorrect side , an error would be recorded, which was not actually an error. Therefore all runs which did not start from a central stick position were discarted.

Minimum Error Threshold- A threshold of 1.5° was used as a minimum stick deflection angle from which an input would be considered to be erroneous and a roll reversal error would be considered. This threshold was chosen to be consistent with previous research in this field [4]

Statistical Analysis- The statistical analysis of the dependent measures that were obtained from the Matlab script were done using IBM SPSS. The Data was checked for normality and for the non-parametric data, a Wilcoxon signed-rank test was used. For the parametric data a paired samples t-test was used. Furthermore, a repeated measures ANOVA was used to compare the performance of the two display depth groups in experiment 1.

F. Hypothesis

The research question that is to be answered by this study investigates the effects of using a MLD for an attitude indicator on the roll reversal errors made. Due to a better separation of figure-ground in the MLD, the horizon symbol will be better interpreted as being on the background and will be less likely confused with the airplane symbol. Also, due to the depth created, the airplane symbol will be pre-attentively processed again reducing the horizon error. Lastly, the horizon symbol will be moved to the ambient extrapersonal space which is used for self orientation.

Based on these principles, the following hypothesis will be tested:

> *Pilots will show a decrease in RRE rate with the Attitude indicator on the MLD when compared to the conventional SLD*

IV. RESULTS

A. Example Output of RRE

In Figure 7 an example can be seen of the control inputs and resulting bank angles during a run where a RRE was observed. At $t = 0$ seconds the display is turned off and a blank screen is observed by the participant.

At $t = 2$ seconds the aircraft model is set to a bank angle of 30° with still the display turned off. At $t = 5$ seconds the display is turned on and the attitude indicator is displayed with a bank angle of 30°. In this case a reaction time of 580 ms was observed at which time the participant reacts by applying a stick input in the same direction as the bank angle, and thereby increasing the bank angle before applying stick

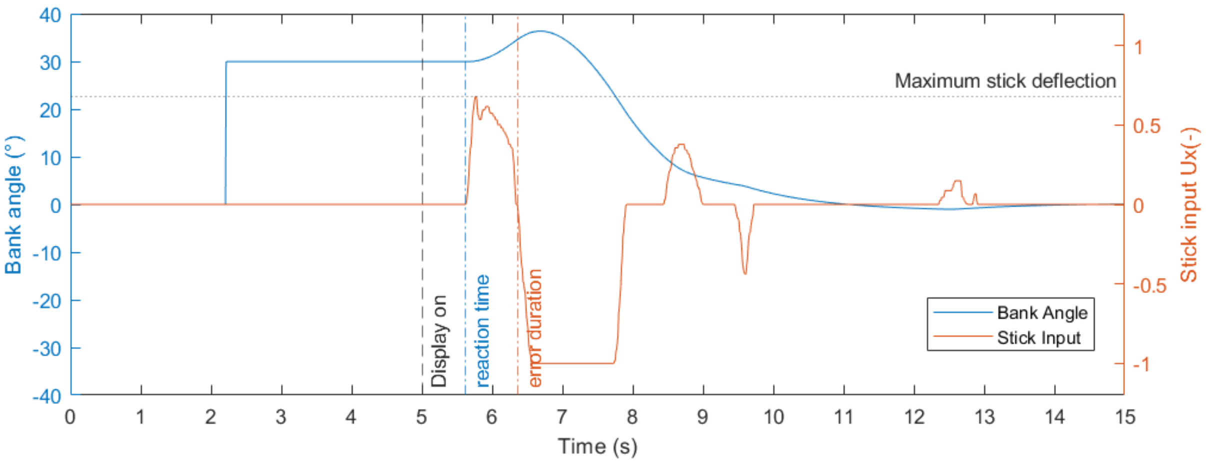

Figure 7. Bank angle and Stick Inputs in an example when a RRE occurred

input to the opposite side of the bank angle to roll wings level. The dependant measures reaction time, error duration and maximum stick input to the incorrect side can also be seen. The error duration time starts when the first incorrect input is received.

B. Experiment 1

A total of 29 runs (1.05%) were unusable and were discarted due to participants not holding the stick centred before initiating the recovery task, or due to excessive joystick noise observed prior to recovery.

1) Error Rate: For a general comparison of the error rates on the SLD and MLD, the data received from the groups presented with a different depth are also combined to a "total group" for this analysis. The average error rates and the corresponding boxplots for the received data points for the total experiment group, as well as for the large and medium depth group can be seen in Figure 8 and Figure 9 respectively. A total of 185 errors were made of which 102 errors were made in the SLD mode and 83 in the MLD mode. The error rates for both display types were not normally distributed, W(23)=0.870 p =0.006 and W(23) = 0.872 p =0.007, therefore a Wilcoxon signed-rank test was used for this non-parametric, related samples data. This test showed that there was no significant difference between the two sample medians of 5% for the SLD and 3.333% for the MLD, Z(23) = -1.334 p = 0.182.

A 2x2 (Display Depth x Display Type [SLD/MLD]) mixed model analysis of variance was performed on the data of the two groups presented with different depth to investigate which of these two displays showed the best improvement in error rate. The resulting Estimated Marginal Means of error can be seen in Figure 10. The outcome of the between-subject test showed no significant difference in improvement between the two displays, F(1,21) = 1.059 p=0.315, however when the Slope of both Estimated Marginal Means of Error curves are ordered by size, the slope corresponding to the group presented

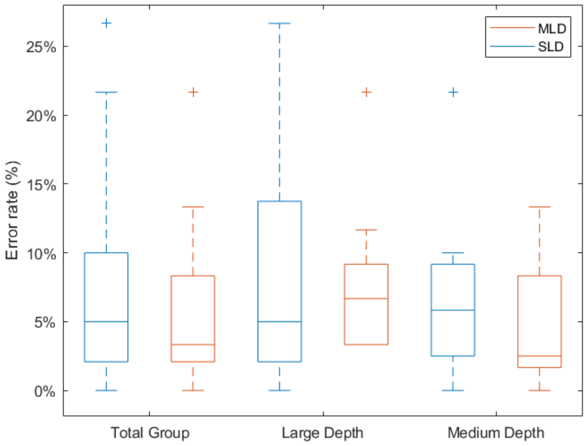

Figure 8. Box plot of Average RRE Rate per group

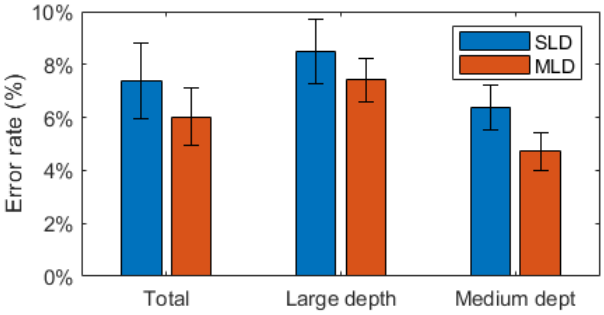

Figure 9. Average RRE Per group

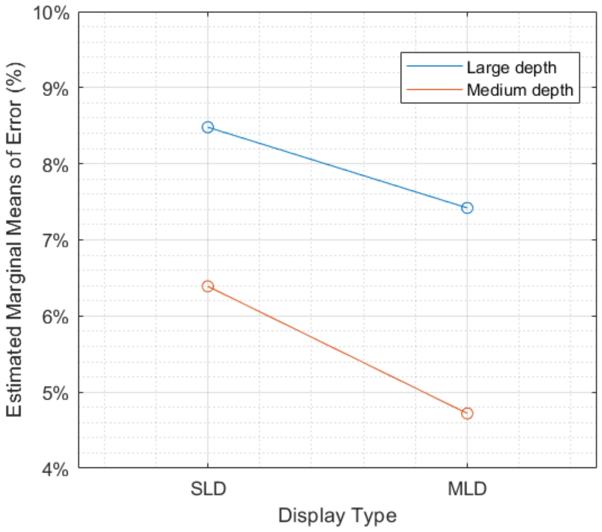

Figure 10. Estimated Marginal Means of Error

with the Medium depth display shows the largest decrease. Therefore it was chosen to continue with only the medium depth for experiment 2 with pilots to keep the experiment as uniform as possible.

2) Reaction Time: The observed average reaction times per participant for both the SLD and MLDs were likely normally distributed, W(22) p = 0.691 and W(22) p=0.138, therefore a paired samples t-test was used to compare the sample means. A significant difference was found between the reaction time of the SLD of 591 ms and for the MLD 605, t(22) = -2.608 p = 0.016, which meant that the Reaction time was shorter for the SLD compared to the MLD.

3) Error Duration: For the error duration, there were some participants who did not make any mistakes with either the SLD or the MLD. Therefore there were 18 valid pairs to compare the error duration. The error duration for the errors with the SLD were likely normally distributed W(18)=0.898 p = 0.052 however the errors with the MLD were not normally distributed, W(18) = 0.788 p = 0.001 therefore a non-parametric test is used to compare the two sample medians, using a Wilcoxon Signed-rank test. This test showed no significant difference between the sample medians of 125 ms for errors on the SLD and 163 ms for errors on the MLD, Z(18) = -0.327 p=0.744.

4) Error Severity: The error severity was measured by both the maximum bank angle that was achieved in the incorrect direction and the maximum stick deflection in the incorrect direction. For these two parameters, a comparison between the data obtained from the SLD and MLD can only be performed for the participants who made errors in both displays. In this case 18 valid pairs were formed. For maximum stick deflection, the data was found to be normally distributed, W(18)=0.960 p= 0.604 for SLD and W(18) = 0.920 p = 0.131 for the MLD, therefore a paired samples t-test was used which returned no significant difference in the two means of u_x = 0.33, 6.6° stick deflection, for the SLD and u_x = 0.42, 8.4° for the MLD, t(17) = -1.415 p = 0.175.

For maximum bank angle in the incorrect direction again 18 valid pairs were observed. and this data was not normally distributed neither for the error made with the SLD or for those made with the MLD, W(18) = 0.729 p =0.000 and W(18)=0.763 p = 0.000 respectively. A Wilcoxon signed-rank test was used which showed a non-significant difference between the two sample medians of 0.3° for SLD and 0.4° for the MLD, Z(18) = -0.544 p = 0.586 It can be noticed that the median observed maximum bank angle in the incorrect direction is quite small, this is due to the error duration being also quite small, meaning that the errors were in general quickly realised and therefore not a large bank deviation was observed.

C. Experiment 2

Based on the analysis for error rates observed with non-pilot participants, it was opted to perform experiment 2 with pilots using only the medium depth setting of the MLD. A total of 20 runs (0.93%) were discarted due to participants not holding the stick centred before initiating the recovery task, or due to excessive joystick noise.

1) Error Rate: With pilots, as expected, lower levels of reversal errors were observed, and and a box plot of the observed RRE values per display can be seen in Figure 11. In total 51 errors were observed in the SLD layer mode and 46 errors in Multi Layer Mode. The data set for error rate was found to not be normally distributed for both the SLD and MLD error rates, W(18) = 0.745 p = 0.000 and W(18) = 0.854 p=0.010 respectively. Therefore, a Wilcoxon signed-rank test was used. This test showed no significant difference between the two sample medians which in this case was 3.33% for both the SLD and the MLD, Z(18) = -0.475, p = 0.635.

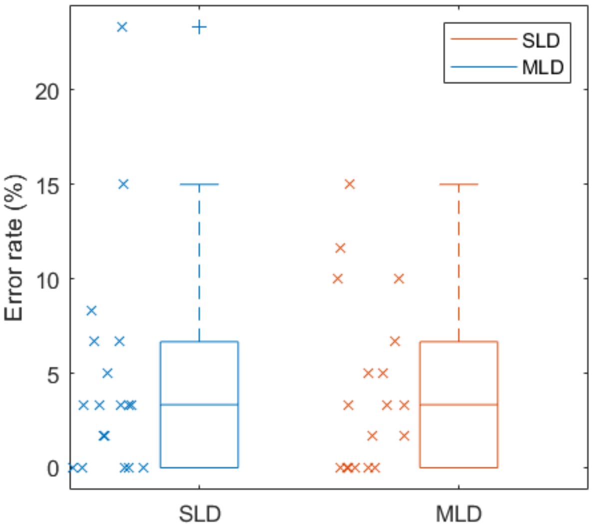

Figure 11. Box plot of Average RRE Rate per display type

2) Reaction Time: The difference in reaction times observed with pilots was small, where the SLD reaction time was measured to be 648 ms and the reaction time with the MLD was measured to be 657ms. The reaction times with the SLD were not normally distributed W(18) = 0.876 p=0.022 however the reaction times with the MLD were likely normally distributed W(18)=0.932 p = 0.212. As one of the two parameters is not normal, a Wilcoxon signed-rank test was used to compare the two sample medians. This test showed no significant difference between the two sample medians of 625 ms for the SLD and 644 ms for the MLD, Z(18) = -1.241 p = 0.215.

3) Error Duration: For error duration there were 9 valid pairs that could be used to compare the error duration between the SLD and MLD. The observed data was normally distributed for both the SLD and the MLD, W(9) - 0.845 p=0.066 and W(9) = 0.854 p = 0.082 for the SLD and MLD respectively, therefore a paired samples t-test was used to compare the mean error duration's which were 269 ms for the SLD and 350 for the MLD. This test showed no significant difference between the two sample means, t(8) = -1.414 p=0.195

4) Error Severity: For error severity both the stick deflection and maximum bank angle to the incorrect side were used. For both these parameters there were 9 valid pairs that could be used for the comparison between SLD and MLD. The data for the maximum stick deflection for both the SLD and the MLD was normally distributed being W(9) = 0.843 , p = 0.062 and W(9) = 0.941, p = 0.594 for the SLD and MLD respectively. A paired samples t-test showed no significant results between the sample means of u_x = 0.44 or 8.8° and u_x = 0.46 or 9.2° for the SLD and MLD respectively, t(8) = -0.301 p = 0.771. For maximum bank angle to the incorrect side, the SLD data was not normally distributed, W(9) = 0.618 p = 0.000 however the MLD data was likely normally distributed W(9)= 0.061, therefore a non-parametric model is likely to accurately describe the population underlying the sampled data. A Wilcoxon signed-rank test was used to evaluate this data, and this test showed no significant difference between the two sample medians of 0.72° for the SLD and 1.07° for the MLD bank angle to the incorrect side Z(9) = -0.889 p = 0.374. It should be noted that in this case the observed error duration with pilots was slightly higher than with non-pilots, and therefore this lead to larger observed bank angles to the incorrect side on the attitude indicator.

5) Mental Effort: The participants rated their mental effort with each display type, after a block of experiment with that display type. This resulted in an average rating of 30.8 for the SLD and 28.0 for the MLD. The mental effort rating was normally distributed for both SLD and MLDs, W(18) = 934, p =0.231 and W(18) = 953, p = 0.474. Therefore a paired samples t-test was used to compare the means of the two data set. This test showed a insignificant difference between the mental effort between the two displays t(18)=1.393 p=0.182.

An overview of all the observed dependent measures per experiment observed during the experiment can be seen in Table I. If that specific dependent measure is normally distributed, the corresponding means are presented. If the data is non parametric, the observed sample medians are shown.

D. Subjective Measures

Participants were in general quite successful at observing the depth between layers, with non-pilots on average observing the large depth to be 2.5 cm (SD = 1.1) while the actual depth was measured to be 2.1 cm and the medium depth being observed to be 2.0 cm (SD = 0.8) while the actual depth was measured to be 1.6 cm. There were also 2 participants who did not observe the horizon to be at a different depth level from that of the aircraft symbol. Pilots on average observed the distance to be 1.4 cm (SD = 0.9) and were only presented with the medium depth. There was one pilot participant who did not perceive the depth. The participants furthermore found the bank angle on the SLD to be as easily interpretable as the bank angle on the MLD. This ease of interpretation was rated a 2.8 (SD = 0.8) for non-pilots on a 5 point likert scale, ranging from 1 (very easy) to 5 (very hard) and 2.3 (SD = 0.6) for pilots, meaning that pilots found the bank angle slightly easier to interpret on the MLD compared to non-pilots.

V. DISCUSSION

The error rates that were observed with the attitude indicator with depth presented on the MLD, when compared to the SLD were not able to conclusively show a clear effect in the usage of such a display to lower the occurrence of RRE. Therefore in the current case, it is not possible to reject the null hypothesis.

The current study is performed as a fixed base experiment, without the addition of any expectation of bank angle or any other leans cues. With this experiment it is therefore shown that the addition of depth in this way, by using a MLD, does not succeed any more then a conventional SLD representation of the attitude indicator to convince the user of the true aircraft attitude. The attitude indicator with depth is just as good at convincing the user to provide the correct input as the attitude indicator without depth. Furthermore, as it has previously been shown that participants sometimes make a control input before truly perceiving the attitude indicator, and thereby letting expectation lead their control input [4], the current attitude indicator with depth is not better at convincing them to correctly perceive the correct aircraft state. Therefore, it is not expected that the usage of this exact display type with the addition of expectation or other leans cues will lead to a significant reduction.

Because of this finding that the attitude indicator with display depth is as effective at convincing participants of the aircraft state, it can be the case that using the horizon with display depth can be used as a second depth layer on the instruments or displays to improve self orientation at times when the attitude indicator is not being directly observed. In such a scenario, a horizon symbol presented at a depth can be placed behind other instruments, such as the Heading Indicator, Horizontal Situation Indicator (HSI) or behind the Flight Management System (FMS) display and thereby keeping the pilots oriented to the horizon even when the attitude indicator

Table I
OVERVIEW OF ALL DEPENDENT VARIABLES OBSERVED DURING EXPERIMENT 1 AND 2

	Experiment 1 (Non-pilots)				**Experiment 2 (Pilots)**			
	mean/median	**SLD**	**MLD**	**p**	**mean/median**	**SLD**	**MLD**	**p**
Error Rate [%]	median	5%	3.33%	0.182	median	3.33%	3.33%	0.635
Reaction time [ms]	mean	591	605	0.016	median	625	644	0.215
Error Duration [ms]	median	125	163	0.744	mean	269	350	0.195
Error Severity Stick Deflection [-]	mean	0.33	0.42	0.175	mean	0.44	0.46	0.771
Error Severity Bank angle [°]	median	0.3	0.4	0.586	median	0.72	1.07	0.374
RSME Subjective Workload [-]	-	-	-	-	mean	30.8	28.0	0.182

is not being directly observed, and preventing the pilots having to quickly re-orient themselves when the attitude indicator is again observed, with a possible RRE as a result. There the depth of the display can therefore also be used to not create the sensation of a cluttered display when the horizon is placed behind another instrument or display.

It was observed that when the attitude indicator with depth on the MLD is first presented, participants do observe the depth between the two displays, however this is accompanied by some head motion and therefore the participants are observing the MLD from different angles. This head motion however, is actually not desired when performing the experiments or when using this type of attitude indicator, as vertical head motion leads to a perceived pitch up and down of the aircraft symbol, but more importantly, vertical head motion in a banked attitude indicator results in the perception of a different angle of bank. Therefore the participants are instructed to not move their head during the experiments. However when the attitude indicator with depth is used used continuously without any head motion, it was observed by participants that the depth perceived between the two displays is not perceived anymore. This is due to the fact that the attitude indicator on the MLD is observed from directly in front of the attitude indicator. In other words, there is no motion of stimuli on the virtual display, which is the display layer located closest to the participant. This suggests that this type of MLD application can only effectively be used when the stimuli on the front display also have some motion, which allows the participant to experience the depth between the two displays. This observation is also supported by earlier studies with display layering in which the effect of using display layering is only observed when more cluttered displays are used and with more and different stimuli [15] [16], or if the display is used with tasks that are sufficiently difficult [28]. The current task with the attitude indicator might therefore not lead to a display which is sufficiently cluttered, or a task that is not sufficiently hard to perform to be able to observe the effects of display layering. It is however possible to further investigate the usage of display depth in attitude indicator, however in that case more monocular depth cues have to be added to make the depth perceivable even when the attitude indicator is displayed from directly in front of the display.

It has also however been shown previously by Dunser [15] that the same design principles cannot be used when different depth layers are used to display information, and that the addition of depth needs different display design principles to allow for optimal perception of the desired stimuli. Therefore, it might be the case that the design of the attitude indicator specifically for depth is considered, whereas in the current study an attitude indicator designed for a flat representation is used with a representation with depth. Design elements such as the aircraft symbol design or the contrast of the colours and texture for the attitude indicator with depth can therefore be considered.

The observed difference in error rate with the MLD when compared to the SLD was larger with non-pilots compared to the observed error rates with pilots. This may be due to the fact that non-pilots are less familiar with attitude indicators in general, and therefore are not used to using either of these types of displays. Furthermore, during testing, some pilot participants indicated that the usage of the MLD did take some time to get used to. This might also be expressed in the slightly higher reaction times that were observed with the MLD when compared to the SLD in both pilots (non-significant) and non-pilots (significant). This difference might be caused by binocular rivalry in which it takes a bit more time to cognitively observe both depth layers of the display and the perception alternates between the two depth layers [29].

The total average error rates off both displays combined, which is to say the total overall observed error rate, that were observed with this type of recovery task, which was 6.7% for non-pilots and 4.5% for pilots match previous observations in which recovery type tasks are used very well [4] [7] [3] [30]. Especially the experiments conducted by Muller [7] match the current observations quite well for both non-pilots and pilots. Also an error rate of 7% was observed during the matching "filler" runs in another fixed base study by Landman with non-pilots [4].

Another anecdotal observation that was made by participants during the experiment was that the reaction of the aircraft model seemed different when using the two displays, while the used aircraft model was for both display types the same model. It was said that the aircraft model on the MLD was perceived to react slower then the aircraft on the SLD, as if the inertia of the aircraft model was larger with the MLD . This might be due to the fact that the distance to the moving element, in this case the horizon, is larger and therefore when the motion of the horizon is compared to the SLD, the latter seems to move quicker and has less inertia. This perceived change in inertia due to the addition of depth should be accounted for in further research of depth addition in the attitude indicator.

