European Rotorcraft Forum

VISUAL-VESTIBULAR MOTION CUEING ASSESSMENT IN MARITIME ROTORCRAFT FLIGHT SIMULATORS

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Abstract
Confidence in the Modelling and Simulation (M&S) tools used in flight simulators depends upon the identification of the fidelity requirements for a particular application. The critical M&S elements integrated into the helicopter-ship dynamic interface simulation environment are motion and visual cueing, the flight dynamics model, unsteady ship's airwake and deck motion. The paper reports the results of a piloted flight simulation experiment conducted in a full-motion simulator, to study the effects of varying the visual and vestibular motion cueing fidelity on the pilot's perception, task performance and workload. Three different motion tuning sets were tested in three visual cueing scenarios for a representative SH-60B 'Seahawk' helicopter landing on a naval single-spot destroyer at different wind and sea-state conditions. It was found that when high-fidelity vestibular motion was provided to the pilot, the dependency on the visuals to capture aircraft state information was reduced. Similarly, when the high-fidelity visual cueing was provided, the pilot perceived balanced and synchronised overall motion cues leading to reduced workload and improved task performance. Moreover, the individual and combined effect of visual-vestibular fidelity was found to be more noticeable at higher wind and sea conditions, for which an 'Optimised' vestibular motion tuning set and a High Visual Cueing scenario combination was obtained, this led to reduced pilot workload and improved simulated maritime helicopter operational capability.

1. INTRODUCTION

There are several factors which increase the difficulty of operating helicopters to and from naval ships, particularly in adverse weather, such as the combination of a confined ship deck landing space, together with irregular ship motion, rain and/or sea spray and the unsteady airflow over and around the ship's deck and superstructure known as the 'air-wake'. Together, these elements form the Helicopter Ship Dynamic Interface (HSDI) environment, which can produce a high risk and operational demand on the helicopter, ship and crew [1]. In HSDI operations, the airwake creates unsteady aerodynamic forces which act upon the helicopter and which the pilot needs to compensate for in order to successfully perform the required landing task. To determine the safe operating limits for helicopter operations to/from ships, Ship Helicopter Operating Limits (SHOLs) are constructed, normally through First of Class Flight Trials (FOCFTs). The SHOL represents the safe conditions for launch and recovery operations [2].

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FOCFTs are performed at sea and are inevitably very expensive, time-consuming and safety critical, and often the required wind and sea conditions may not be available, resulting in the development of a restrictive SHOL. Therefore, Modelling and Simulation (M&S) tools are being developed and utilised in flight simulators to create and better understand the complex interaction between the helicopter and the ship within different HSDI environments, prior to the FOCFTs [3-6]. However, despite their utility, flight simulators still possess limitations such as the fidelity of visual and vestibular cues, flight models and the integration of the unsteady ship airwake into the flight control loop (Figure 1). Attempts have been made to assess the fidelity of the rotorcraft simulators [5], however, a standardised guideline to assess and optimise the overall simulation fidelity is a challenge which is yet to be fully addressed [7].

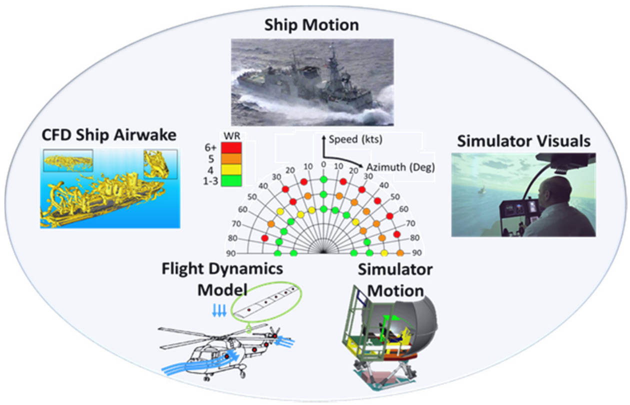

Figure 1: HSDI modelling and simulation elements

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, September 17-20, 2019.