VI. CONCLUSION

While the absolute observed error rates during the recovery task seem to show an effect of the MLD on error rate, no significant difference between the data set for error rates of the two displays was found, neither for non-pilot participants or for pilot participants, therefore the null hypothesis was not rejected. Therefore, the attitude indicator presented with depth performs at the same level in convincing users to make correct roll inputs or to keep self-orientation, compared to the conventional SLD. With non-pilots, a slight advantage was observed with group that was presented the MLD at medium depth in the reduction of error rate. It was observed that the depth effect between the aircraft symbol and horizon symbol dissipates when the MLD is used for extensive time period and viewed from directly in front of the display. For future research it is therefore recommended to add monocular depth cues in the attitude indicator such as texture gradient and motion based depth cues, as well as other display design principles that are specifically used for display design for multiple depth layers to investigate the figure-ground relation further. Placing the horizon symbol with depth behind other instruments to keep users oriented while using other instruments and thereby not creating a cluttered display may also merit further investigation to decrease spatial disorientation and therefore reduce LOC-I accidents.

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II

Preliminary Report

Note:
This part has already been graded under Literature Review (AE4020)

1

Introduction

Loss of Control in flight (LOC-I) has for a long time been a leading major cause of many fatal aviation accidents. LOC-I is the situation in which the flight crew is not able to maintain control of the flight path of the aircraft which results in an unrecoverable situation[1].

Due to this accident type long being a leading cause in many fatal aviation accidents the industry sees a need to apply any and all means necessary to mitigate this risk, from implementing design/ manufacturing fixes to pilot awareness and training. LOC-I covers such a broad category of aviation related accidents which involves too many factors to all be considered in one study. One of these contributing factors has been identified as attitude indicator misinterpretation, in which a pilot fails to correctly interpret the information being presented by the attitude indicator. This results in the pilot making an erroneous input to the flight controls which leads to departed flight from the intended flight path. In the current study only the bank angle information of the attitude indicator is considered.

It has previously been established that erroneous interpretation of the attitude indicator bank angle information can be caused by a misleading motion stimuli which can give pilots an incorrect assumption of the aircraft bank angle[2]. This situation, in which the pilot has an incorrect interpretation of the total aircraft state, including altitude, attitude and airspeed is defined as spatial disorientation. One of most well known forms of this incorrect interpretation when with the bank angle of the aircraft is known as ”the leans”, where a false perception of the horizontal exists in the pilots perception. In the aforementioned incorrect interpretation, the tilt angle of the horizon on the attitude indicator is being incorrectly interpreted as the bank angle of the aircraft. This study aims to investigate the possibility to conceptually separate these two elements in the pilots frame of reference, by using figure-ground relations.

A multi-layer display (MLD) may be an effective way to create this conceptual separation of figure and ground or of the ”self” and ”world” and thus making it easier for the pilots to distinguish the tilt of the angle of the horizon (”world”) from the bank angle of the aircraft (”self”). This MLD system has proven significant benefits in search and detection tasks [3], as well as clutter prevention on displays [4] but this layering has never been investigated with respect to the self orientation capabilities of humans, in this case pilots. If successful, this method will be the beginnings of an implementable solution to reduce spatial disorientation within pilots and therefore reduce the amount of LOC-I accidents that happen as a consequence of spatial disorientation.

Research Question

The objective for this thesis research issued by the Delft University of Technology in cooperation with TNO Human Factors in Soesterberg is as follows:

The main research objective of this thesis is to investigate the use of depth in displays to improve display interpretation for self-orientation ***by*** *testing whether pilot performance under spatial* *disorientation improves when using a Multi-Layer Display version of the attitude indicator with the aim to reduce the amount of LOC-I accidents due to bank angle misinterpretation*

This main research goal is further subdivided into more tangible sub-goals which are easier to achieve, and when combined aim to achieve the larger main research objective.
In order to successfully achieve this research objective a central research question is formulated as follows:

What are the effects of using a Multi Layer Display for an attitude indicator on the interpretation of the attitude indicator bank angle measured by roll reversal errors made?

This question can further be split into three sub-questions that will be answered either in a feasibility study at the start of the assignment, through literature research or performed in a later phase of the proposed research.

1. Can a Multi Layer Display be used to convey attitude indicator information/ orientation information?
2. Does a Multi Layer Display allow for enough distance to perceive a figure ground distinction?
    - Can attitude indicator design elements be used to improve the depth perception in the MLD attitude indicator to make even clearer that the viewer is perceiving the outside world?
    - How much can the attitude indicator design elements be changed while still maintaining the fidelity to conventional attitude indicators
3. What is the optimum distance between displays to convey the attitude indicator
    - Is an increase in distance always beneficial to the figure ground relationship?
    - At what point does the distortion due to multiple layers combined with possible head motion start occurring with the given MLD
4. Does the attitude indicator presented on a Multi Layered Display result in less roll reversal errors when compared to the conventional 2D attitude indicator

Report Structure

This report is set out as follows. First off, in chapter 2, the research context and background knowledge related to this field of research is presented to discuss in which context the research is being performed. Then in chapter 3 the topic of using depth cues in displays is introduced and elaborated upon, including the many techniques present to create physical depth in a display, and what research has been conducted on these displays. Here the technology basis for the used display is presented. In chapter 4 a review is done on current literature and pertinent previous research that has been conducted and the main conclusions that will be used for the current research are presented. This chapter will be concluded with the research gap and the research question that will be answered. Then in chapter 5 it is investigated what aspects of the human operator are to be used to give answer to the research question. To answer this research question, an experiment is to be conducted. The initial testing and findings during the preliminary setup of the Multi Layered display can be found in chapter 6. The complete experimental setup, including the participants briefing and software setup can be found in chapter 7.

2

Research Context

The proposed research is aimed at investigating the usage of display layering and depth in displays for self-orientation as a possible aid to prevent Loss-of-control in flight (LOC-I) accidents. These LOC-I accidents have been identified by industry as being the major problem to be solved, by any means necessary. In this chapter the exact context of the proposed research is presented. It has previously been established that LOC-I accidents have multiple causes, which are too broad to be considered all at once. The nature of these LOC-I accidents and the factors affecting it will be presented in section 2.1. When LOC-I accidents are further diagnosed, it can be concluded that the largest cause for LOC-I accidents is the phenomenon named Spatial Disorientation (SD). This phenomenon has been singled out as of interest for further study and will be elaborated upon in section 2.2. More specifically, the design of attitude indicators and especially with regards to SD prevention has been selected for further study. These design aspects related to the attitude indicator misinterpretation will be further elaborated upon in section 2.3

2.1. Loss of Control In-flight (LOC-I)

In order to properly investigate the LOC-I accident scenario problem, which has been identified by industry, it is of importance to understand what LOC-I means and why it is of importance to investigate it. This section will discuss the relevance of LOC-I accidents by means of looking at accident history.

Loss of Control In-Flight (LOC-I) can be defined as the situation in which the flight crew unintentionally is not able to maintain control of the flight path of the aircraft in flight which results in an unrecoverable situation [1]

When the total percentage of commercial accident that are related to LOC-I are considered, as can be seen in Figure 2.1, it can be seen that LOC-I related accidents only account for a relatively small percentage of the total number of commercial aviation related accidents. However, in Figure 2.2, when the fatality rate of these accidents is considered the following can be concluded:

- LOC-I accidents account for the largest number of fatal aviation accidents, almost twice as much as the second category.
- LOC-I accidents have the highest number of resulting casualties in all the other categories, 3 times higher then the second highest category.
- practically all LOC-I related accidents are fatal accidents.

Thus it can be concluded that although LOC-I accidents do not occur with a high frequency, when they do occur, they are practically always fatal and leave an extremely high number of casualties.

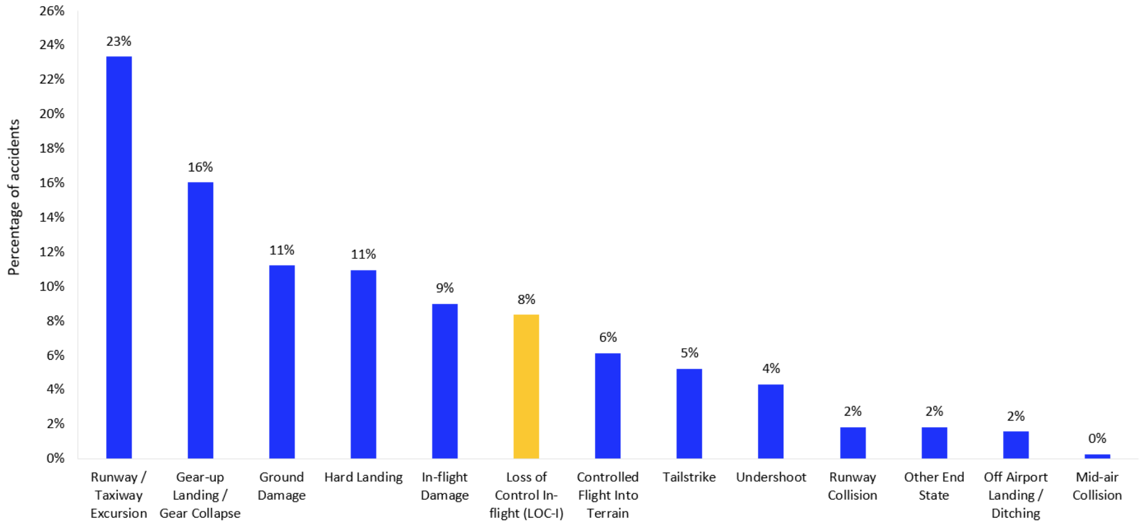

Figure 2.1: *Commercial accident categories as a percentage of the total accidents[1]*

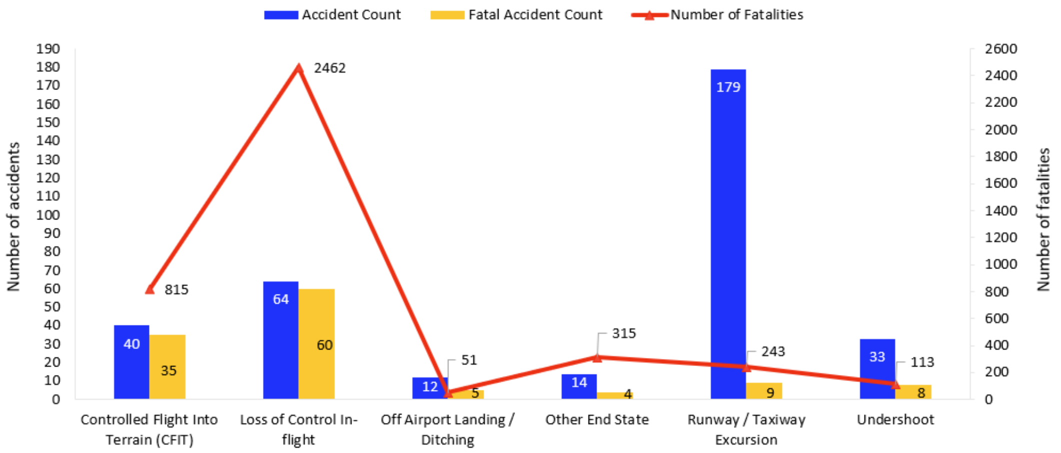

Figure 2.2: *Fatality rate of top six fatal accident categories [1]*

LOC-I covers such a broad category of aviation related accidents which involves too many factors to all be considered in one study. It has been suggested that the causes and contributing factors to these LOC-I scenarios can be divided up into 3 major segments [5] namely:

- Adverse on board Condition, including crew action or inaction, system or component failures, and vehicle impairment
- External hazards and disturbances, including obstacles, poor visibility and other inclement weather
- Abnormal Dynamics and vehicle upsets, including stall/ departure from controlled flight, abnormal altitude airspeed angular rates or asymmetric forces.

The current study focuses on Spatial Disorientation, which is a causal factor that falls under ”Adverse on board conditions” as it concerns crew action or inaction. When these accidents are considered, as can be seen in figure Figure 2.3 it can be concluded that Spatial Disorientation contributes to 12% of all accidents and is responsible for 26% of the total fatalities [5]. It is the contributing factor with the largest fatality rate in LOC-I accidents. Spatial disorientation will be further discussed in the following section.

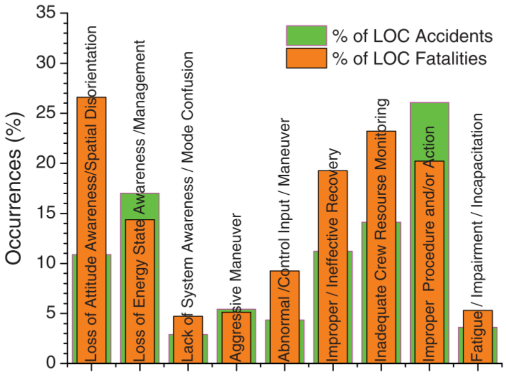

Figure 2.3: *Aviation LOC-I accidents related to crew action or inaction [5]*

2.2. Spatial Disorientation

As stated in the previous section, accidents related to spatial disorientation have proven to be a highly fatal type of LOC-I accident. In this section the phenomenon is further discussed to understand what it is and what causes it, and how this relates to the proposed study.

Spatial Disorientation (SD) can be defined as an orientational illusion in which the pilot has a false perception of state of the aircraft relative to the Earth's surface[6]. The aircraft state includes its position, attitude and/or motion.

Furthermore it has been identified that a distinction can be made between three types of SD scenarios [6]:

- Type I: Unrecognised, in which the pilot is not aware of the fact that he is disoriented
- Type II: Recognised, in which the pilot is aware that there is an information mismatch but does not know this is due to spatial disorientation
- Type III: Vestibulo-ocular disorientation, also known as Incapacitating SD, in which the pilot is aware of the information miss match and is unable to obtain orientation information due to vision blurring and counteracting vestibulo-ocular reflexes.

In the current study a focus is placed on Type I SD scenarios as there is the intention to provide the pilot with enough information to perform self-orientation but the pilot will not be aware of the SD scenario. Spatial orientation is performed by combining inputs from many of the motor and sensory systems in the human brain such as the vestibular, proprioceptive, somatosensory and visual sensory systems [7]. These systems will further be elaborated upon in chapter 5. However of the aforementioned sensory systems, arguably the visual system is by far the most important for maintaining oneself oriented, and its effects somewhat overshadows the inputs from other sensory systems. This phenomenon is known as visual dominance [8].
SD is by itself the cause different types of vestibular illusions that can occur in flight which can all separately lead to a LOC-I scenario, such as the Coriolis illusion, "graveyard spiral", somatogravic illusion, 'the Leans', inversion illusion and the elevator Illusion. It is important to note that these are only the illusions that are well-known and have occurred so often such that they have been described by researchers[6]. For the current study, the leans illusion is chosen for further investigation.

The Leans

The leans is a form of orientation illusion in which there is a false perception of the actual bank angle of the aircraft. It is named after the fact that affected pilots often tends to correct for the illusion by leaning, or tilting, the head in the direction of the incorrectly perceived horizontal plane as can be seen in Figure 2.4. The leans occurs due to the deficiencies of the otolith-organ and semicircular canals. The exact working of these organs, and their shortcomings that lead to the leans illusion will be further elaborated upon in chapter 5. In principle, the leans occur after a prolonged turning event that is below the perceptional threshold of the otolith organ, or an event at which the turning has continued for such a long time that the subjective vertical of the otolith-organ has been adjusted to an incorrect new specific gravity present.

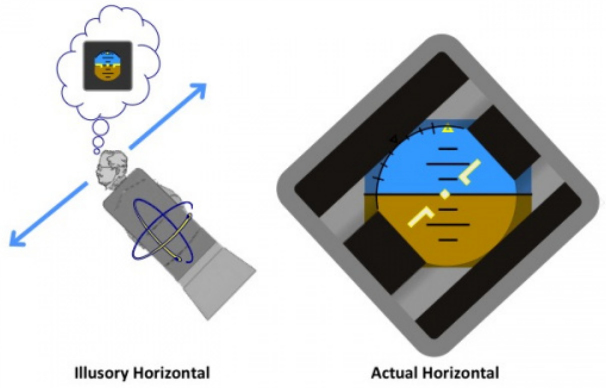

Figure 2.4: *Visual representation of the Leans*

The leans can occur in multiple forms and can give the illusion of either being in a bank while flying straight and level or the illusion of being straight and level wile being in a bank.

If a pilot encounters this illusion in an upset condition under low visibility, which mostly occurs after a period of prolonged distraction, the other sensory organs will dominate their ability to self-orient, especially the otolith-organ and semicircular canals. When it is then necessary to control the aircraft, the pilot may have conflicting inputs from sensory systems when confronted with a visual cue from a different source, such as the natural horizon or a certain type of attitude indicator. In that scenario the pilot may roll the aircraft away from level when actually trying to level it. This phenomenon is known as a Roll Reversal Error (RRE), where a pilot creates a roll input to the opposite side of required to correct an upset. [9],[10]. The nature of these Roll Reversal Errors and how they occur will be further elaborated on in chapter 4.

It has been shown previously that an incorrect expectation of the angle of bank, caused by SD, can lead to the pilot making RREs. This has been shown in studies where an incorrect expectation of angle of bank was given to pilots in a fixed based simulator [2] as well as when a SD scenario was created for pilots while in flight [11]. Furthermore it has also been demonstrated that it is possible to recreate this SD scenario in a hexapod simulator, where pilots also made RREs as a result of SD [12]. The exact nature of these studies and the conclusions that will be used for the current study will be presented in chapter 4. From these studies it can be concluded that it is possible to simulate the conditions conducive to a SD scenario which can cause LOC-I in a simulator, in which actual pilots make RRE in these simulated conditions.

Simulating spatial disorientation

Next to the aforementioned studies on the effect of expectation, in which spatial disorientation, and more specifically the leans, was simulated, there exist numerous studies that simulate spatial disorienting phenomenon which allows for study of the phenomenon and resulting effects for many different other scientific reasons. Simulating spatial disorientation has such an importance that there are numerous studies that make usage of varying techniques to simulate SD in normal equipment, however there are specific simulator designed to simulate SD. Two examples of such simulators are the Airfox Advanced Spatial Disorientation (ASD) simulator [13] and the polish Spatial Disorientation Simulator [14]. From the usage of these simulator has lead to new insight into the usefulness of simulating this phenomenon. For example from these simulators it was concluded that not only is it practically possible to simulate many spatially disorienting scenarios, but that this safe triggering of SD conditions enables the successful training for pilots when self orientation is lost [14].

From the study using the ASD it was concluded that there is a direct relationship between spatial disorientation and the visual scan of the instruments, highlighting the necessity of correct instrument interpretation. It was also noticed that once SD is noticed, the number of glances to the AI increased significantly from 45.3 ± 25.7 to 64.3 ± 29.8 , while the time spent looking at the AI decreased from 0.62 ± 0.20 to 0.44 ± 0.15. These results can be used for the current study because this means that when SD is noticed, pilots look more often to the attitude indicator but spent less time looking at the instrument [13] which further highlights the need for correct instrument interpretation, or making AI misinterpretation easier.

When SD scenarios are encountered and recognised (SD Type II), conventional pilot training teaches pilots to ’trust the instruments’ and primarily the attitude indicator. This approach teaches pilots to fully disregard their sensory signals and attempt to regain aircraft control solely by reference to the instruments. Heavy emphasis is placed on the attitude indicator for self orientation. However it has been shown that there are some aspects of attitude indicator design that have a certain effect on pilots making more (or less) Roll reversal errors when a spatial disorienting scenario is simulated. These aspects will be discussed in the next section.

2.3. Attitude Indicator Design

The proposed study focuses heavily on the attitude indicator, and all the design elements that are present in current attitude indicators. It is therefore of importance to understand these elements and what factor they play in the usage of the attitude indicator for self-orientation.

The Attitude Indicator (AI) functions as the primary source of self-orientation instrument in the cockpit when a natural horizon is not present. It is therefore of paramount importance that this instrument be interpreted correctly. There have been numerous studies with the aim to investigate how the human pilot actually perceives this instrument and how the information is used to perform self-orientation. A few of the main studies are discussed in this section. To start this discussion first the elements of any attitude indicator are discussed.

Attitude indicator design elements

An attitude indicator has numerous elements that aid in the self-orientation of pilots as well as allow pilots to fly very precise manoeuvres. These elements change dramatically throughout the years and even from one manufacturer to another. These elements are:

- the aircraft symbol: there are multiple ways of displaying this aircraft symbol, two different types of aircraft symbols can be seen in Figure 2.6 in which on the left an inverted V-type aircraft is show and Figure 4.2, where only two wings are displayed with a Dot symbolising the aircraft nose. The latter is mostly found in commercial aviation type AIs.
- the horizon symbol: this can be extended or only conventional within the instrument as can be seen in Figure 4.2.
- the sky pointer: which indicated the exact bank angle when compared to the bank angle scale and can be slaved either the horizon symbol or to the aircraft symbol.
- bank angle scale (roll scale): is simply a scale to interpret the exact bank angle .
- pitch angle scale (pitch scale): also simply a scale to interpret the exact pitch angle.

As stated before, these elements are present in all attitude indicators, however the exact form in which they are present has vastly changed over the years and from one manufacturer to another.

However it has been shown that the design of most of these elements have a significant effect on how pilots interpret the attitude information presented on the AI, especially the relative motion of the aircraft symbol to the horizon, the horizon symbol design and sky pointer. The exact results of the latter two studies will be elaborated upon in chapter 4.

Attitude indicator type

One of the most controversial issues in this field is which type of aircraft attitude indicator is best used to present attitude information. Here the discussion ranges between the ”inside out” or Western display, in which the horizon element of the AI rotates (and the aircraft remains stationary) and the ”outside in” or Russian display in which the aircraft symbol on the AI rotates [10]. In literature these attitude indicator types are also referred to as Moving Horizon (MH) or Moving Aircraft (MA) respectively. An example of each of these types of attitude indicator can be seen in Figure 2.5

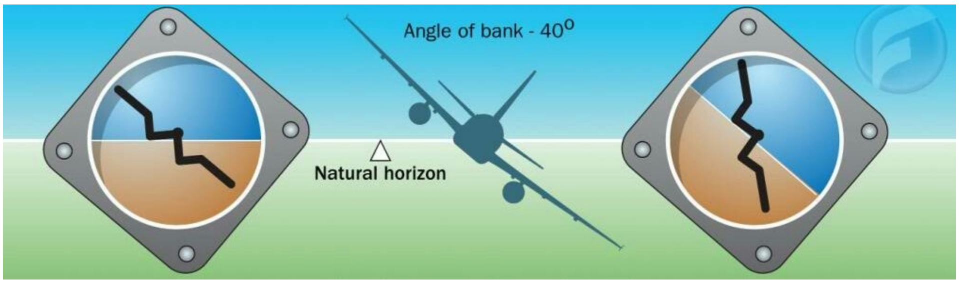

Figure 2.5: *Two types of attitude indicator with the Western "Moving Horizon" display (left) and the Russian "Moving Aircraft" display (right)*

It has been shown on multiple occasions that the Russian MA display is far superior to the western display when RREs are considered [15, 16]. The reason for this is mainly due to the principle of the moving part: which implies that the human operator performs better on control tasks if the element being controlled moves in the same direction as the inputs being provided by the human[17]. The aforementioned principle is closely related to the control-display compatibility principle, in which the arrangement of the controls and the corresponding manipulation should be easily distinguishable [18]. The western MH type attitude indicator is designed according to the principle of pictorial realism, in which the horizon represented by the AI is pictured the same as an observer would see the actual horizon when viewed from the pilots perspective. The bank angle of aircraft, as seen from behind, can therefore be misinterpreted as the horizon symbol on the moving horizon type attitude indicator, as can be seen in Figure 2.6. However by definition these two are exact opposites of each other, meaning that in a left banked turn, the horizon symbol will actually be tilted to the right. This means that if the horizon symbol is identified as the bank angle, the incorrect direction of bank is then assumed leading to a roll reversal error. This phenomenon is named horizon errors [17]

Figure 2.6: *Horizon Errors in which the horizon symbol on the AI (left) is mistaken for the bank angle of the aircraft from a rear view (right)*

The Russian MA type of attitude indicator is designed according to the principle of the moving part, which leads to far fewer RREs being made when this type of AI is used [19].
However, it can quickly be concluded that the de facto standard in modern aviation is the Western Type of attitude indicator (MH type of AI), and that it is practically impossible to switch to the Russian display type, even for its obvious superiority to prevent RREs [17]. Therefore all efforts are made to improve the representation of the western inside out display, which is also a focus of the current study. Furthermore in currently designed aircraft, Heads Up Displays (HUDs) are being applied more often. In these HUDs the aircraft attitude is overlaid onto the real world. This creates the same view as a MH type display. If a MA type attitude indicator would then be used on the instrument panel, the pilot would have to constantly switch between the two types of attitude display.

Conclusion and Problem Statement

From this chapter, it can be concluded that Loss-Of-Control In flight accidents, although they do not occur very often and only compromise a small percentage of aviation accidents today, LOC-I is still the leading cause of fatal aviation accidents, resulting in the most aviation related deaths per year. Therefore, industry has been determined to drive down this type of accidents by any means necessary. When the LOC-I accident are considered, these can be subdivided into multiple groups with each different causes for the accident. When the group of accidents related to crew action or inaction is further investigated, it can be observed that spatial disorientation is the leading cause of crew action related LOC-I accidents. Spatial disorientation by itself can have multiple causes, which result in pilots misinterpreting the instruments used for self-orientation and make an incorrect input to roll the aircraft wings level. In this case specifically the attitude indicator is considered, as it is the primary instrument used for self-orientation. This error, in which the horizon symbol of the attitude indicator is misinterpreted as the aircraft symbol which results in an erroneous control input, is known as a Roll Reversal Error and is the main focus of investigation for this study. Thus the current study is to be done within the context of improving self-orientation to reduce these RREs. Depth cues have the potential to provide a solution to the occurrence of this error. These depth cues will be created by means of using display layering techniques. In the next chapter, these display layering as well as adding depth to displays will be further elaborated upon as well as the existing literature in that field.

3

Depth cues in displays

The proposed study focuses on creating a clear figure-ground relation by using depth cues in the Attitude indicator displays. This will realised by the usage of a Multi-Layered Display (MLD). In this chapter, the usage of depth in displays is further elaborated upon. In section 3.1 depth perception techniques are presented and elaborated upon. In section 3.3 the Multi-Layered Display concept is further elaborated upon and the most prevalent types of Multi-Layered displays are presented. Furthermore the Multi-Layer Display that is to be used in the current study is elaborated upon in section 3.4 and finally in section 3.5 the conclusions from previous studies using Multi-Layered displays will be presented.

3.1. Depth perception techniques

The current study focuses on using depth cues to aid in self-orientation for pilots. It is therefore important to understand how human (and by extent pilots) perceive depth and what techniques are used to display a three-dimensional image to a human operator.

Depth perception is the ability to visually perceive three dimensional space and corresponding distances to objects. Depth perception is made possible by the perception of depth information cues, which can be oculomotor or visual cues [20]. Oculomotor cues are cues that are provided to the brain by means of the internal working of the eyes, such as the eye focus, or eye rotational angle. These cues are the only cues able to identify real physical depth, while the visual cues are only able to 'trick' the brain into perceiving depth that is not actually present.

Visual cues, also known as pictorial depth cues, are cues that can be provided by an external 2 dimensional image. These cues can be further subdivided into the more well known monocular and binocular cues, which make use of either one or both eyes respectively. Monocular cues can be further subdivided into Static cues, and Motion based (dynamic) cues such as motion parallax. The static monocular cues are the most well known depth cues also referred to as "classic pictorial depth cues" such as:

- **Texture gradient**, in which objects that are closer by have more texture then items far away. These objects have more detail distinguishable then the items far away, which appear as one single item.
- **(Linear) Perspective**, in which parallel lines are used that converge to a single (or multiple) points, thus creating the illusion of depth
- **Interposition**, in which the item to be perceived closer by is used to overlap the other items to be perceived in the back.
- **Relative and Known size**, where items that have a known size to the human observer are used as reference to different objects and object placement.
- **Light and Shadow distribution** is the technique in which the location of and relative size of the well lit objects, combined with its shadow, produce depth cues.
- **Height in picture plane** in which the location of the item on the picture frame is used as a cue. Here, an item that is placed higher in the frame is perceived as being further back. This cue is mostly used in combination with relative sizes.
- **Aerial Perspective** which makes usage of the assumption that items further back are more obscured by the atmosphere, and thus are less visible.

These classical pictorial depth cues are mostly combined in a manner to create the required amount of depth for the observer, and have been used for centuries to create depth. Some of these depth cues have also been applied in attitude indicator design, which will be elaborated upon later in the current section.

Binocular cues make use of the distance between the two eyes and can only provide depth information when viewing with both eyes. Binocular vision gives rise to binocular disparity also known as stereopsis, which is the principle by which the majority of three-dimensional imaging is done, in which a different visual cue delivered to each eye is used to perceive depth by the observer. It is a type of stereopsis that is used for 3D movies. The subdivision of the depth information cues can be seen in figure Figure 3.1.

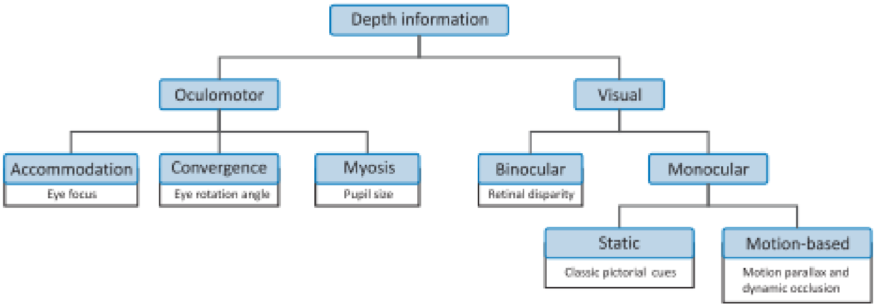

Figure 3.1: *Subdivision of depth information cues [20]*

In practice, many of these different types of cues are used in multiple different ways to deliver depth information cues. In some of the most well known 3D portrayal methods, glasses or other elements are to be worn by the observer to observe depth. There are however display techniques, that also make use of depth information cues, that allow the observer to experience depth without the usage of glasses. These 3D displays will be discussed in the following section.

Types of Depth perception (3D) Displays

There exist numerous technologies for the visualisation of three-dimensional elements using two dimensional screens, some of which use the aforementioned cues to create the illusion of three dimensions, while others are able to actually create three dimensional images by enclosing a three dimensional volume. Generally, 5 types of 3D displays can be distinguished [21]. These types of displays are:

- **Binocular displays**, which make use of conventional principles of stereoscopic vision by delivering two different images to the observers left and right eye. It is this type of displaying technique that may require passive eye-wear, in which the display is known as a stereoscopic display. If no eye-wear is used, this display is named an auto-stereoscopic display. Advantages of this type of display are the ease of applicability, but the drawbacks include being limited to binocular parallax as visual depth cue. Also if auto-stereoscopic displays are considered, only a single viewer is possible due to the limited viewing angle.
- **Multi-view displays**, which is a stereoscopic display that provides discrete views across the entire viewing field. Advantages include the possibility to view this display from multiple angles. The major disadvantage is that the display resolution is divided over the available viewing directions, resulting in decreased image resolution.
- **Integral Imaging displays**, make usage of multiple 2 dimensional images taken with different perspective. Advantages of this type of display are the ability to provide stereo parallax and continuous motion parallax, allowing a wide viewing angle. The disadvantage is the limited depth range that can be portrayed.
- **Volumetric displays** is the type of display in which an actual 3 dimensional space is enclosed. Here, each point of the image is actually displayed at its actual required depth position in space. This can be done by either directing laser beams or by using layered images stacked on top of one another. Advantages of volumetric displays are their ability to create true 3D depth cues and thus provide full continuous motion parallax, however the disadvantage is the visual depth

is limited by the number of layers being used, as well as the image brightness decreasing when more layers are used. The multi-layered display being used in this study is a type of volumetric display, which will be further elaborated upon in section 3.3

- **Holographic displays**, which is based on diffraction, in which a true 3 dimensional image can be created in space by modulating coherent light in different directions with for example a space light modulator. True real time holographic displays are considered to be the ideal 3D display technique, however this type of displaying technology remains extremely expensive and not easily implementable [21].

It can be concluded that the majority of the displays capable of delivering depth information cues have some advantages and disadvantages. In the current study a type of volumetric display is used due to its ability to create true depth cues to the observer, while still being easily implementable and easily available. The exact working of this type of display will be further elaborated upon in section 3.3. Although true depth displays have not been implemented in the aviation sector, display designers have started to make extensive usage of visual depth cues in displays, especially to display attitude information. This will be further elaborated upon in the next section.

3.2. Depth Perception in current Attitude Indicators

Attitude indicator designers and manufacturers have identified the need to create depth in the attitude indicator displays. This is mostly due to the fact that it has been shown that if the attitude image presented to pilots is thought to be emanating from the outside world, this leads to the subconscious idea of the horizon being infallible, as is the true horizon, thus making the display being interpreted with relative ease. This causes the pilots to make significantly less attitude indicator misinterpretation errors, such as RREs [10, 16]. An example of this can be seen in Figure 3.2

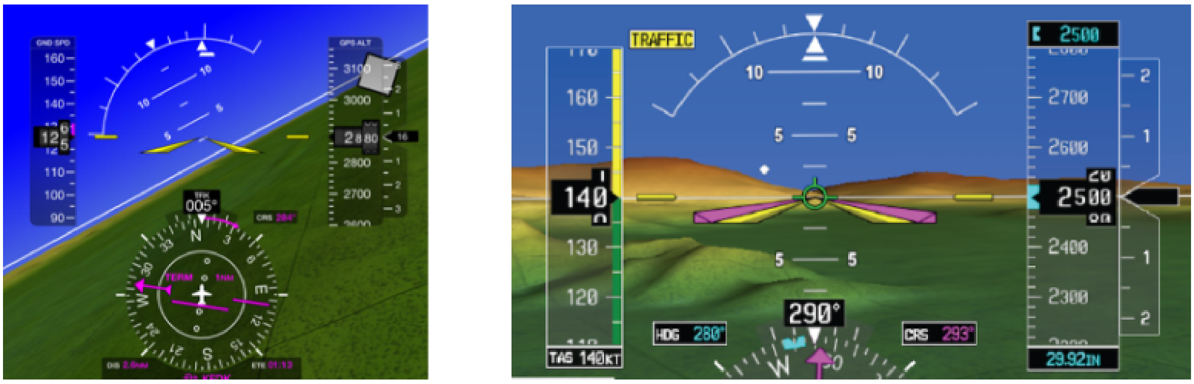

Figure 3.2: *Examples of static monocular visual depth used in current Attitude Indicator design [22] (L) texture gradient (R) known-sized items*

In Figure 3.2 it can be seen that designers make extensive use of many elements to create the illusion of depth with the attitude indicator. Here it can be seen that texture gradient is being used on the left image and the placement of known sized items on the right image. The latter is an element of the recently being implemented synthetic vision technologies, which makes usage of many visual depth information cues, both static cues, such perspective, and motion-based cues, such as motion parallax, to create the illusion of depth in the Attitude indicator. An example of the usage of the aforementioned motion parallax in the attitude indicators is by displaying pathways on the attitude indicator through which the pilot has to fly, as can be seen in Figure 3.3. This is also known as the tunnel-in-the-sky effect [23].

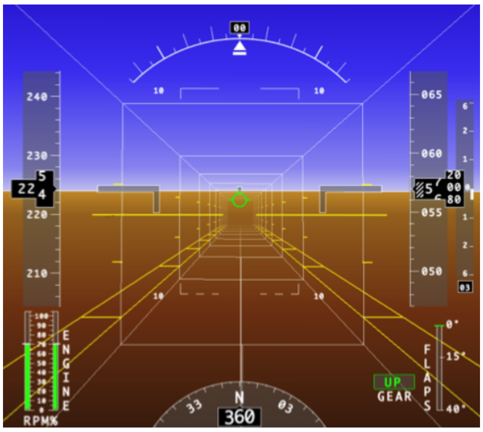

Figure 3.3: *Pathways creating depth information cues by using motion-based cues [23]*

From the aforementioned examples it is clear that attitude indicator display designers have identified many elements to create depth in the AI display. In the current study however, actual depth will be used in the attitude indicator by means of a multi-layered display. This multi-layered display will be discussed further in the following section.

3.3. Multi-Layered Display for Depth Perception

As seen previously there are multiple methods to create depth in displays. For the current study, a Multi-Layered display has been chosen to be used to create actual depth in the display, especially due to its ease of applicability within the required research and its availability. This multi-layered display will be further elaborated upon in this section as well as the two main types of multi-layered displays that are currently in use.

A multi-layered display is, as the name implies, a type of display consisting of multiple layers onto which information can be projected. In general there exist two main ways of creating multiple layers to display information on, namely the half silvered mirror-approach and the conventional multiple LCD displays separated by a perspex layer.

Conventionally, when first the MLD was introduced, it consisted of two or more LCD displays separated by perspex layers, in which all but the rear LCD displays were fully transparent. Therefore by manipulating transparency, the movement of the visual information to be presented, and by using other depth information cues, such as perspective, different layers are created onto which information can be projected [24]. An example of the construction of such a conventional MLD can be seen in Figure 3.4

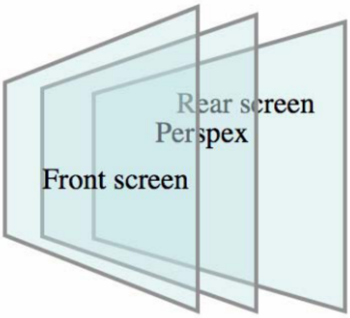

Figure 3.4: *Schematic representation of transparent LCD screens separated by Perspex to create a MLD [25]*

This type of Multi-Layered display has been further developed into a commercially available prototype by the company PureDepth for usage in the automotive industry, but this was mostly only done for pure aesthetics.

3.4. Half Silvered Mirror MLD

The other major approach into creating multiple layers on which to display information, is the approach to be used within the current research. This type of display is constructed using two conventional LCD displays placed orthogonally to each other with a half silvered mirror placed at a 45 degree angle between them, as can be seen in Figure 3.5.

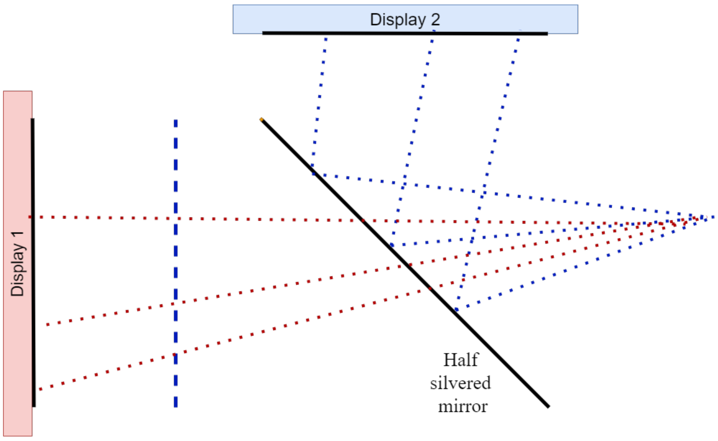

Figure 3.5: *Schematic on how the second layer is observed as a virtual image in front of the first display*

How exactly this virtual display is created optically will be further elaborated upon in chapter 6. As can be seen from Figure 3.5 the image from the rear display (display 1) passes completely through the half silvered mirror, while the image from the upper display (display 2) is reflected onto the half silvered mirror and projected toward the direction of the viewer. This creates the impression to the viewer that the image from the upper display is actually being projected from a small distance in front of the rear display. This image is in fact a virtual image of the second display. By changing the position of the rear display this distance between display 1 and the virtual image can be adjusted, however this can not be done dynamically, only by manually removing the rear display and placing it at a larger distance.
This, however creates only two discrete layers onto which information can be projected, namely the virtual image plane and the display 1 plane, as the information can only be displayed on the two LCD screens, hence this type of display also being known under the name 'Dual-Layer Display (DLD)'. The MLD used in the current study was developed by TNO for testing personalised intuitive displays for pilot performance [26]. Multi-layer display technologies is in itself not a new technologies and has been used in other fields. This will be further elaborated upon in the next section.

3.5. Depth perception techniques in other fields

The proposed study focuses on using depth to improve information uptake for self-orientation from a display. The depth is to be created by using display layering techniques. The use of display layering is not by itself a new technology and has been studied before. The main study areas for the usage of display layering are in the area of clutter prevention [4], [24] and in improving visual search performance and information uptake [3].

Visual Search Performance

It has long been postulated that using techniques of display layering has the potential to increase visual search performance as well as information uptake [3]. In a study related to visual search performance a multi-layered display was used to place different kinds of stimuli on the different layers of the MLD. These stimuli included different kinds of combinations of shapes with different colours. The task of the observer was to find a specific combination of shape and colour.
From this study it was concluded that the MLD significantly improved search performance. However, care should be taken in the choice of location for the stimuli on the foreground or background. Displaying the target on the foreground makes the display more salient and easier to detect.
In another study the effect of transparency, colour and form of the data presented on the different layers was studied [25]. Here legible text was used on the different layers of the MLD, as well as other

task that required the user to read and make decisions based on what was read. From this study it was concluded that there is no significant advantage of using display layering for simple reading and interaction task. However there was a very significant improvement when using an MLD with increased task difficulty, and especially when tasks are to be completed under demanding conditions or more cognitively demanding tasks are to be completed [25].

Clutter Prevention

In the area of display clutter prevention there has been some research into the possibility to use display layering techniques to declutter displays. This was done in a study where command and control displays were investigated for emergency ambulance dispatchers where users were presented with details of an emergency of varying difficulty and their mean response time was evaluated. From this study again it was concluded for that in scenarios with a low difficulty and low clutter on the displays there was little to no advantage of using display layering when compared to a single layered display, however in more cluttered scenarios the usage of display layering showed significant improvement.[4]. This study furthermore highlights the necessity to further understand the display design principles across multiple layers, stating that the conventional display design principles may not always be applicable when two or more layers are considered.

Clutter prevention was also investigated in the aviation sector in a study where an MLD was implemented in the Multi-Function Display of a combat mission simulator[26]. Here the MLD presented an overview of the combat scenarios and information of the radar of the aircraft. This study was focused on the ability of the pilot to personalise certain displays in the cockpit. Due to the fact that the display depth in the MLD is not dynamically adjustable by the user, the user's preferred depth was not investigated. However, it was found again that pilot performance, on overall mission effectivity and mission workload , could benefit from using types of displays that are more intuitive to the application being considered.

Conclusion

From all the aforementioned research it can be concluded that the usage of MLD technologies increases the information uptake in general if the correct design choices are made to place the correct stimuli on the foreground and background [25]. However, none of these studies use the display layering techniques for self orientation.

4

Previous Research

The proposed research will be done within the context of LOC-I accidents with a focus on Spatial Disorientation accidents that occur as a result of Attitude misinterpretation. Within this context, the figure ground separation aspect will be further investigated by creating actual depth in displays. There has already been some research performed into the occurrence of Roll Reversal Errors in general and in a simulated environment and into creating spatially disorientating scenarios in a simulator and This will be further elaborate upon in section 4.1. Aside from that there has been research conducted in the field of attitude indicator misinterpretation as a result of incorrect expectation of bank angle, as well as other possible mitigation methods in the design of the AI itself. This will be the further elaborated upon in section 4.2 and section 4.3 respectively. This previous research will lead to the identified research gap and research goal formulation in section 4.4.

4.1. Roll Reversal Errors

The occurrence of roll reversal errors is well known and has been well studied in the past.

Roll reversal errors (RREs) are a type of control error in which a pilot makes a response during recovery from any attitude that causes an increase rather than a decrease in the aggravated state of the aircraft [10].

This commonly only occurs on the roll axis hence the term roll reversal errors.

There are multiple ways in which this type of error can be induced, both in a fixed-based or PC-based simulator as well as a simulator with motion platform and in flight. On a fixed-based or PC-based simulator this error can be created purely based on the Horizon errors that users make, which has been explained in section 2.3 or can be created by creating an incorrect expectation of the bank angle which will be further elaborated upon in section 4.2.

Any time in which motion cues are used to induce these RREs, such as in a motion simulator as well as in flight, a combination of the given motion cues combined with a misinterpretation of the AI leads to the occurrence of the RREs[11]. However it should be noted that it is also possible to make RREs purely based on vestibular information. In this case the motion cues cause an incorrect expectation of the bank angle.

As stated earlier there are multiple ways of inducing these RREs, and their occurrence has been studied with non-pilots as well as with trained pilots. An overview of some of these results on the occurrence of RREs can be found in Table 4.1. However this table only serves as an indication for the order of magnitude of the RREs made, as there are multiple ways in which a RRE can be triggered and there are multiple scenarios which can create a RRE.

Table 4.1: *Occurrence of Roll reversal errors in ground-based and in-flight experiments*

Type of experiment	Participants	RREs Made
Ground-Based	Non-Pilots	10-15 % [9]
	Pilots	3.9 - 8 % [19] [17]
In-Flight	Non-Pilots	18- 21 % [10]
	Pilots	1.5-3.1 % [27]

Furthermore during these aforementioned experiments, the effect of bank angle expectation was not explicitly addressed. The expectation was either minimised by showing a level aircraft in between runs, or by showing the attitude indicator in random order. It has been shown that when the expectation of bank is explicitly added into the experiment scenario, by means of creating explicit leans cues or creating an incorrect bank angle expectation, the amount of RREs can increase significantly, up to 58 - 75 % [11][2]. The effect of this incorrect expectation will be further elaborated upon in the next section.

4.2. Effect of expectations on roll reversal errors

Another element that is well studied is the role that the expectation of bank angle plays on the occurrence of roll reversal errors when only the attitude indicator is used to correct for a bank angle. This effect was studied both in flight [11] as well as in a fixed-based simulator [2].

In the first study an in flight experiment was created in which participants, non-pilots, were placed in an aircraft in which spatially disorienting cues were induced. Here their primary task was to roll the wings of the aircraft level solely based on information on the attitude indicator. The participants were first blindfolded during which one of four scenario was created:

1. Matching condition: in which a leans cue (supra threshold turn) was given to the same direction as the direction of the turn.
2. No leans condition: in which a sub-threshold turn to a given bank angle was created.
3. Leans Opposite: in which a sub-threshold turn was first induced to a steep bank angle, followed by a supra-threshold turn was created to a given bank angle
4. Leans Level: in which a sub-threshold turn was first induced to a certain bank angle followed by a supra-threshold turn to level flight.

This study resulted in an extremely high rate of RRE occurring, with 58.0% of the leans opposite runs and 63.0% of the leans level runs resulting in a RRE. From this study it was concluded that solely the presence of leans cues significantly increased the amount of RREs made, by a factor of 2.6. Furthermore there was no significant difference between the leans opposite and the leans level condition suggesting that expectation strongly affects the occurrence of RREs.

This was further confirmed by a study done in a fixed base simulator, again where an erroneous expectation of the bank angle was created by starting simulated flight in a turn, then switching off the AI display and ,after a few seconds, switching this display back on with a given AI with bank angle. This bank angle would sometimes match up with the ongoing turn (matching condition), it would sometimes be the opposite of the ongoing turn (opposite condition), and it would sometimes be straight and level (level condition).

This study showed again an extremely high rate at which the RREs were occurring, with 75.0 % (25.6 SD) of the opposite conditions and 30.0 % (37.7SD) of the level conditions resulting in a RRE. From this study it was concluded that an incorrect expectation of the bank angle leads to a significantly higher occurrence of RRE. These findings were further investigated in the Simona research simulator, which will be discussed in the next section.

Simona Research Simulator

The current study will be building directly upon a previous study in which it was investigated if true lean sensation based on only vestibular cues can accurately be simulated in a hexapod simulator and what the effect of expectation and display perception would have on the resulting control reversal errors [12].

In this study a group of pilots was placed in the Simona Research Simulator in which they were given a primary task to roll the wings level. This primary task was to be accomplished after a period of distraction by a secondary task. In some of these runs the motion profile of the simulator was first used to create a sub-threshold tilt angle to a certain small angle, then the motion profile induced an illusion of the aircraft entering into a bank. These scenarios were named the ’motion scenarios’. In other scenarios there was no motion present, and these scenarios were named the ’no-motion’ scenarios. The concept of visual dominance was used to mask the initial sub-threshold tilt to a small angle by displaying visuals corresponding with straight and level flight.

After this simulator motion profile setup the outside visuals were removed and the AI instrument also shortly after. After a short period only the AI was presented together with an aural warning of the autopilot disconnecting indicating that the primary task of the pilots had to be completed. The presented AI would then sometimes match with the given motion stimuli through the motion profile (’motion-matching’), the AI would sometimes be banked in the opposite direction (’motion-opposite’) and sometimes the AI would display a straight and level attitude (’motion-level’). The current study will make use of this same scenario to create a spatially disorienting scenario and will be further elaborated upon in chapter 7.

The main results from this study have shown that in the motion opposite scenario 16.7% of the runs resulted in a RRE, and in the no-motion turn scenario 5.7% of the runs resulted in a RRE. Furthermore, on the first occurrence of the motion-opposite scenario 33.3% of the pilots made an RRE. This in itself confirmed that the leans could be successfully simulated with the given scenario, leading to pilots making roll reversal errors.

From this study it was also concluded that not all of these errors are due to AI misinterpretation, but some are also attributable to the pilots having an incorrect expectation of the bank angle. This effect will be further elaborated upon in section 4.2. However, as stated earlier, 5.7% of the no-motion turn scenarios resulted in a RRE. From that result, combined with the fact that zero errors were made during the motion-level condition, it was suggested that these errors made during the no-motion turn scenarios are mostly attributable to the attitude indicator misinterpretation, such as horizon errors. This was suggested due to the fact that in the no-motion scenario there was no motion in the simulator and therefore, there could be no wrong expectation. However for the 16.7% of the errors on the motion-opposite scenario, this results from a combination of a wrong expectation, and attitude indicator misinterpretation. From the large increase in the amount of errors it shows that expectation has a significant influence on the occurrence of RREs. It should therefore be noted that the currently proposed study is only aimed at reducing the ’attitude indicator misinterpretation’ segment of these RREs and can only lower that aspect of the ’total RREs’ made because the same expectation will be created within the pilots with the spatially disorienting scenario.

From the aforementioned studies it can be clearly concluded that the expectation of bank angle is an important factor in the occurrence of RRE and causes, in some cases, misinterpretation of the Attitude indicator. This expectation can be created by vestibular cues or any other visual cues. However it should be noted that the currently proposed study is not aimed at removing this expectation. The currently proposed study will still involve misleading motion stimuli which will also create an incorrect expectation. The current study is only aimed at investigating the possibility of reducing the AI misinterpretation that occurs as a result of the incorrect expectation.

4.3. Existing mitigation methods in AI design

As stated in chapter 2 the effect of using certain attitude indicator design element in a different manner has also been studied. The most

Extending the horizon symbol

The horizon design in the current MH attitude indicator is based on the history of the instrument. In older ’classical’ type AIs the attitude instrument consisted of electro-mechanical components, attached to gyroscopic elements. This meant that these components had to all fitted be into an instrument which had to be placed on the instrument panel resulting in the attitude indicator being circular and limited in size, as displayed in Figure 4.1. This attitude indicator forms the central point of the ”basic T” or basic 6 instruments that are still present in conventional round gauge aircraft. This basic T display of instrument has since then become the standard in instrument layout on the panel. Later, when displays started being used to present information to the pilots, the same basic T layout was practically copied to the displays. This can be seen in early 737 models in which the attitude indicator was still displayed as a circular instrument on a display. In those cases the horizon on the AI was limited to be only within the circle of the AI.

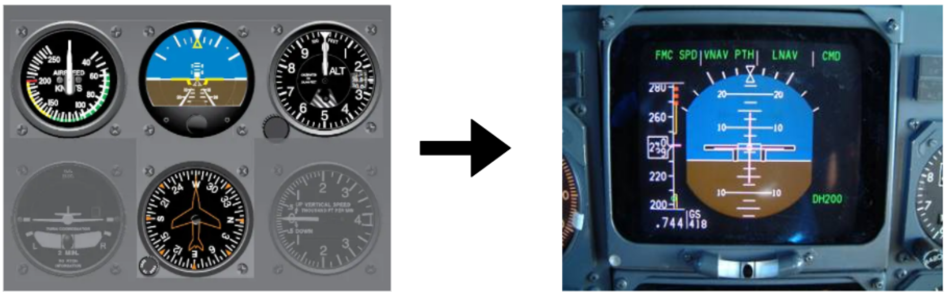

Figure 4.1: *The Basic T configuration of AI, which later lead to the circular AI on digital displays*

Later, in more modern displays, the position of the AI has remained the same however the horizon element was allowed to fill the entire Primary Flight Display and be on the background of all the other instruments. It was proposed that this would also create a better figure-ground relationship which would reduce the amount of RREs being made with the western type display[9]. This effect was studied with a PC-setup in which 4 types of AIs were investigated as can be seen on Figure 4.2. In the experiment, pilots were given a tracking task, which is to maintain wings level when disturbances are presented, as well as a recovery task which is a task to roll the wings level after an upset condition was presented, and no vestibular cues were given.

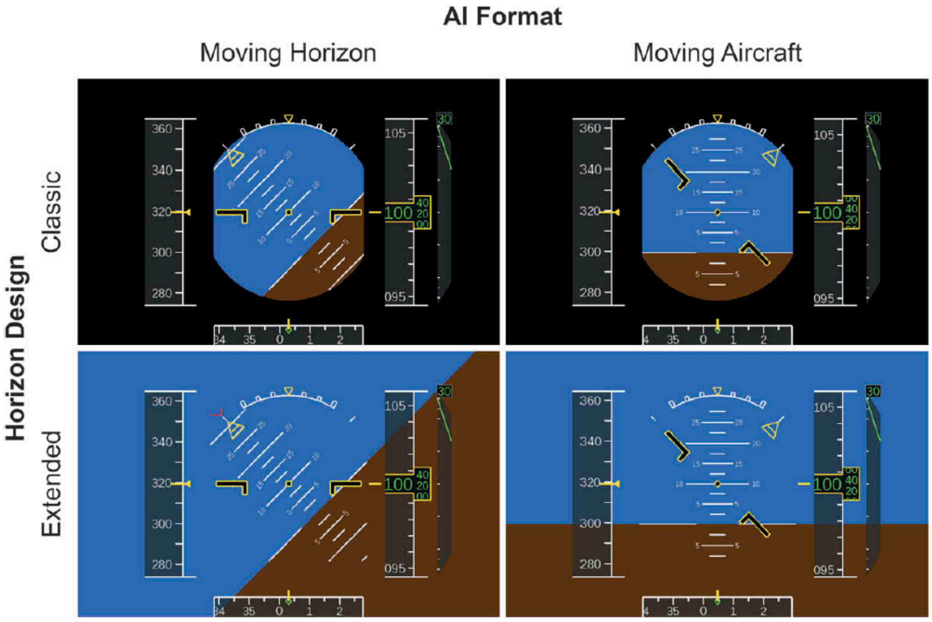

Figure 4.2: *Four AI configurations, being Classic Moving horizon, Classic Moving Aircraft, Extended Horizon Moving Horizon and Extended Horizon Moving aircraft [9]*

The results from this study have shown that for the recovery task, again the Moving Aircraft representation performed generally better then the moving horizon type of display when RREs are concerned, which was to be expected. However when the extended horizon type AI was used the difference in performance between the MA and MH type displays decreased significantly, meaning that the pilots performed less RREs due to a better figure-ground relation [9]. Meaning that extending the horizon has resulted in less RREs occurring. These results suggest that the idea of creating a better figure-ground relation is a valid way to reduce RREs. However in the aforementioned study it is also noted these results cannot be directly generalised to real flying scenarios, for example due to the absence of vestibular cues among others. The current proposed study may provide more insight into this fact by also providing vestibular cues.

Sky Pointers

The roll index, also known as the sky pointer, is also an important component of the aircraft attitude indicator. Its primary function is to indicate the exact bank of the aircraft in degrees, however it can also be used to identify in which direction the bank angle is occurring, i.e. left or right.

The primary function of the roll index can be done in a few different manners. In aviation there are three options that are currently being used in which the sky pointer is either slaved to the horizon symbol, or to the aircraft symbol [19]. It is to be noted that the sky-pointer is applied in both moving aircraft as well as the moving horizon type of attitude indicator. The aforementioned three options of sky pointers currently in use are the following:

- Commercial aviation sky pointer, present in most commercial aircraft (i.e. all Boeing and Airbus types). Here the sky pointer is slaved to the horizon and therefore in the moving horizon type of AI, when a left bank is initiated the aircraft symbol stays stationary, and the horizon moves in the opposite direction of the turn. Due to the sky pointer being slaved to the horizon it will also then move in the opposite direction of the turn.
- General aviation sky pointer, present in most general aviation aircraft using conventional gyroscopic attitude indicators. The sky pointer is slaved to the aircraft symbol in this type and therefore when a left bank is initiated in the moving horizon type of AI, the aircraft symbol stays stationary and therefore so does the sky pointer, producing the effect that the sky pointer is moving in the same direction of the turn. In conventional gyroscopic attitude indicator this is done by slaving the bank angle scale to the horizon and therefore rotating the bank angle scale and keeping the sky pointer stationary.
- Military aviation ground pointer. In this type the pointing element is slaved to the horizon symbol in the same way as the commercial aviation sky pointer, however it does not point upward to the blue element representing the sky but downward, and is therefore aptly named a ground pointer. It produces the same motion as the commercial aviation sky pointer but pointed towards the ground

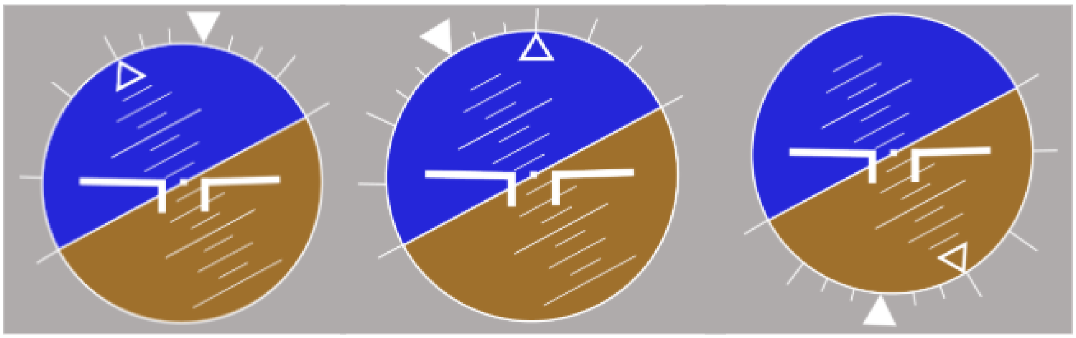

Figure 4.3: *Three sky pointer configurations Commercial (L), General Aviation (C), Military (R)*

In the aforementioned experiment, a PC-setup was used to create an experiment in which again a recovery task was presented to pilots, and their performance was measured concerning the occurrence of roll reversal errors. The results from the study show that the commercial aviation sky pointer performs significantly worse then all the other two types of pointers, and is almost five times more likely to induce a roll reversal errors in pilots when compared to the general aviation and military aviation pointers. The control-display compatibility principle is here again cited as a probable source of the increase in roll reversal errors made, as the controlled element is to the opposite side of the required input and also moves in an opposite direction to the control input. Therefore it can be concluded that the sky pointer has a notable effect on the occurrence of roll reversal errors.

Furthermore it has also been investigated what the effects are of adding multiple other AI design characteristics on the amount of RREs made, such as the effect of adding an ”error dot” on the AI or using a compensatory tracking or pursuit type AI display [15], all in which progress has been made to improve the understanding of how the human operator perceives the AI display. However the addition of these design elements will not be considered for the current study because these design elements, especially the compensatory or pursuit type AI significantly change the fundamental way attitude information should be interpreted by the pilot and therefore is not within the scope of this study.

Conclusion

From previous research it can be concluded that there is a large amount of research done to what causes spatial disorientation and how spatial disorientation can be simulated. Furthermore, it can be seen that creating a more quickly and clearly identifiable figure-ground relation has proven to be a valid solution to reduce the occurrence of these RREs. This has previously been done by extending the horizon symbol on the attitude indicator. Furthermore depth cues have been previously added to attitude indicator, however there is no published study if adding actual depth using display layering aids in human self-orientation. This is exactly the gap the current research aims to fill. This will be further elaborated upon in the next section.

4.4. Research gap and research goal formulation

From the previous sections it is clear that there has been quite some research in the area of spatial disorientation and display interpretation for self-orientation as well as in the area of using depth cues to improve information uptake and for clutter prevention. However in all the research presented there has been a major focus on different ways to display the attitude information on a 2-dimensional display in order to most effectively help with pilot information uptake and to aid in self-orientation. It is shown that the most prevalent type of attitude indicator, which is also on a 2-dimensional display, still produces RREs with pilots when placed in a spatial disorientation scenario. Also it has been shown that the use of display layering has been somewhat studied in other areas of research and has shown great potential to improve information uptake. It has however never been investigated if this increase in information uptake, together with a clear distinction of the figure-ground relation actually improves the pilots ability to self-orient and therefore increase the display interpretation for self-orientation purposes, which is the key objective of the proposed study. This will be further elaborated upon in the next section.

Research Objectives, Research Question and Sub-goals

In the previous section it has been shown that there is still little to no practical oriented research in using depth in displays for self-orientation. Therefore the proposed thesis is primarily practice oriented. In this type of practice oriented research there are usually five stages, namely Problem analysis, Diagnosis, Design, Change and Evaluation. In the proposed project the Problem Analysis concerns the fatal LOC-I accidents. The Diagnosis of the problem has resulted in the aspect of spatial disorientation being singled out as of interest for further study. Here the Design of attitude indicators and especially with regards to SD prevention has selected for study. The proposed change is to be done by adding true physical depth in these displays by means of using a Multi-Layer Display. This will be evaluated by obtaining data from pilots in a hexapod simulator. Together this cycle leads to the research objectives and research question presented in this section.

Research Objective and Sub-Goals

The objective for this thesis research issued by the Delft University of Technology in cooperation with TNO Human Factors in Soesterberg is as follows:

The main research objective of this thesis is to investigate the use of depth in displays to improve display interpretation for self-orientation ***by*** *testing whether pilot performance under spatial disorientation improves when using a Multi-Layer Display version of the attitude indicator with the aim to reduce the amount of LOC-I accidents due to bank angle misinterpretation*

This main objective can further be divided into more tangible sub-goals. The first sub-goal is to gain knowledge on the design elements of attitude indicators, and which elements can be used to enhance the figure ground relation. This includes gaining knowledge on gestalt theorems, on figure-ground theorems and how these can be applied to an attitude indicator or for self orientation techniques. The gaining of knowledge on the working principles of display layering and the benefits and drawbacks that come with it for self orientation is also contained within the first sub-goal.

The second sub-goal is to investigate the feasibility of using a MLD to display attitude indicator information. With this it is meant to investigate if using the equipment and tools at our disposition it is feasible to recreate an attitude indicator with 2 layers of information. This feasibility may be tested out by using a small population of pilots and/or non-pilots with some understanding of basic attitude instruments.

The third sub-goal is concerned with designing an experiment in which existing pilot disorientation simulation methods are modified to an experiment to be done focused on the attitude indicator.

The fourth sub-goal is performing the designed experiment in the Simona Research Simulator and gather the data that follows from this experiment.

Lastly the fifth sub-goal is to analyse the obtained data and perform the hypothesis testing required to form a conclusion.

Research Question(s)

In order to successfully achieve this research objective a central research question is formulated as follows:

> *What are the effects of using a Multi Layer Display for an attitude indicator on the interpretation of the AI bank angle measured by roll reversal errors made?*

In this context a roll reversal error (RRE) is an error in which a pilot makes an input to the opposite side then the required side to roll the aircraft to wings level [19]. This can be quantified by the following parameters:

- Error Rate which can be defined by how many roll reversal errors are occurring in a set number of runs, including filler runs
- Error Severity defined by the magnitude of the input made by the pilot in the wrong direction
- Reaction time which can be defined by how long does it take the pilot to react

This question can further be split into three sub-questions that will be answered either in a feasibility study at the start of the assignment, through literature research or performed in a later phase of the proposed research.

1. Can a Multi Layer Display be used to convey attitude indicator information/ orientation information?
2. Does a Multi Layer Display allow for enough distance to perceive a figure ground distinction?
    - Can attitude indicator design elements be used to improve the depth perception in the MLD attitude indicator to make even clearer that the viewer is perceiving the outside world?
    - How much can the attitude indicator design elements be changed while still maintaining the fidelity to conventional attitude indicators ?
3. What is the optimum distance between displays to convey the attitude indicator
    - Is an increase in distance always beneficial to the figure ground relationship?
    - At what point does the distortion due to multiple layers combined with possible head motion start occurring with the given MLD?

5

Human Self-Orientation with Display Depth (MLD)

The human pilot plays an important role in the currently proposed study. From the previous chapter it has been concluded that there are multiple studies on using depth in displays and display layering techniques for clutter prevention and for visual search performance but there is a clear gap in using this type of technique for human self-orientation. Therefore the theoretical basis for this principle and the underlying reasons for which display layering will be used for self orientation will be further elaborated upon in this chapter. In section 5.1 human self-orientation will be further elaborated upon together with the models that exist for human self-orientation. In section 5.2 the role of the preattentive processing capabilities of the brains will be highlighted and its relation to using depth in displays. In section 5.3 the Gestalt theorems will be elaborated upon with an emphasis on the figure-ground theorems as it is an important aspect in the usage of depth in displays for self-orientation. Then in section 5.4 a neuropsychological basis for using display layering for self orientation will be elaborated upon.

5.1. Human Self-Orientation

In order to understand the basis for which using depth in displays is helpful for human self-orientation, it is first important to understand how humans orient themselves and what brain systems gives rise to human self-orientation and situational awareness. It has long been determined that human self-orientation occurs due to a combination of stimuli from three main sensory systems present in the human body, the visual system, the vestibular system and the proprioceptive system [28]. Each of these three systems has its own specific function for human self-orientation and the information from these sensory systems is then combined in the brain which creates the perception of self-orientation [29]. In this section these three main sensory systems will be elaborated upon with an emphasis on the role they play in using depth in displays for self-orientation. It should be noted that the auditory system has also been proven to provide cues for self orientation and or self motion [30], this is however mostly related to self-motion rather then self-orientation. Therefore to exclude any possibility of self motion, during the current experiment these auditory cues will be masked as much as possible with the use of noise cancelling headphones.

The Visual System

The role of the visual system in human self-orientation has been well researched and understood. Of all the self-orientation sensory systems, it is the most versatile, and the one over which the human has the most active control. The primary function of the visual system is of course not for self-orientation, but for visual perception of the surroundings. However input from the visual system is used to perform spatial orientation. The human is therefore able to actively decide where to focus his visual attention and thereby actively engaging different visual systems for different purposes. These two different visual systems both have a different primary purpose as follows:

- **foveal visual system** which is primarily responsible for the recognition of objects and can do this in a high level of detail with a high resolution and a high frequency of observation.

- **peripheral visual system**, also known as the ambient visual system, is primarily responsible for more general information about the environment and on motion of the environment or objects in the environment. This visual system primarily provides input for spatial orientation. It does this with a lower resolution and frequency of observation.

Though these two separate visual systems have a different primary function, in the total perception of self motion both the peripheral and foveal visual systems are of importance and the foveal system can be used as an input for spatial orientation [31]. Conversely the peripheral system is also able to recognise objects although this also takes specific attention to do so.

Next to its functions for self orientation, the visual system is also primarily responsible for depth perception. The three dimensional structure of the environment is therefore also perceived by the visual system consisting of two eyes, which essentially produce two 2-dimensional images of the environment, using both the foveal and peripheral visual system. The actual depth perception and interpretation takes place in the brain and not in the actual eyes. Therefore the three dimensional perception can be hampered by a problem or illusion within the eyes or by a problem or illusion within the interpretation by the brain. These illusions lead to a flawed imagery and flawed interpretation respectively [32].

The two aforementioned visual systems both engage many different visual sections in the brain and which have different importance on spatial orientation. The perceived depth by these two visual systems plays an extremely important role in which specific brain system is engaged, as each of these brain systems is not primarily for self orientation. This will be further elaborated upon in section 5.4.

The Vestibular System

In contrary to the visual system, the vestibular system has the primary function of gathering information for spatial orientation and self motion. This system consists of two separate organs with both a different function and entity to be measured, namely linear and rotational acceleration:

- Otoliths, which are the organs that measure the linear acceleration, such as gravity and forward acceleration. They consist of two organs, the utricle and saccule each at a $90°$ angle to each other. The main receptors of these organs are sensitive hair-cells (cilia) located in a gelatinous layer with crystals of calcium carbonate embedded in them. Specific forces parallel to these organs will cause the gelatinous layer to shear, causing motion of the hair-cells which leads to the perception of linear acceleration.
- Semi-circular canals, which are the organs that measure the angular acceleration, around each possible rotation direction of the head. There are therefore 3 semi-circular canals for each possible head rotation axis. These canals are tubular and filled with a fluid with high density, endolymph. Due to head motion the fluid lacks behind due to inertia and exists the canals. This fluid motion is then sensed by the ampulla, which also contains sensory hair-cells.

Although the vestibular system does not contribute to depth perception, it is still a part of the currently proposed study. It is the motion thresholds of this organ, in combination with its inability to measure velocity, and only accelerations, that gives rise to leans cues. Furthermore due to the spatially disorientating scenario that will be used for this study, it is important to mask the perception of rotation and tilt angle. Therefore it is of importance to understand that both the aforementioned organs in the vestibular system have a threshold for perception. The actual motion and orientational threshold are known to vary from human to human and are known to change as a result of age, but they have accurately been measured and found to be between 0.092 and 0.221 m/s^2 for translational acceleration, and between 0.0032 and 0.0393 rad/ s^2 for rotational acceleration, which is between 0.188 and 2.255 °/s^2 [33].

Proprioceptive System

The proprioceptive system is the system that composes many mechano-sensory neurons in the muscles. These are a type of stretch receptors in the muscles and tendons, that are able to measure the muscle stretch. This gives the brain the ability to determine the position of the limbs in space. This mostly concerns with tactile sens.

The proprioceptive system forms part of the central sensory system, which then in combination with the Vestibular system and Visual system provide all the information for self orientation. There exist many models in which the combined working of these three systems is modelled such that human self-orientation can be modelled. The most well-known models here are the visual attractor model, which shows the importance of visual information on total self orientation, also known as visual dominance, and the subjective vertical which models how the otolith organs combine to form a subjective gravity vector. These models will not be further elaborated upon, as they only form a small part of the elements that will be used to create the spatially disorienting scenario. The way in which the brain processes visual information however has been chosen for further investigation, as the display layering techniques will allow for some items of the image to be pre-attentively processed. This will be further elaborated upon in the next section.

5.2. Preattentive Processing

In the current discussion of depth perception, much attention has been paid to how the physical information on depth perception or for self orientation is measured by the human body using the sensory system. This discussion was mostly centred on how the sensory system gathers the informational cues. It was previously mentioned that the brain combines the sensory information to complete perception and to perform self-orientation, however this perceptional process was always described from cue to sensory system to the brain. This is also known as a ”bottom up” approach [34]. However equally important, is the way in which the brain uses experience and previous knowledge to assign relative importance to cues, and ”fill in the gap” when some cues are not complete, confusing or missing. This method of creating perceptional information is known as ”top down” processing. The combination of bottom up and top down processing forms the total perception, by which deficiencies in one of the processing methods can be compensated by the other. This can be seen in Figure 5.1

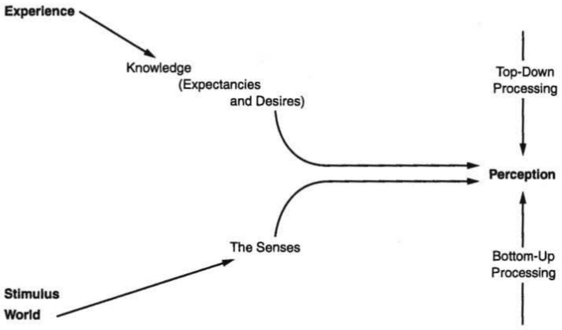

Figure 5.1: *Top-Down versus Bottom-up approach [34]*

The role which the brain plays in perception gives rise to fact that not all cues and stimuli are processed the same way. This causes some stimuli to be processed and interpreted before actual cognition takes place. This is known as preattentive processing. This role in which the brain plays in perception also allows cognitive grouping, pattern recognition as well as the simplification of complex images. This phenomenon has been described by the Gestalt principles. Preattentive processing, as well as its relation to the current study will be discussed in the current section, and the Gestalt principles will be discussed in the next section. It is relevant to note the importance of the brain in the perception process in order to conceive of preattentive processing and the Gestalt principles. Preattentive processing mostly arises from a bottom up processing of stimuli while the Gestalt principles arise due to top-down processing [35].

All stimuli that are gathered by the brain to form perception are preattentively processed, however only the most salient stimuli are selected for conscious and attentive processing [36]. Preattentive processing is also done to perceive information from the environment without focusing attention to a single element, however due to preattentive processing, focus can be drawn to a single element which makes it ”pop-out” from the other stimuli. This leads to the stimuli that pops-out being cognitively processed before other stimuli [36], and that is exactly the intent of the current study. There are some visual attributes that are preattentively processed, these can generally be divided into two groups [37]:

- Form: when one visual cue has another form than the others, only that item will be preattentively processed. Form factors that are preattentively processed include: size, shape, curvature, oreitnation, length and width

- Colour: when one visual cue has an element of colour or shading that is different then the rest, that item will be preattentively processed. Colour items include: hue, intensity, flicker, spatial position and stereoscopic depth

It should however be noticed that the combination of form and colour is not preattentively processed, meaning that when both elements are combined, the result is not preattentively processed. This can be seen in Figure 5.2.

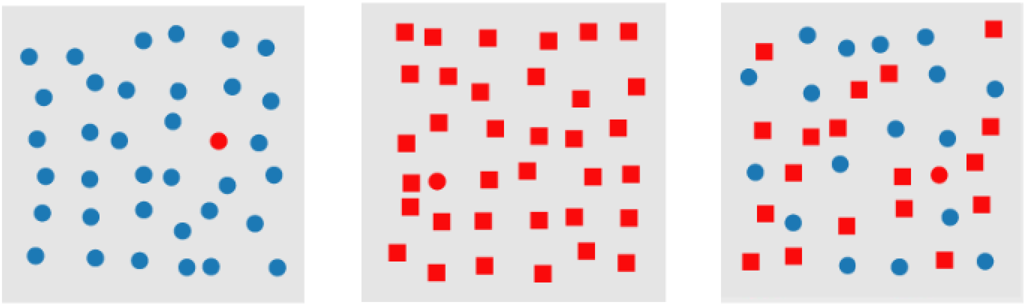

Figure 5.2: *Locate the red circle: Colour and shape examples of preattentive processing [37]*

Elements that allow an item to be detected within less then 200 to 250 [ms] on a multi-element display are considered to be pre-attentive attributes [37].

Stereoscopic depth is one of the items that is preattentively processed, meaning that whenever a single item is given a depth cue over other stimuli, that item will be preattentively processed [38]. It has also been shown however then when depth cues are added, another ”dimension” of attribute can be preattentively processed, meaning that on a 2D display only a single dimension of either form or colour can be preattentively processed, however when depth cues are added, a combination of shape and size can be preattentively processed in parallel [39].

In the current study, due to the existing depth in the displays, the aircraft symbol will be preattentively processed meaning that it will be cognitively processed prior to other items on the AI display. Another principle that will make the aircraft symbol more salient is the gestalt principle of figure ground. These principles will be further elaborated upon in the next section.

5.3. Gestalt Theory: Figure-Ground Relation

All visual stimuli gathered by the brain is preattentively processed, that is the first step in the perceptional process in which features are extracted from the stimuli, some of which are processed before others as discussed in the previous section. The second step is pattern recognition, in which the brain must determine how to group these features, if grouping is at all possible [35]. This grouping was first proposed by the Gestalt psychologist which postulated that for some type of visual stimuli, the sum of its parts is different than each individual stimuli. The brain subsequently groups these stimuli based on some principles. These theories and principles set forth by these psychologist became known as the Gestalt principles.

The Gestalt principles are similarity, balance/symmetry, continuity, figure-ground, closure, proximity and past experience / isomorphic correspondence [40]. Each of these laws describes a method which the brain uses to group items, perform pattern recognition and simplify complex images. An example of this is the law of closure in which our brain attempts to close existing gaps in images to form a meaningful objects. An example of this is the IBM Logo as can be seen in Figure 5.3 where only the letters IBM are recognised instead of all the individual lines. For brevity these principles will not all be discussed in the current discussion.

Figure 5.3: *Example of Gestalt Law of Closure*

The Gestalt laws have proven to be very useful in display design and have proven to be a valuable tool in many types of interface design[40]. For this study however there is one principle which deserves extra attention as it forms an important concept that will help the human operator correctly distinguish the horizon symbol from the aircraft symbol and identify these two elements as separate. This is the Gestalt law of figure-ground and will be discussed next.

Figure-ground relations

Figure-ground relations or the law of figure-ground is one of the Gestalt principles by which the brain distinguishes a foreground and a background in an image, even when such a distinction does not exist [41]. In this principle the mind thus identifies an item as the focal point, the figure, and make the rest a background, the ground. This principle is most famously illustrated by the example in Figure 5.4 where the mind will either identify two faces as the figure, and the white spaces as a background, or a vase as the figure and the black spaces as a background.

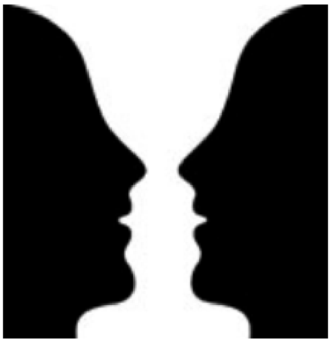

Figure 5.4: *Example of Figure-Ground relation*

However, which stimuli exactly is identified by the brain as being the figure or the ground is probabilistic by nature [42]. It is also argued that the mind has the highest probability to perceive items in our surroundings as figures if they are symmetric, small, convex and enclosed [41]. In the current study the aim is to increase the probability of correctly identifying the aircraft symbol as the ”figure”. Furthermore, when an image is presented in which the figure and ground can be identified differently, such as Figure 5.4, if the observer has the intention of observing one or the other item as the figure, the observed figure can be cognitively switched. With this it is meant that the observer has influence on what is identified as the figure, and if they ”want” to observe one item as the figure, this will increase the probability that they will. In the case of the current study, it is assumed that the subjects have an intrinsic drive to identify the aircraft symbol as the figure. This drive is however subconscious.

Figure-ground in Attitude Indicators

The topic of figure-ground relations within the attitude indicator has been studied before. In many of the studies that focus on the reason why the moving horizon (MH) type attitude indicator is being perceived incorrectly, or how this perception can be improved, the issue of figure-ground relationship is raised in which it is argued that in the current display technologies the aircraft (or ”figure”) is not being correctly distinguished from the horizon (or ”ground”) [10, 16]. In this case the horizon, which is clearly a background item, is not thought of as emanating from the outside world.

It has even been postulated in as early as 1947 that the figure-ground relation is the main reason for the occurrence of roll reversal errors. In his paper, Grether states that normally the actual horizon is accepted by the pilot as a reference frame that is fixed and stable, and therefore it becomes the background. When the pilot shifts its focus from the natural horizon to inside, the cockpit of the aircraft becomes the stable background around which all the instruments and dials rotate around, including the horizon[43].

Grether (1947) then states: *”The small, narrow, and fallible moving bar cannot substitute for the distant massive and infallible true horizon as a stable reference frame by the pilot. By reacting to the gyro horizon bar as a figure instead of ground, he is led to an exactly reversed interpretation”*

It is hypothesised that creating depth within the display may allow for this distinction to be made more easily as pointed out in a study on visual orientation mechanism. With depth it is aimed to convincingly display to the pilot that the horizon is actually emanating from outside of the aircraft, which clearly distinguishes it from an enclosed 2D display in the cockpit [7]. The fact that creating depth will convince the pilot that what he is looking at, is emanating from the outside has a neuropsychological basis. This will be discussed in the following section

5.4. Neuropsychological basis for MLD usage

In addition to the figure-ground relation, it is hypothesised that creating depth has another effect on the interpretation of the attitude indicator display, namely that it changes the brain system which is used when perceiving the display. Initially it was thought that the peripheral vision was responsible for observing the horizon and that therefore creating a larger or wide Field of View (FOV) attitude indicator, able to create stimuli for the peripheral vision would reduce the amount of RREs present. This was first tested with a 70° wide attitude display which was not able to reduce the RREs[44]. This was furthermore also tested with a wide FOV umbrella type display, however here the RREs almost quadrupled in rate [45]. In a study on the neuropsychology of 3D space and how it is perceived by the brain for self-orientation, Previc [46] put forth an argument that there are four main brain systems used to interact with the three dimensional world. These are:

1. **Peripersonal system** responsible for the ability to manipulate objects (within one arms-length reach).
2. **Focal extrapersonal system** responsible for object recognition , receiving detailed visual information and visual search. This system is used when cockpit instruments are to be read and interpreted, when focused upon.
3. **Action extrapersonal system** used for navigating and orienting the observer in topographical space such as a room or relative to a target
4. **Ambient extrapersonal system** used for self-orientation in a earth-centred coordinate system. This system transforms the movement of the visual world into self-motion.

A graphical representation of these systems can be seen in Figure 5.5. This argument of four brain systems is well supported, and suggest indeed that items placed in the focal extrapersonal range are not used well for self orientation. It has also been shown that even a small periscope view of the outside world greatly reduces the amount of RREs because this view is placed in the Ambient extrapersonal space [15].

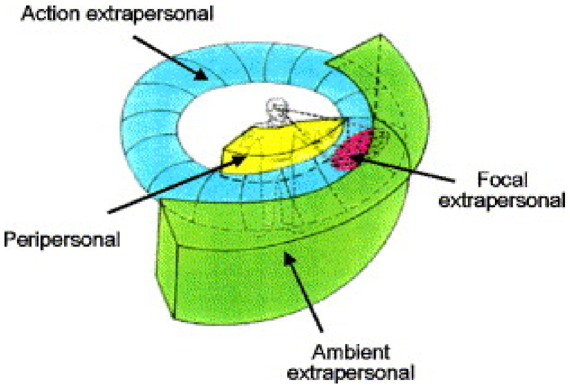

Figure 5.5: *Four Brain systems to interact with three-dimensional world proposed by Previc [46]*

In the current study it is hypothesised that creating depth in the cockpit display of the attitude indicator will move the perception of the horizon bar from the Focal extrapersonal space into the Ambient extrapersonal space and therefore allowing it to be more effective for self orientation, as this will again create the perception that what is viewed is actually a periscope to the real outside world [7]. This idea that a human can use information from a small periscopical view on two depth layers for self-orientation has been touched upon by using results from a study with vection which will be presented in the next paragraph.

Vection with foreground and background

Vection is the illusion of self-motion due to the environment moving, and is purely created by visual stimuli. Self-motion is experienced in the opposite direction of the perceived environment motion. This is best observed and felt by the classical example of siting in a train and observing a different train depart the station, where one will experience the sensation of the other train being stationary and ones own train moving in the opposite direction. This illusory self-motion has been well studied as well as the effect of having multiple moving displays at different depth ranges. Vection was also studied to occur when the human observed a moving display by itself as well as observing the moving display through a stationary window [47]. Furthermore, it was demonstrated that when two displays were presented with both vection inducing cues, vection was controlled by the display perceived to be in the background or located further away even when in fact this display was located closer by [48]. These studies were however conducted for circular-vection and not for self-orientation, however this result demonstrates that self-motion is mostly governed by the display perceived to be in the background.

Conclusion

From this chapter, it can be concluded that the human brain plays a large role in the perceptional process, and that some well established and researched phenomenon support the usage of depth in displays for self orientation in the attitude indicator. First the preattentive processing capabilities of the brain were highlighted in which it is shown that stereoscopic depth makes a cues be preattentively processed over all other cues. It has also been shown that figure-ground relation has been identified as one of the main contributing factors of roll reversal errors when the attitude indicator is concerned. Using depth in the display will increase this figure-ground separation by moving the horizon symbol in the attitude indicator from the focus extrapersonal space to the ambient extrapersonal space. This ambient space is located on the background. It should be noted that the background screen are more responsible for self motion perception. It is hypothesised that all these factors combined will lead to a better ability for the human pilot to self orient when using depth in displays.

6

MLD Setup and Initial testing

In the current study a Multi-Layered Display is used to create physical depth in the attitude indicator display. The general working principles of such a display that creates physical depth has been elaborated upon previously, however practically applying such a display in an attitude indicator and using it for an experiment brings with it some challenges that have to be considered. These challenges will be discussed in the current chapter. First of all it is investigated if it is at all possible to convey attitude information on a Multi Layer Display and how such a setup should look. This will be elaborated upon in section 6.1. Furthermore, it is important to accurately be able to measure the perceived depth in the display in order to know what the actual physical depth is that is created by the display. This will be elaborated upon in section 6.2. The effect of the miss-alignment of the two displays and of participant head motion will be elaborated upon in section 6.3 and section 6.4 respectively. Finally, the area from which the display can properly be viewed from is elaborated upon in section 6.5

6.1. Attitude Indicator Setup on a Multi Layered Display

The to be used Multi-Layered display is capable of creating two discrete layers on to which information can be projected. These two layers are physically separated by a distance which can be adjusted to three different depth layers. Also it is possible to allow for only one single layer to be activated at any time and engage the Display in the ”Single Layer Mode”. In the current section, the setup of the Multi-Layered display and the inner workings of this display will be elaborated upon. With the setup of the display, it is also meant which items are projected onto which layer of the MLD to create an attitude indicator. In Figure 6.1 the Multi-Layered display to be used for the current study can be seen.

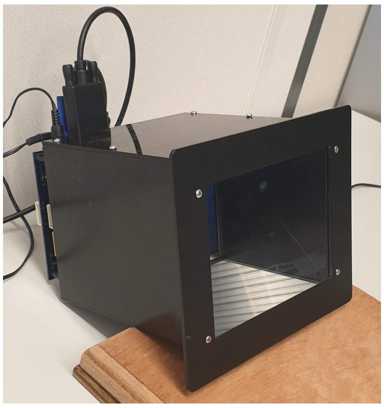

Figure 6.1: *Multi-Layered Display provided by TNO Netherlands*

It can be noted that the both the two displays used to display information as well as the half silvered mirror are all enclosed in a protective casing, with a glass front screen to prevent dust or contaminants entering the system. The inside of the MLD protective casing is covered with a matte black finish to prevent the light from the displays to be reflected in an undesirable manner, which makes it impossible to view the any displays via a reflection of the inside of the protective casing.

MLD setup for an Attitude Indicator

The Attitude indicator used for the current study is part of the Primary Flight Display of a conventional Boeing 747 attitude indicator. For the current study the entire PFD is displayed. This attitude indicator was chosen as it has also been used in the previous studies into the occurrence of roll reversal errors conducted at the Delft University of Technology [2, 12]. It should be noted that this attitude indicator is chosen to remain consistent with those studies, and because it is a real attitude indicator that is in use by commercial aircraft manufacturers to this day, however it contains two items which have shown to increase the RRE rate. First it contains a sky pointer which is slaved to the horizon symbol, and secondly the horizon symbol is not allowed to continue to cover the entire screen. It is only present within the Attitude indicator element of the PFD.

It is possible to configure the MLD in two different modes when it is used. These modes are defined by which displays are active and displaying images.

- **Multi Layer Mode**: It possible to display image on both displays 1 and 2 seen in Figure 6.4. This mode is named the Multi-Layered Mode of the display and is the mode that is most important for this study. When the display is in Multi Layer Mode a different image is presented on both displays. On the foreground, the aircraft symbol and sky pointer are presented together with the bank angle scale. Furthermore the the other instruments are presented on this foreground layer. On the Background, the horizon symbol together with the pitch ladder is displayed. The exact alignment of these two layers is important and will be elaborated upon in section 6.3.

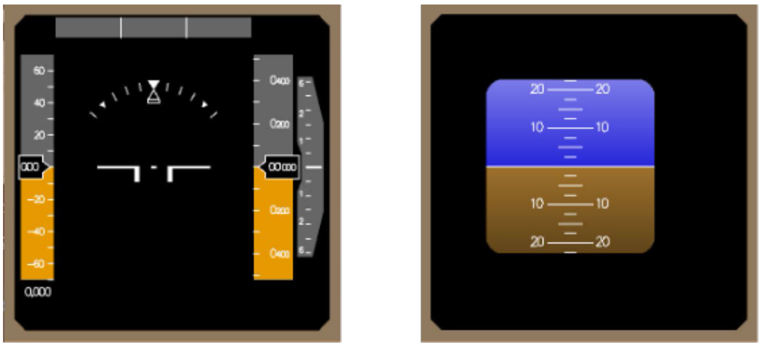

Figure 6.2: *Attitude indicator foreground (L) and background (R) in the Multi Layer Mode*

- **Single Layer Mode**: It is however also possible to either have display 1 or display 2 display a single 2D image, just like any other normal display. These modes are named the Single Layer Mode. It should be pointed out that, in a Single Layer Mode, when only display 1 is displaying an image, display 2 is completely dark, however this means that on the virtual image that is normally created is just a dark screen. The image from display 1 must therefore pass through this and the half silvered mirror display to be observed by the observer. This results in the colours presented on display 1 being a slightly different hue, then the ones perceived if the same colour is presented on only display 2. Furthermore the image displayed on only display 1 has slightly less contrast and less intensity then if the image would be only presented on display 2. Therefore it has been chosen to only use display 2 when the setup is to be used in the Single Layer Mode. In the single layer mode the entire PFD is displayed only on display 2. This can be seen in Figure 6.3.

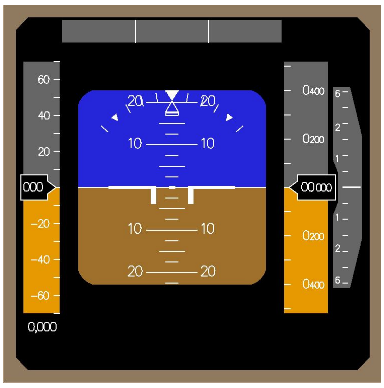

Figure 6.3: *Attitude indicator in the Single Layer Mode*

6.2. Perceived Depth

As the used Multi-Layered display is an experimental tool, which was used previously in a study by TNO [26], it does not contain documentation on the distances that are presented between the two information layers. Therefore in order to use it for the current study, the physical distance between the two layers had to be determined. There are a few ways in which this can be done.

Initially it was proposed to measure this depth by creating two horizontal lines on both display layers with a known distance in between the two lines. The distance between layers could then be determined by accurately measuring the required displacement of the observer, at a distance from the screen, to make these two lines overlap, and using simple trigonometry to figure out the distance between the two layer. However this method was not chosen, due to two major reasons which lead to inaccuracy. First, it was found to be quite difficult to measure the distance between the two horizontal lines as the glass in front of the protective casing makes this difficult to do. It was however possible to measure this distance on the rear display (display 1 in Figure 6.4), but on the top display (display 2 in Figure 6.4) this was a bit more challenging. Furthermore this method was not used, because it was quite difficult to accurately measure the displacement of the observer as it was hard to exactly define a point at which the two horizontal lines overlapped. Therefore this method was abandoned.

The other method of accurately determining the distance between the layers is obtained by making a schematic representation of how the ”virtual display” is created by the second display. This can be seen in Figure 6.4.

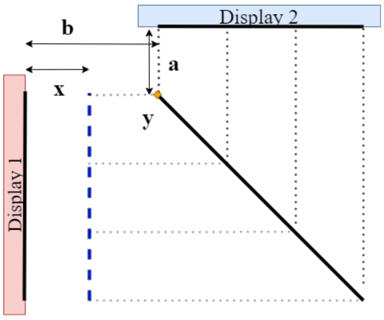

Figure 6.4: *Schematic of inter layer distance within the Multi Layered Display*

This schematic representation is a representation of how the two displays are actually positioned within the MLD protective casing and how the half silvered mirror is setup in this box. This method of measuring the distance is quite straight forward. A few aspects should be defined in this schematic:

- Point Y: This is the physical starting point of the half silvered mirror. The line of mirroring, of course, can be continued on both sides but point Y is the starting point of the real mirror.
- Distance A: This is the vertical distance between display 2 and point Y.

- Distance B: This is the horizontal distance between display 1 and the starting point of the screen of display 2. It should be noted that both displays have an edge which does not display images and that this edge is not displayed onto the virtual image of the second display, because it does not project any light. Therefore, distance B must be measured until the starting point of the displays and not to the starting point of the edges.

- The Virtual display: this is the location where all the pixels of display 2 are perceived to be coming form by an external observer. On the schematic it is represented by the blue dashed line.

If these distances B and A are known, the distance between layers, which in this schematic is labeled as "X" can then be easily be calculated as $X = B - A$. This comes from the fact that from properties of mirrors, the distance A, is the same as the distance from point y to the virtual display. These distances B and A are in practice easily measurable. Furthermore it should be noted that with the current setup of the MLD, the distance X is not dynamically changeable. It can not be made to be any required value. However this distance X can be adjusted by physically moving Display 1 to a position further from, or closer to point Y. At this position, the display is slid into a slot present within the MLD casing. In the current design there are only 3 possible slots where display 1 can be placed. From observation it was concluded that the first slot provided to little distance between the two displays to be considered for the current study, and therefore only the second and third slot were considered. The distance between layers for these two slots are 1.6 cm and 2.1 cm respectively. These two distances were considered for the experiment as being the Medium and Large Depth respectively, when the MLD is displayed in the Multi Layer Mode.

Due to the distance between these two layers, it is possible that the information required on the attitude indicator is seen differently form the observer if viewed from different angles. This introduces false cues of incorrect attitude. These cues will be discussed int he next section

6.3. False cues due to Miss-alignment

One of the most important aspects in the practical usage of the MLD to convey attitude information was identified as being the proper alignment of the foreground and background. With this it is meant that a lot of care should be taken to properly align these two items, and it should be visually checked that these two layers are aligned. It is therefore desirable to create an alignment mechanism to ensure that this is always the case.

If proper alignment is not achieved, the user will not be able to make sense of the information on the attitude indicator, and will always be in a state of spatial disorientation because they will be unaware of the actual aircraft state. This is best illustrated by means of an example: For this example lets consider the aircraft being in a nose high attitude and climbing. In this case if the attitude indicator is not aligned properly and the aircraft symbol is projected too low on the attitude indicator display. The observer will then not be able to make sense of this scenario because they will observe a nose down attitude while the aircraft is climbing and increasing altitude and decreasing speed. It is therefore of extreme importance to properly align these two displays, or else the instrument becomes unusable as a source of orientation information.

These false cues to the observer can also be caused by observer head motion. This will be discussed in the following section.

6.4. Apparent Pitch due to head motion

False Cues can be presented to the observer of the MLD Attitude indicator due to miss alignment but these false cues can also be introduced due to head motion of the observer. This head motion can be deliberate or accidental.

Vertical Head motion (up and down)

During the initial testing of the attitude indicator on the Multi-Layered display, it was noticed that with an attitude indicator with the pitch set to straight and level flight, due to parallax, a head motion up resulted in an observed apparent pitch down cue on the attitude indicator, and vice versa a head motion down resulted in a pitch up.

As stated, this effect is caused by parallax due to change of the line of sight used to observe the aircraft symbol relative to the horizon before, and after observer head motion. This affect is larger when a larger display depth is used, or when the angle between the original line of sight and the line of sight after head motion is larger. Therefore, the distance from observer to the display would also play a role in the apparent pitch up or down cues, as a head motion at small distance would result in a larger angular change in the two line of sights, leading to a larger apparent false pitch up or down cue.

In initial testing it was observed that indeed the parallax, and therefore the apparent false pitch cues, increase when a larger display depth is used. However, it was also quickly concluded that based on the expected distance from the display to the observer these apparent pitch cues were negligible. The distances that were used to make the assumptions were obtained from the dimension information from the SRS SIMONA[49], where the distance between the display and the Eye reference point was considered. At these distances the apparent pitch cues were small, and less then 1°, when normal head motion of the observer was considered.

However, these apparent pitch cues on the attitude indicator due to observer head motion up and down can be introduced accidentally as well. Both in the real aircraft, or in a simulated environment, the main source of accidental observer head motion will likely come from turbulence. If this MLD is to be used in a scenario where turbulence is introduced, the pilot will most probably not be able to control the aircraft pitch very accurately, as they will be constantly seeing apparent nose up and down pitch motions. This is however not a consideration for the current study, as the bank angle remains quite constant with observer head motion up and down.

Lateral Head motion

Another false cue that is introduced when using a Multi-Layered display for an attitude indicator is only present when the aircraft on the AI is presented in a bank.

In this case, this false cue also results from parallax. If the aircraft on the attitude indicator is in a bank, and the observers head is moved laterally, then this will introduce an apparent pitch change as well. For example if the aircraft is in a left banked turn, and the observer moves their head to the right, this will result in an apparent pitch down, and if the observer moves his head to the left they will observe an apparent pitch up motion. In general it can be said that if the lateral head motion of the observer is in the same direction as the turn this will result in an apparent pitch up, and if in the opposite direction of the turn this will result in an apparent pitch down.

Both these false cues due to lateral and vertical head motion occur after extremely large head motions and are relatively small at the distances the MLD is to be observed if it is to be used in the current experiment setup. No more then a 2° apparent pitch change is observed when the head is moved within the viewing pyramid of the Multi Layered display. The exact location of this viewing pyramid will be elaborated upon in the next section.

6.5. Viewing angle and viewing pyramid

The half silvered mirror MLD can not be viewed form all angles. This was noticed early on in the preliminary research. This is an important consideration if the display is to be used in further testing and experiments. The area from which, if the observer is placed within it, the MLD will be correctly visible is described by a pyramid shape, which can be seen in Figure 6.5

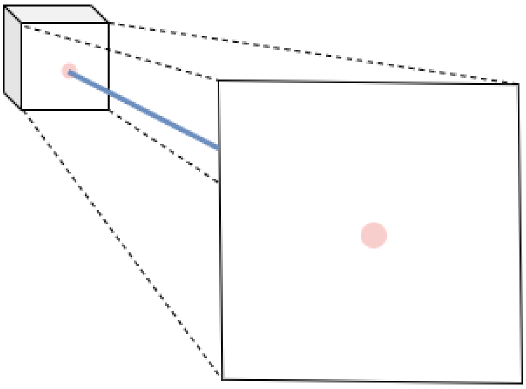

Figure 6.5: *Schematic of viewing pyramid*

It is important to note that the MLD can only properly be viewed by an observer placed perpendicular to the displays, and thus perpendicular to the glass on the protective casing. In Figure 6.5 this perpendicular line is displayed in blue. If the observer is placed above this perpendicular line, the observer will start to see items on the ceiling as they are not observing the virtual display anymore, rather they are just seeing an ordinary mirror. It is possible that the observer can see themselves if they move further above this perpendicular line.

If the observer is placed to far below this perpendicular line, they will start to see the display 2, which is mirrored and upside down, and will form a source of distraction from the image on the virtual display layers.

The viewing pyramid is restricted on both sides by the protective casing of the MLD, therefore if the observer moves to far laterally they will simply not see the items on the virtual display or display 1 anymore.

Conclusion

In Conclusion it can be said that it is possible to display the attitude indicator on a Multi Layered Display with the airplane symbol on the most foreground layer. The perceived depth in this case was measured to be either 1.6 cm or 2.1 cm in the medium MLD Depth and deepest MLD Depth respectively. However due to the introduction of this depth a few false cues are possible. If the two layers of the MLD are not properly aligned visually correctly, the attitude indicator will indicate a pitch up or down while this might not actually be the case, making it impossible for the pilot to have proper pitch control. Furthermore the pilot itself can induce false cues by moving their head up and down, which induces an apparent pitch change. In a Bank, any lateral head motion of the observer will also result in an apparent pitch up motion if the lateral head motion is made in the same direction as the bank direction. If this is to the opposite side then an apparent pitch down will be observed. Lastly it was concluded that it is only possible to correctly view the Multi Layered Display on a line perpendicular to the displays and only within the viewing pyramid. However if not viewed on the perpendicular line from the display, the attitude indicator will display the aforementioned false cues.

7

Experiment Design/Setup

In order to test the hypothesis that less roll reversal errors are made when an attitude indicator on a multi layered display is used, an experiment is to be performed on human subjects. This experiment was designed to measure the Roll Reversal Errors (RREs) from the interaction of the participants solely with the attitude indicator. The setup of this experiment will be presented in this chapter.

7.1. Participants

From previous studies it has been shown that RREs occur in both pilots and non pilots. It has also been shown that non-pilots make more RREs then pilots. As the current experiment will be a ground based experiment without expectation of bank angle, or spatial disorientation, it is necessary to have as many errors as possible to be able to investigate the effect that the Multi Layer Display has on the RREs. Therefore it has been chosen to conduct the experiment with 20 non-pilots.

It will be assumed that these non-pilots have either never seen an attitude indicator before, or that they might have some idea of how it works, therefore all the participants will be given the opportunity to get acquainted with the attitude indicator.

7.2. Experiment Briefing and Procedures

The experiment briefing provided to participants can be found in Appendix A. The participants were allotted time to completely read this briefing.

In this briefing, participants are told that the current study is intended to measure reaction time of pilots with this novel display. This is also verbally briefed to the participants and it is reiterated that a direct and natural response is required. This is done to illicit a natural response to the displayed attitude indicator instead of taking more time to observe the attitude indicator. Also, it is verbally briefed that the main task of the participant is to roll the wings level.

After this briefing the, the attitude indicator is displayed in both the Single Layer Mode and Multi Layer mode, and the features of the AI are explained while the participants are allowed to train a little bit in free flight with the attitude indicator. Here both the Pitch and Roll inputs are used and displayed. When the workings of the attitude indicator are clear, the participants are given ten practice runs both in the Single Layer Mode and the Multi Layer Mode. These practice runs are used to show the actual experiment run and to allow for the participants to get used to the timing and the required task. The required task will be presented in the following section.

7.3. Experiment Run

The primary task of the participant will be to roll the aircraft displayed on the attitude indicator to wings level as directly as possible. This will be the primary task for each run. A timeline of the experiment run can be seen in Figure 7.1

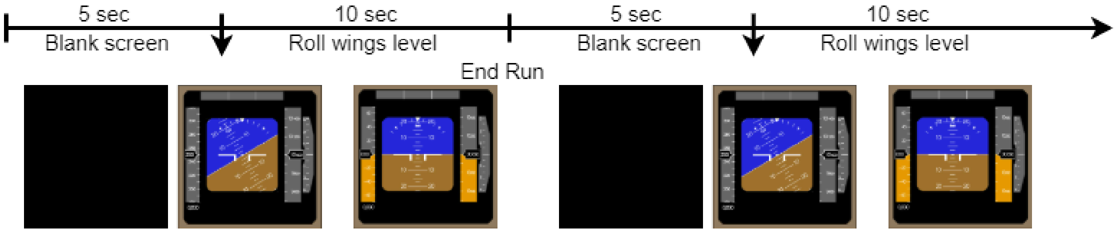

Figure 7.1: *Timeline of Two experiment Runs*

From Figure 7.1 it can be seen that each run starts with a five second period in which the display will be completely blank. This is to simulate a period of inattention or not observing the attitude indicator. During this period the aircraft model will be set to a turn with either $30°$ left or right. After the five seconds have passed, a PFD with the Attitude Indicator with a $30°$ bank angle is displayed in which the participants have to perform their primary task and roll the wings level. They have a total of ten seconds to complete this task. If done correctly the task will not take more then five seconds to get the airplane back to wings level. If a roll reversal error is made, this will take just a bit longer but this will never exceed seven to eight seconds, ten second is therefore more then enough to time complete the task. After this time the screen will again turn blank which signifies the beginning of the next experiment run. This will be done for a total of 30 runs per block. The direction to which the aircraft will be banked, either left or right, is randomised and is set so as to never be more then three times to the same direction to prevent an expectation of bank angle to be created.

In total each participant will perform four blocks of 30 experiment runs. Each block will either be done with either the display in Single Layer Mode or in the Multi Layer mode. The runs in both these modes will be exactly the same. The order, however, in which the displays mode will be presented is randomised per participant. These modes will always be alternating, therefore a participant will either have the blocks as Single - Dual - Single - Dual Mode or Dual - Single - Dual - Single Mode. After the second block of experiment runs, there is time for a break. The software that makes this experiment possible will be described in the following section.

7.4. Dueca Model

To create the software for the experiment runs and to control the Multi-Layered Display, the C++ Framework of the Delft University Environment for Communication and Activation (DUECA) was used. The simulation software was created from modules of DUECA, each of which has a specific function. The modular DUECA structure used for the current experiment was based on a previous study into the role expectation of bank angle plays into the misinterpretation of bank angle [2]. The current module structure can be seen in Appendix B.

There were a few changes needed to the modules and communication structure in order to create the required software for the experiment. The modules that had to be changed were the ”Vis-Model” Module and ”PFDB747” Modules. Furthermore the communication structure to trigger the PFD on and Off at the required interval had to be created and implemented. In the following paragraphs the changes made to these modules are presented.

Vis-Model Mudule

The Vis-Model Module was the module that originally conducted the experiment timing and the stepping through the aircraft model. The aircraft model and aircraft dynamics were placed in a different module named ”FEV-Module” and is based on a small single engine aircraft model. This model however, was set to be able to allow asymmetrical aileron deflections. This feature had to be removed. Furthermore this module needed to be changed to allow communication with the proper channels and reception of the input signal of the correct channels. The module ”osx-stick” was removed for Flexi-stick. The Vis-model module was therefore responsible for taking the stick inputs and stepping over the aircraft dynamics to produce a output. This output was then sent to the Model-output module, which was solely used for logging of the aircraft state. This structure was already working correctly in the Dueca-structure so it was opted to not alter this. The same inputs used for the model-output module were also sent to the ”PFDB747” Module. The vis-model module was also altered to recognise a Roll Reversal Error. This was done in such a way that as soon as the PFD with attitude indicator is displayed, and a control input was received to the opposite side of the bank angle displayed, an Error was recorded. This meant that in the post-processing the error threshold could be determined and changed as necessary.

PFDB747 Module
The ”PFDB747” Module had to be changed to allow two of the same module to be run at the same time, only one of the running modules was set to the ”foreground” mode and one was set to the ”background” mode. The current setup relied more heavily on the dueca.mod configuration file to select the mode in which the PFD and the Attitude indicator were displayed, which could be either the Single Layer Mode or the Multi Layer Mode. When the Single Layer mode was selected, only one PFDB747 module is created by DUECA. Furthermore, a few additional communication channels were needed to the PFDB747 modules to allow for them to be triggered at the same time when the simulation was in multi layered mode.
The apparatus used for the simulation input and output will be described in the following section

7.5. Apparatus

The experiment was conducted as a fixed base PC experiment without outside visuals and only the Attitude indicator.
To display the attitude indicator, both in the Single and Multi layer mode, the Multi-Layered Display presented in chapter 6 was used. A standard Delft University Desktop PC was used to run the simulation. For the stick input a standard Logitech Extreme 3D pro was used which can be seen in Figure 7.2. The maximum angular deflection of this joystick was measured to be $20°$. This input correspond with an input ”$u_x = 1$. This input was disabled during the time in which the screen was dark to prevent unwanted stick inputs. Therefore the aircraft on the attitude indicator was only controllable when an input was desired and thus only when the attitude indicator was displayed. Furthermore, during the actual test, any input on the pitch axis was ignored and only roll input was used. The experiment setup and apparatus can be seen in Figure 7.2

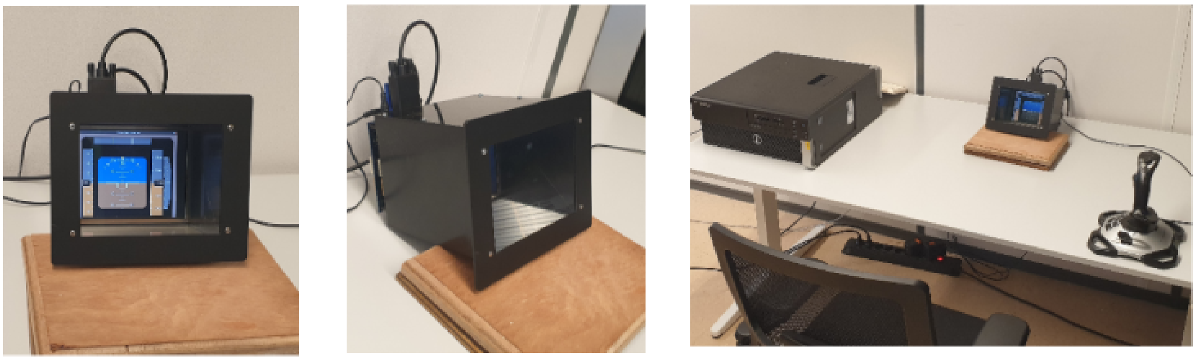

Figure 7.2: *Experiment Setup*

7.6. Data Logging and Dependent Measures

As mentioned previously, all data is gathered by the logger module which receives all data from the primary controls channel and model data that is sent to the PFD which contains the attitude indicator. In this module, all information sent over these channels is stored and written to a single Matlab file containing the parameter value for each simulation step. This was stored for each participant.
In this logger file the model parameters for pitch and bank are stored, also the control inputs for pitch and bank are stored. Furthermore it is also recorded when the PFD module receives an ”on” or ”off” trigger.
This data is used to create the following dependant measures:

- **Error Rate**: A roll reversal error is recorded when a control input is received to the opposite side of the displayed bank angle. The error rate is percentage of the total amount of runs in which an error is recorded.

- **Reaction Time**: this is the time since when the display is turned on, until the time at which the first control input was received. This ”display on time” is defined as the time at which an ”on” trigger was recorded.
- **Error Duration**: this is the total time in which an incorrect control input was given, based on the displayed bank angle. This is the time it takes for the participant to correct their error.
- **Max Deflection**: with this, it is meant when an error is recorded, the maximum stick input to the incorrect side is measured and recorded .
- **Max Bank Angle**: when an error is recorded, the maximum bank angle to the incorrect side is measured and recorded.

Next to these dependant measures all participants are asked to fill in a questionnaire in which they are asked about their general flight experience and a few questions on the Multi Layer Display, such as their perceived depth in distance.
The hypothesis that will be tested using the aforementioned dependent measures will be elaborated upon in the next section.

7.7. Hypothesis

The research question that is to be answered by this thesis investigates the effects of using a Multi Layer Display for an Attitude indicator on the roll reversal errors made. Based on the previous chapters, and from the dependant measures presented the following hypothesis will be tested:

Pilots will show a decrease in RRE with the Attitude indicator on the Multi Layered Display when compared to the conventional Single Layer Display

Due to a better separation of figure ground in the multi layered display, the horizon symbol will be better interpreted as being on the background and will be less likely confused with the airplane symbol. Also, due to the depth created, the airplane symbol will be pre-attentively processed again reducing the horizon error. Lastly, the horizon symbol will be moved to the ambient extrapersonal space which is used for self orientation. These factors were further elaborated upon in chapter 5.

Conclusion

From the current chapter it can be concluded that an experiment was designed in order to give answer to the research question and sub questions. This experiment will be conducted with 20 non-pilot participants. These participants will be briefed that the goal of the experiment is to measure reaction time using a novel display technique and that their primary goal is to roll the aircraft on the attitude indicator to wings level as directly as possible. They will first have the opportunity to practice with both the aircraft model and the actual experiment runs. Each experiment run consists of 5 seconds in a blank screen after which an attitude indicator is displayed with either a bank to the left or to the right of 30°. The software required for the experiment will be developed within the DUECA framework, and the apparatus required for the experiment will be a Multi Layered Display provided by TNO and a standard Logitech extreme 3-D pro. The data that will be gathered from the experiment will be used to measure error rate, reaction time, error duration, maximum deflection and maximum bank angle. This data will be used to test the hypothesis that participants will make less errors when using the multi layer mode compared to when using the single layer mode.

8

Conclusions

From the above report it can be concluded that over the years the aviation industry has identified a need to drive down the amount of accidents caused by Loss of Control In-flight by any means necessary. The large majority of LOC-I accident occur as a result of Spatial Disorientation (SD). Spatial Disorientation has been shown to cause the attitude indicator to be misinterpreted causing an incorrect pilot response to the given attitude indicator. This phenomenon is known as a Roll Reversal Error (RRE).

A lot of research has been conducted to investigate the occurrence of RREs as well as in the areas of attitude indicator design to prevent misinterpretation. From the studies on attitude indicator misinterpretation, it has been concluded that the horizon symbol is being confused with the airplane symbol. This is caused by the Gestalt law of figure ground separation, in which not enough separation is present in the conventional attitude indicator. The attitude indicator is of course the primary source of self-orientation for pilots. Depth perception plays an important role in human self-orientation.

Attitude indicator designers have previously used depth cues in the Attitude indicator, however physical depth has never been added and the effect of adding physical depth on roll reversal errors has never been studied. In the current study a Volumetric Display is used to create multiple display layers onto which information can be projected. This type of display is known as a Multi Layered Display (MLD). Display layering has been previously researched in the areas of information uptake as well as clutter prevention in which it was shown to increase information uptake as well as decrease clutter present on a screen. This display type has however never been used to create depth to improve human self-orientation, which leads to the following research question to be answered:

What are the effects of using a Multi Layer Display for an attitude indicator on the interpretation of the attitude indicator bank angle measured by roll reversal errors made?

It is first necessary to investigate if it is at all possible to display the attitude indicator on two discrete display layers and if this attitude indicator allows for enough distance to perceive a figure ground distinction. This usage of physical depth leads to a creation of figure ground separation of the horizon symbol and the airplane symbol. Furthermore it allows the airplane symbol to be pre-attentively processed. Also, the horizon symbol will be removed from the focal extrapersonal space to the ambient extrapersonal space which is the segment of 3D space used by the brain to perform self-orientation. The aforementioned aspects of adding depth to the attitude indicator brings forth the following hypothesis:

Pilots will show a decrease in RRE with the Attitude indicator on the Multi Layered Display when compared to the conventional Single Layer Display

To test the aforementioned Hypothesis an experiment was designed and presented in the above report, the results of which will be elaborated upon in the final research paper.

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A

Using a Multi Layer Display for the Attitude Indicator: Experiment Briefing

Dale-Allen Arrundell (4341120)
Delft, 11 November 2020

The primary goal of this document is to provide all the necessary information for participation in the preliminary study in using depth perception techniques in the Attitude Indicator (AI). This experiment is performed at the department of Control and Simulation of the Faculty of Aerospace Engineering of the Delft University of Technology. This document outlines the goal of the experiment, along with providing general information to the participant about the setup of the experiment and the task to be performed.

Experiment Goal

The primary goal of the experiment is to evaluate the usage of a novel representation of attitude information by displaying an attitude indicator on a Multi-Layered Display.

Experiment Task

The current experiment aims at measuring participant reaction time with solely the Attitude Indicator represented on a Multi-Layer Display. The scenario to be emulated is a short period of inattention to the attitude indicator followed by the sudden display of a banked attitude indicator. The primary task of the participant is to roll the aircraft to wings level as directly, smoothly and as soon as possible by observing the angle of the aircraft symbol with respect to the horizon. This will be done with the display in Single Layer Mode as well as in Multi Layer Mode.

Experiment Apparatus and procedures

The experiment will be conducted using a fixed base PC setup of an Attitude Indicator on a Multi-Layer display as displayed in Figure A.1. Whenever the attitude indicator is displayed it will be possible to provide roll inputs to the simulated aircraft via a Joystick located on the right hand side of the participant. Other inputs on the joystick axis are not necessary, and are not measured.

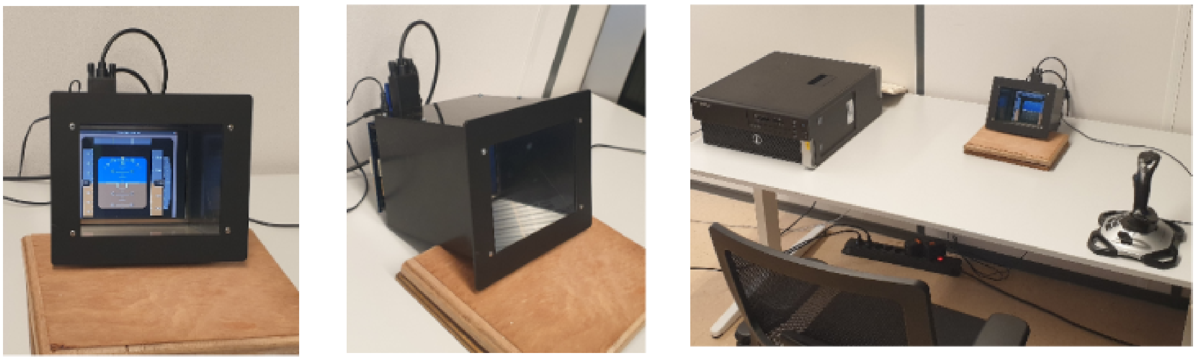


Figure A.1: *Setup of the preliminary experiment*

Before the actual experiment, it will be possible to practice the control feel of the aircraft model, which simulates a single engine piston aircraft. Furthermore a series of 10 practice experiment runs will be provided to demonstrate what the experiment runs will look like and to practice the appropriate responses.
In summary:

1. Look down at the Attitude Indicator
2. As soon as the attitude indicator is displayed, use the joystick to roll the wings level as quickly as possible
3. Try to improve your response time!

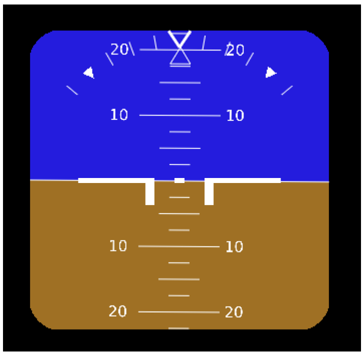


Figure A.2: *Attitude indicator in Straight and Level flight*

Participant Rights

Participation in this experiment is completely voluntary meaning that participants can decide to stop the experiment at any given time.
Furthermore the data to be collected during this experiment will remain confidential and anonymous and will be treated as such that only the experimenter can link the results to a particular participant. This means that none of the results can ever be traced back to you or any other participant. By participating in this experiment you agree that this anonymous data may be published by the experimenter.
Finally, we ask of you not to discuss any further details of the experiment with anyone or any other participant until the complete experiment is completed. This is done to prevent participant bias.
The participant is asked to sign an informed consent form at the end of the experiment briefing to assure the understanding of all the above presented information.

B

DUECA Model overview

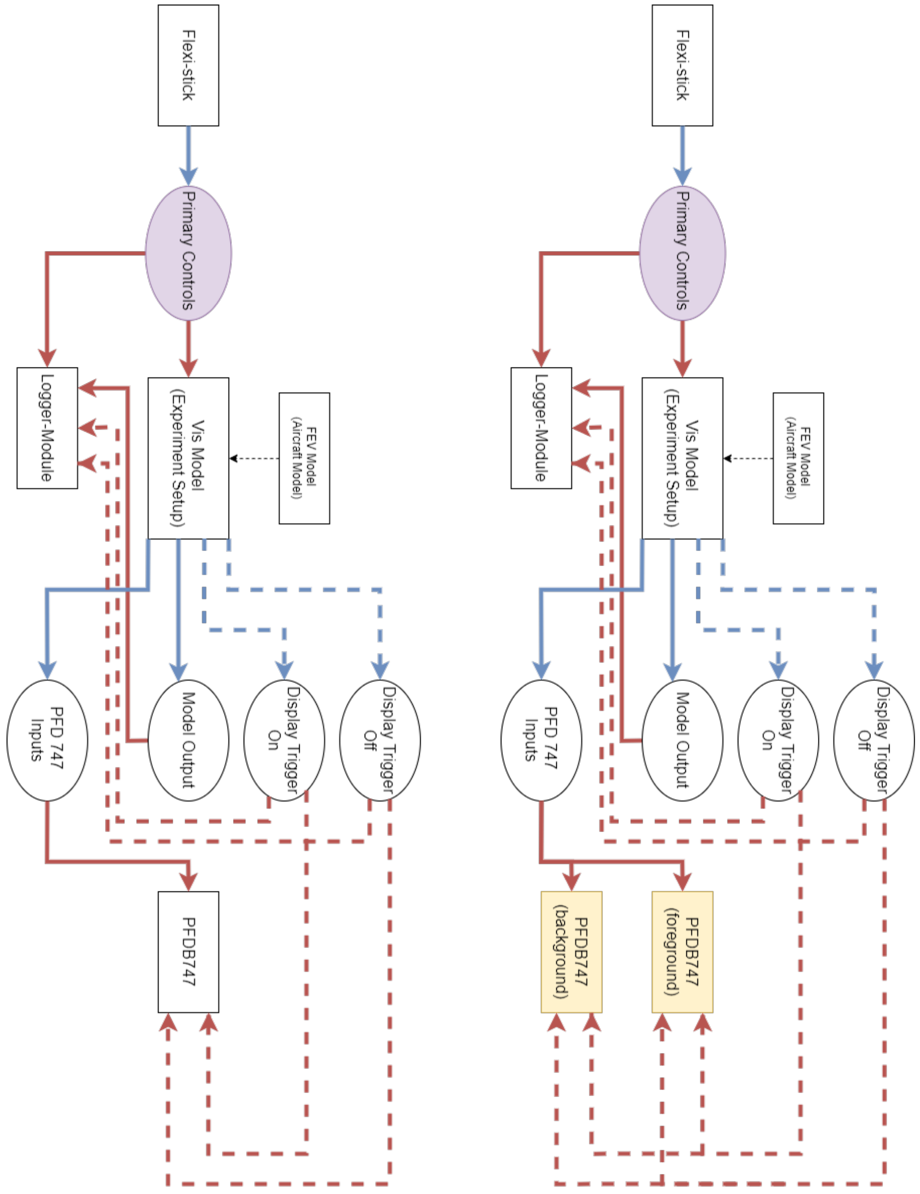


Figure B.1: *Structure of Dueca model in the Single Layer Mode (L) and Multi Layer Display Mode (R)*

C

Participant Informed Consent

Consent Form for Multi-Layer Display in Attitude Indicators

Researcher: **D.A. (Dale-Allen) Arrundell**
Title of research: **Multi-Layer Display usage in Attitude Indicators**
Responsible professor: **Prof. Dr. Ir. M. Mulder**

Please tick the appropriate boxes	**Yes**	**No**
I have read and understood the experiment briefing presented by the researcher dated 30-07-2020, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent to voluntarily being a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	○	○
I understand that taking part in the study involves doing a primary task to roll the aircraft straight and level and that I also have a secondary task to perform.	○	○
I understand that the data that I provide will be used for scientific reports and or publications and that the researcher will not identify me by name in any report or publication that will result from this experiment and that my confidentiality as a participant in this study remains secure.	○	○
I confirm that the researcher has provided me with a detailed safety and operational instructions for the Simona Research Simulator	○	○
I confirm that the researcher has provided me with detailed safety briefing and operational instructions to guarantee that the experiment can be performed in line with the current RIVM COVID-19 guidelines and that I have understood these instructions, and that this experiment shall at all times follow the RIVM guidelines	○	○
I understand that this research study has been reviewed and approved by the TU Delft Human Research Ethics Committee (HREC). I am aware that I can report any problems regarding my participation in the experiment to the researchers using the contact information below or, if necessary, the TU Delft HREC(hrec@tudelft.nl).	○	○

Signatures

______________________ ______________________ ________

Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

_________________________ ___________________ ________

Researcher name Signature Date

Study contact details for further information: Dale-Allen Arrundell, +31640278333
darrundell@student.tudelft.nl

III

Appendices to the thesis paper

Note:
This part corresponds to the Thesis paper and is still to be graded.

D

Post-processing and Run verification procedure

In this appendix the general post processing procedure will be elaborated upon, together with a general description of how the verification of RREs was performed. This was done to ensure that all runs that were marked as containing an error, actually contained an error and that the runs not containing an error did in fact not contain an error.

As stated in chapter 7, all of the Data logging was performed by the logger-module in the DUECA project. However the logger-module and vis-model module were setup to make the post-processing easier, and by performing a few initial post-processing tasks directly during the experiment. The vis-module was set up in such a way that, when the display on trigger was sent, the module would compare the bank angle of the aircraft module to the first control input recorded. If this input was to the other direction then required to bring the aircraft to straight and level, a RRE was recorded by the logger-module by means of an event. Furthermore, the time to first input was also measured by the vis-model module and sent to the logger-module as the reaction time.

The logger-module created a large post-processing .txt file for each experiment block that contained all the aircraft model data, including the parameters that were not necessary for the experiment such as pitch and yaw etc. This .txt file also included the three major parameters required to form the dependant variables, which were Sim time, model bank angle (ϕ) and control input received on the roll axis (u_x).

A Matlab script was then created to extract the dependant variables from this data, which included the reaction time per run, maximum stick deflection and bank angle if an error was observed and error duration. This was done per run, resulting in all the parameter data being summarised in one single row per run containing all the dependant variables for that run. All these runs were stored in Excel for all the participant together as well as per participant.

This per-run data was then, again, used in a Matlab script to obtain the overview of all runs and to obtain the dependant variables per participant which could be used in IBM SPSS to perform the statistical analysis outlined in the research paper.

All these runs had to be verified before usage. With this it is meant that all the runs that were flagged by the DUECA code or Matlab as having an RRE did in fact contain a RRE, and the runs that were discarted as not having an RRE did in fact not contain a RRE. During this process a few abnormalities were discovered which lead to the data form those specific runs to be unusable.

In general these unusable runs were due to very small erroneous inputs from the joystick. Three examples of such discovered abnormalities are discussed below, and a graph of corresponding parameters was created to illustrate each case.

Case 1: Experiment run Flagged as Error but does not contain error
This case can be seen in Figure D.1. In this scenario, a very small input u_x is observed after the display on trigger is received, because before this time the inputs are not fed through to the aircraft model or compared to determine the presence of a RRE. It should be noted that the observed inputs are extremely small but sometimes were just higher then the threshold for inputs to be considered an error ($u_x = 0.075$). From Figure D.1 it can be seen that if the initial input direction of this small input is to the opposite side, this run will be flagged as ”containing an error”. However, the actual input, which is signified by a continuous increase to max deflection, is in the correct direction. This run therefore, does not contain an error, but will be flagged by the DUECA module. In the post processing if such small erratic inputs are found in runs that are flagged as error, the run is removed from the run overviews and as such the reaction time is not used for further analysis.

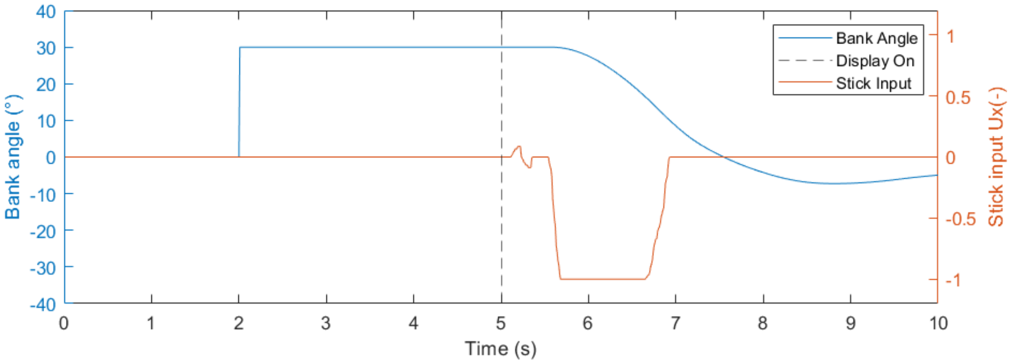


Figure D.1: *Visualisation of Output of Case 1: Experiment flagged as error but does not contain error*

Case 2: Experiment run not flagged as error but does contain error
The opposite scenario of scenario 1 can be seen in Figure D.2. In this scenario again a small input on the controls is observed right after the display on trigger. In this scenario however, the initial direction of that small input is to the correct side, meaning that the run will not be flagged as containing an RRE, however the actual input does shows an error when the actual control input is observed.

In the case of these runs, when an actual error was observed these runs would be manually flagged as containing an error in the first part of post processing, however the reaction time was not used for analysis but the other parameters are.

This scenario was however very rare, because in general the occurrence of such small noisy control inputs were rare and did not occur often, meaning in less then 0.5% of the total runs. This meant that those specific runs could manually be checked for the actual control input when such a small input was noticed followed by a normal control input signified by a continuous increasing control input.

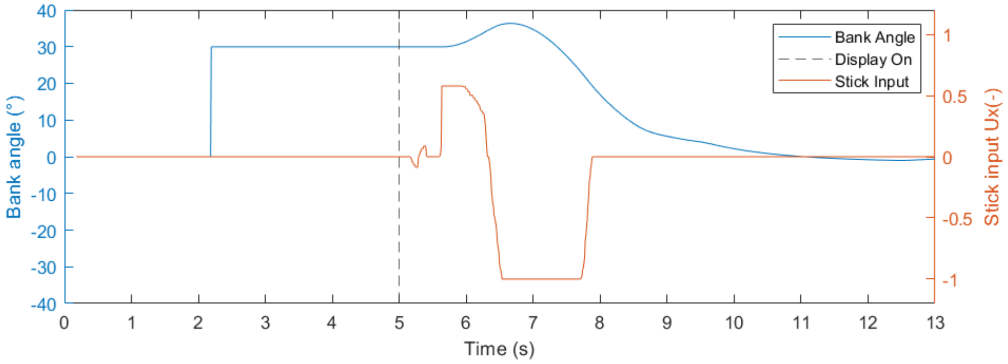


Figure D.2: *Visualisation of Output of Case 2: Experiment run not flagged as error but does contain error*

Case 3: Participant Initial Reaction was to the correct side

The third case that was considered during verification of the runs, was that it should also be investigated if the actual participant input was first to the correct direction, but then a clear switch over to the incorrect input. This run would not be flagged as an error, however, this run signifies a misinterpretation of the attitude indicator and therefore should be flagged as an error. A visualisation of this case can be seen in Figure D.3.

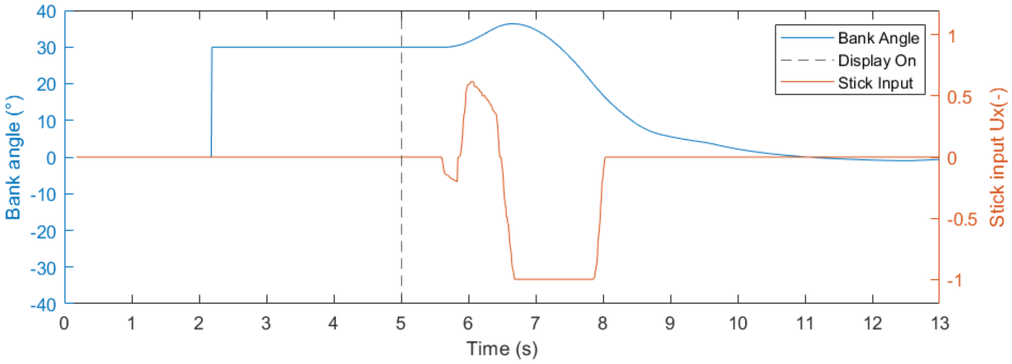


Figure D.3: *Visualisation of Output of Case 3: Participant initial reaction is to the correct side followed by a RRE*

The data for input on the previous visualisations was manufactured in order to make clear what was actually happening, but the noisy inputs were not as large or as long. An actual participant example is displayed in Figure D.4 and Figure D.5 for cases 1 and 3 respectively.

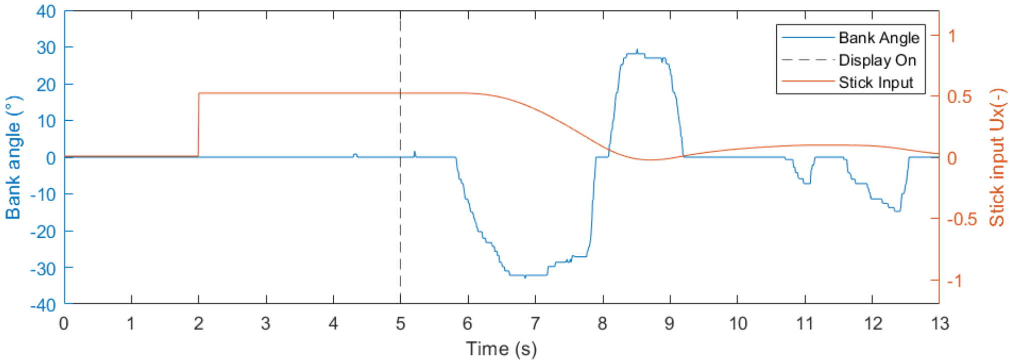


Figure D.4: *Actual example output of Case 3: Participant initial reaction is to the correct side followed by a RRE*

From this example in Figure D.4 it can be seen that the first single blip input happened before the display on trigger, which for our verification method does not matter but the second blip occurs right after the display on trigger. In this case that is to the opposite side then the required input, while the actual participant input is correct. After the initial input, the rest of the input can be seen which is used by the participant to get the aircraft back to wings level.

This can also be seen in the example output of case 3, where the initial input is to the correct side, and followed by an incorrect input. Also the final control inputs of the participants are seen to level out the wings.

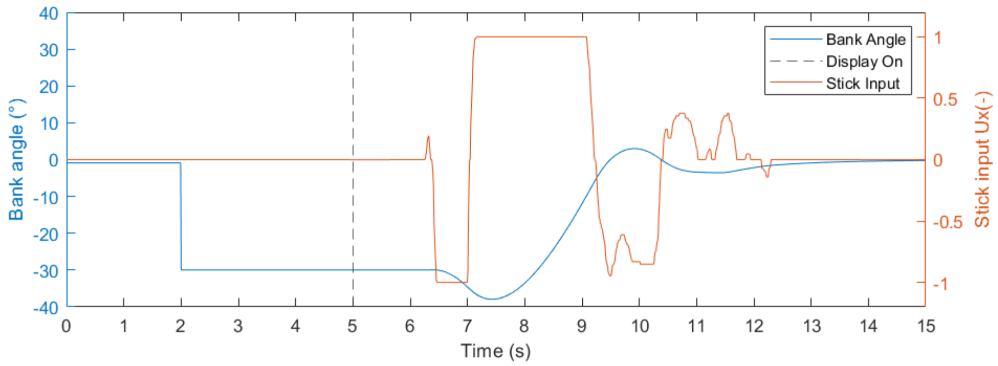


Figure D.5: *Actual example output of Case 3: Participant initial reaction is to the correct side followed by a RRE*

Case 4: Small non-zero participant input when display is triggered on Lastly it was also noticed that sometimes the participants did not hold the stick centred when the display was turned on. This meant that if the participant would be holding the stick to the incorrect direction when the display on trigger was sent, this would automatically result in that run being flagged as an error, while the actual input might not actually contain an error. The used joystick did have a spring meaning that this scenario also did not occur often. This would then result in a reaction time of 0.02 seconds as the first input would be immediately after the display on trigger. All these runs were also manually investigated and removed from the reaction time data set. An actual example output of this case can be seen in Figure D.6

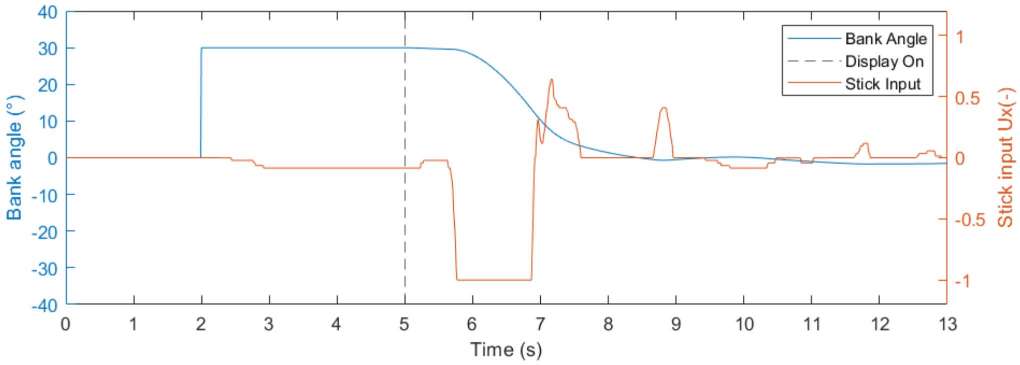


Figure D.6: *Actual example output of Case 4: Small non-zero input when display is triggered on*

So in summary during verification of the runs, four cases were identified which needed to be corrected for

- Case 1: is when an experiment run was flagged as containing an RRE but it did not contain an RRE due to a small noise input on the control.
- Case 2: is when an experiment run was not flagged as containing an error but it did contain an error .
- Case 3: is when a participants initial reaction was to the correct side followed by a misinterpretation.
- Case 4: is when a small non-zero participant input was received when the display is triggered on.

During verification all these cases were investigated for all runs, and it was found that for experiment 1 (non-pilots) contained 29 runs (1.05%) and for experiment 2 (pilots) contained 20 runs (0.95%) with any one of the aforementioned four cases. With this small percentage of faulty runs, many of them were investigated manually to see if they did in fact contain an error, and the reaction time in those runs were excluded from the final data set.

E

Extended Results: Experiment 1 (non-pilots)

This appendix contains the extended results of the post-processing of the data of Experiment 1, which was done with non-pilots. The boxplots of the relevant data is presented here to form a more thorough understanding of all parameters. An overview of the observed dependent variables per participant can be seen in Table E.1

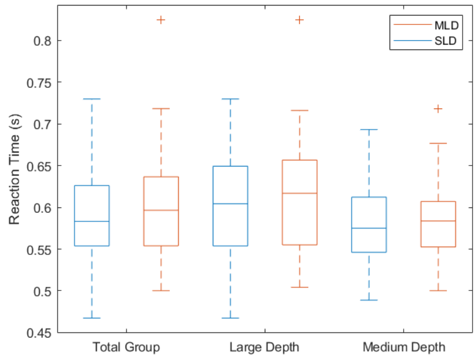


Figure E.1: *Observed reaction time for the total group as well as for the Large and Medium group*

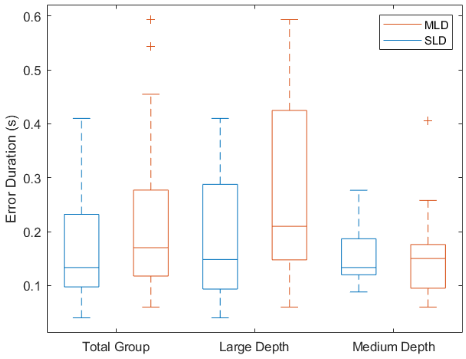


Figure E.2: *Observed error duration*

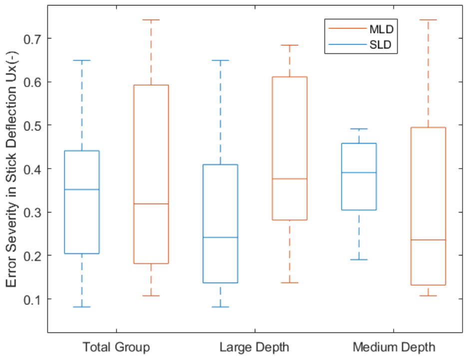


Figure E.3: *Error severity expressed in maximum stick deflection U_x note: all errors with $u_x \leq 0.075$ are removed*

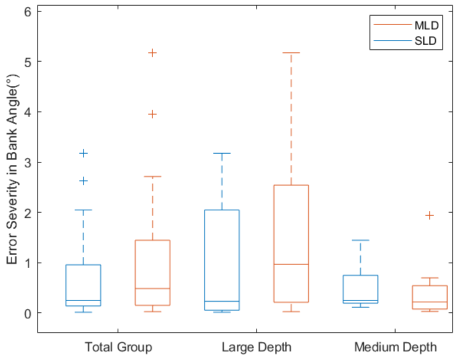


Figure E.4: *Observed error severity expressed in bank angle in degrees*

Table E.1: *Overview of all Dependent Variables: Experiment 1 (Non-Pilots)*

Participant #	MLD Depth	Errors SLD	Errors MLD	Error Rate SLD [%]	Error Rate MLD [%]	Total Error [%]	Reaction Time SLD [s]	Reaction Time MLD [s]	Error Severity Bank SLD [°]	Error Severity Bank MLD [°]	Error Severity Stick Deflection SLD [-]	Error Severity Stick Deflection MLD [-]	Error Duration SLD [s]	Error Duration MLD [s]
1	Large	2	7	1.667	11.667	6.667	0.628	0.663	0.014	1.281	0.08	0.68	0.04	0.23
2	Large	2	4	1.667	6.667	4.167	0.607	0.633	0.054	2.714	0.11	0.63	0.1	0.33
3	Large	8	5	5	3.333	4.167	0.657	0.638	0.303	0.209	0.22	0.28	0.2	0.17
4	Large	9	5	15	6.667	10.84	0.467	0.504	0.198	0.227	0.41	0.58	0.09	0.09
5	Large	3	3	3.333	3.333	3.333	0.583	0.617	0.053	0.156	0.16	0.3	0.1	0.14
6	Large	8	3	10	3.333	6.6665	0.491	0.504	0.100	0.026	0.27	0.14	0.09	0.06
7	Large	10	4	15	6.667	10.84	0.604	0.614	2.048	0.969	0.65	0.62	0.29	0.21
8	Large	7	7	10	10	10	0.552	0.550	2.635	2.027	0.63	0.34	0.36	0.18
9	Large	5	4	5	5	5	0.727	0.716	0.266	5.174	0.14	0.58	0.22	0.59
10	Large	20	16	26.667	21.667	24.167	0.559	0.570	3.177	3.958	0.35	0.38	0.41	0.54
11	Large	0	3	0	3.333	1.667	0.730	0.825	-	0.896	-	0.27	-	0.45
12	Medium	4	5	6.667	8.333	7.5	0.529	0.540	1.166	1.939	0.39	0.74	0.25	0.26
13	Medium	5	5	6.667	8.333	7.5	0.489	0.500	0.244	0.700	0.48	0.7	0.12	0.18
14	Medium	2	1	3.333	0	1.667	0.621	0.615	0.749	-	0.49	-	0.17	-
15	Medium	3	3	3.333	3.333	3.333	0.569	0.569	0.195	0.078	0.29	0.2	0.12	0.1
16	Medium	2	2	1.667	1.667	1.667	0.576	0.597	0.162	0.172	0.3	0.28	0.13	0.15
17	Medium	7	1	10	1.667	5.84	0.574	0.571	1.447	0.038	0.42	0.11	0.28	0.08
18	Medium	6	4	8.333	1.667	5	0.564	0.566	0.115	0.031	0.19	0.14	0.09	0.06
19	Medium	0	2	0	3.333	1.667	0.658	0.677	-	0.486	-	0.13	-	0.41
20	Medium	3	1	5	0	2.5	0.604	0.597	0.196	-	0.35	-	0.14	-
21	Medium	7	9	10	13.333	11.6665	0.593	0.599	0.745	0.543	0.46	0.32	0.19	0.16
22	Medium	0	1	0	1.667	0.83	0.693	0.718	-	0.143	-	0.13	-	0.15
23	Medium	14	11	21.667	13.333	17.5	0.507	0.504	0.254	0.267	0.39	0.49	0.12	0.13

F

Extended Results: Experiment 2 (Pilots)

This appendix contains the extended results of the post-processing of the data of Experiment 2, which was done with pilots. The boxplots of the relevant data is presented here to form a more thorough understanding of all parameters. An overview of the observed dependent variables per participant can be seen in Table F.1

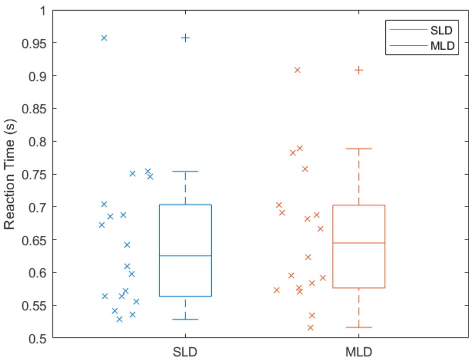


Figure F.1: *Observed reaction time for both display types*

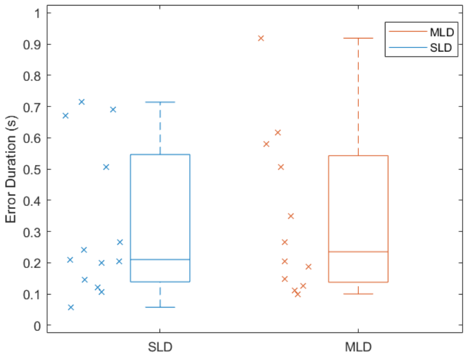


Figure F.2: *Observed error duration*

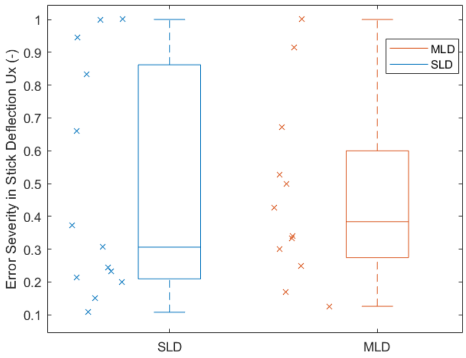


Figure F.3: *Error severity expressed in maximum stick deflection U_x note: all errors with $u_x \leq 0.075$ are removed*

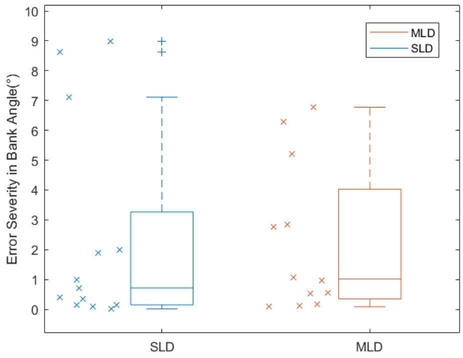


Figure F.4: *Observed error severity expressed in bank angle in degrees*

Table F.1: *Overview of all Dependent Variables: Experiment 2 (Pilots)*

Participant #	Errors SLD	Errors MLD	Error Rate SLD [%]	Error Rate MLD [%]	Error Rate Total [%]	Reaction Time SLD [s]	Reaction Time MLD [s]	Error Severity Bank SLD [°]	Error Severity Bank MLD [°]	Error Severity Stick Deflection SLD [-]	Error Severity Stick Deflection MLD [-]	Error Duration SLD [s]	Error Duration MLD [s]	RSME SLD	RSME MLD
1	9	6	15	10	12.5	0.542	0.595	1.985	2.839	0.66	0.67	0.27	0.35	37	26
2	4	3	6.667	5	5.8335	0.563	0.583	0.015	1.073	0.11	0.5	0.06	0.19	57	57
3	0	1	0	1.667	0.8335	0.754	0.757	-	0.086	-	0.13	-	0.11	37	26
4	0	0	0	0	0	0.535	0.534	-	-	-	-	-	-	34	20
5	1	0	1.667	0	0.8335	0.687	0.667	7.114	-	0.83	-	0.67	-	37	37
6	2	0	3.333	0	1.6665	0.598	0.591	0.347	-	0.21	-	0.2	-	2	2
7	0	2	0	3.333	1.6665	0.642	0.691	-	0.964	-	0.25	-	0.27	11	37
8	2	2	3.333	3.333	3.333	0.751	0.702	0.410	2.763	0.2	0.43	0.2	0.51	33	33
9	2	0	3.333	0	1.6665	0.609	0.623	0.152	-	0.25	-	0.15	-	60	53
10	3	3	5	5	5	0.556	0.573	0.141	0.111	0.15	0.17	0.12	0.13	26	20
11	1	6	1.667	10	5.8335	0.572	0.571	0.995	0.523	1	0.53	0.21	0.15	24	24
12	4	2	6.667	3.333	5	0.746	0.789	0.719	0.543	0.37	0.34	0.24	0.21	26	13
13	0	1	0	1.667	0.8335	0.685	0.687	-	6.294	-	1	-	0.58	26	26
14	2	7	3.333	11.667	7.5	0.958	0.908	1.897	5.214	0.23	0.3	0.51	0.92	37	34
15	5	0	8.333	0	4.1665	0.703	0.782	8.626	-	1	-	0.69	-	45	37
16	14	10	23.333	16.667	20	0.673	0.681	8.983	6.776	0.94	0.91	0.71	0.62	2	2
17	2	4	3.333	6.667	5	0.528	0.516	0.096	0.176	0.31	0.33	0.11	0.1	25	20
18	0	0	0	0	0	0.563	0.576	-	-	-	-	-	-	37	37

G

Participant Questionnaire and Rating Scale Mental Effort (RSME)

The following post-experiment questionnaire was presented to the participants after the experiment was performed. Before the experiment the participant had to sign the informed consent form and provide their basic information such as gender, age, their general experience with the attitude indicator and their general flight experience. With pilots this is meant with the licenses they hold and the amount of flight hours and instrument hours they have. For the non-pilots it is what experience they have with aviation.

Also between the experiment blocks, between the two display types, the participants were asked to rate their mentor effort on the Rating Scale Mental Effort, which is also presented in this appendix.

Post experiment questionnaire

In the Multi-Layer Mode did you perceive the horizon as being at a different depth than the aircraft symbol

Yes ○ ○ No

If Yes, how much approximate distance did you perceive with the multi-layer mode? (in cm?)

______ cm

In general, how easy-to-understand does the attitude indicator show the aircraft's bank angle in the Multi-Layer Mode?

	1	2	3	4	5	
Very Easy	○	○	○	○	○	Very Hard

Was this roll angle easier to interpret in the Dual Layer Mode compared to the Single layer Mode?

	1	2	3	4	5	
Much Easier	○	○	○	○	○	Much harder

Did you have a response strategy to perform this task?

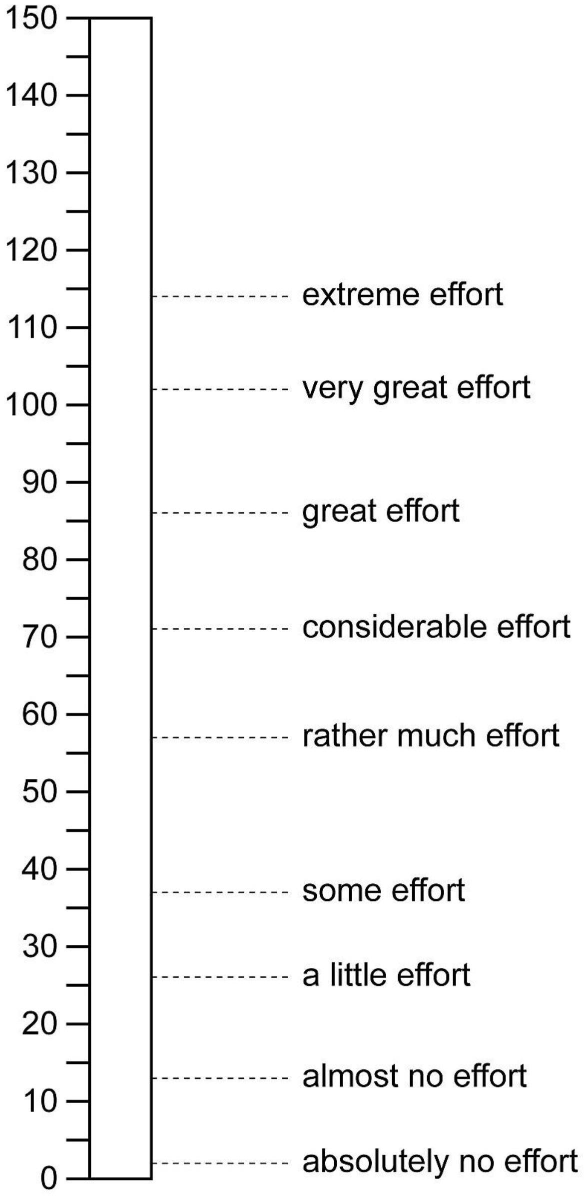
Yes ○ ○ No

If yes, please elaborate on your response strategy used:

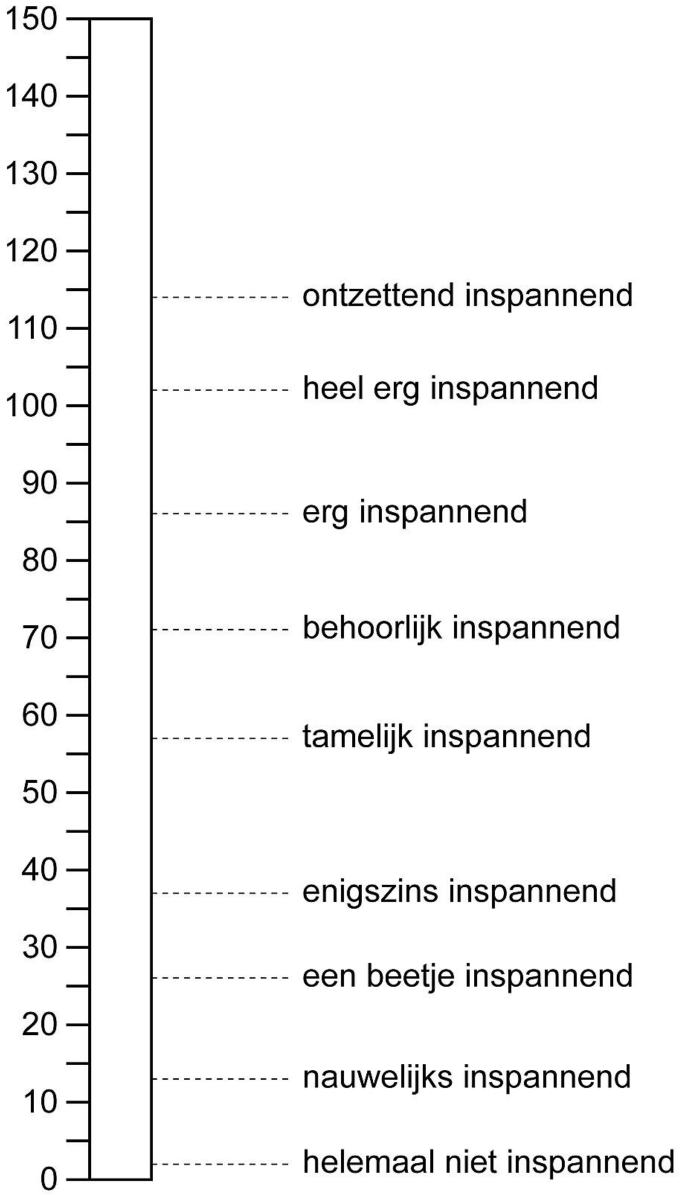
Do you have any other comments on the usage of such a display on an attitude indicator?

Rating Scale Mental Effort in English and in Dutch

“Please indicate, by clicking the mouse on the vertical axis below, how much effort it took for you to complete the task you’ve just finished.”



“Hoe inspannend vond je deze taak? Geef dit aan door te klikken in onderstaande schaal.”



Hierbij gaat het om hoeveel je je moest concentreren en hoe mentaal zwaar de taak is.