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Over the past few years, flight simulators have been increasingly utilised to better understand the complex interaction between helicopter and ship within the challenging HSDI environment, and for deriving helicopter/ship operational guidelines and constructing preliminary simulated SHOL envelopes [8-12]. The aim has been to offer a wide range of benefits to the at-sea SHOL development process by testing various HSDI scenarios and environmental conditions repeatedly with a range of pilots, prior to the FOCFTs. A notable milestone in the use of M&S in maritime aircraft clearance trials was the use of piloted flight simulation in preparation for the F-35B Lightning II FOCFTs on the UK's new aircraft carrier, HMS Queen Elizabeth [13]. To emulate this success, it would be desirable to have M&S tools that can inform helicopter-ship FOCFTs; the development of such a toolset is the theme of this paper.

Helicopter-ship research undertaken at the University of Liverpool (UoL) Flight Science and Technology (FS&T) research group has examined the effect of motion, visual and airwake fidelity on overall simulation fidelity, pilot workload, task performance and subjective assessment [6-11], using a full-motion flight simulator, HELIFLIGHT-R (Figure 2) [7]. FS&T has been at the forefront of academic research to develop high-fidelity HSDI simulation environments since 2003 [3, 12-15], including efforts to quantify the overall fidelity of rotorcraft simulations [16, 17] for use in design, development, training and qualification.

Figure 2: UoL's HELIFLIGHT-R simulator (foreground)

The research presented in this paper is part of a longer-term project being carried out at the UoL, jointly funded by QinetiQ and Dstl, which is undertaking a structured examination, analysis and improvement of the M&S elements, i.e. the visual and motion cues, vehicle modelling and the airwake integration into the HSDI simulation. The overall aim of the research is to develop a new robust simulation fidelity matrix which will help to define the requirements for components of HSDI simulation that are needed to inform the 'real-world' SHOL trials. Previous research has been conducted by the authors to examine the fidelity requirements for vestibular motion cues in maritime rotorcraft flight simulators [8, 10]. Results were reported on the optimisation of motion drive laws considering vestibular cueing only, whilst the visual cueing fidelity/ scenario remained constant.

This paper extends the previous work by developing a range of different visual cueing scenarios which have been examined alongside different vestibular motion configurations. Results are presented on the effects of the variation in the visual and vestibular cues on the simulator pilot's perception of overall motion fidelity, task performance and workload. Moreover, the coherence, interaction and sensitivity between visual-vestibular motion cueing fidelity in various HSDI conditions are analysed and reported.

2. HELIFLIGHT-R MOTION AND VISUAL SYSTEM: PRINCIPLES AND IMPORTANCE

Motion cues in flight simulators are perceived from visual information projected onto the human eye (i.e. vection), from a simulator's movement detected by the vestibular system present in the human ear (i.e. vestibular cues) and somatosensory receptors consisting of tactile and proprioceptive senses used to sense the change of forces on the body and relative body parts position [18]. Vection depends on the fidelity of the visual cues (i.e. scene content, resolution, field of view, and texture) which help the pilot to perceive their position/orientation in relation to the outside world. The inertial motion of the simulator is calculated by a Motion Drive Algorithm (MDA) and provided by the simulator hexapod system, which can be tuned based on the specification of MDA washout filters. Both cues, visual and vestibular, play an important role in contributing to the overall perceptual fidelity of the flight simulator, especially in the highly dynamic HSDI environment where the pilot requires feedback of the disturbance from the external factors for successful task performance. Motion cues obtained from the simulator platform's physical movement should be in harmony with the motion cues obtained from the visual projection system. Poor synchronisation of the optical flow and inertial motion response can result in inaccurate visual and/or vestibular motion cues, leading to imbalanced self-motion perception and task performance [19].

Figure 3 shows the response of the visual and vestibular motion perception systems to an angular velocity stimulus. The visual system exhibits a low-pass response and, when suddenly exposed to a

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rotating scene without vestibular cues, a pilot may initially misperceive their position as stationary and the visual scene to be rotating. A change of sensation from outside world motion to self-motion occurs after a delay of around 2 seconds and gradually builds [20-22]. The vestibular system, on the other hand, responds quickly to the motion onset, exhibiting high-pass characteristics, and then the response decays once the input angular rate is constant. The visual cues are dominant in the perception of low-frequency motion response below 0.1Hz whilst the vestibular is dominant when high-frequency motion is encountered [23]. In the real world, visual-vestibular information is normally harmonised and together form a coherent perception of motion.

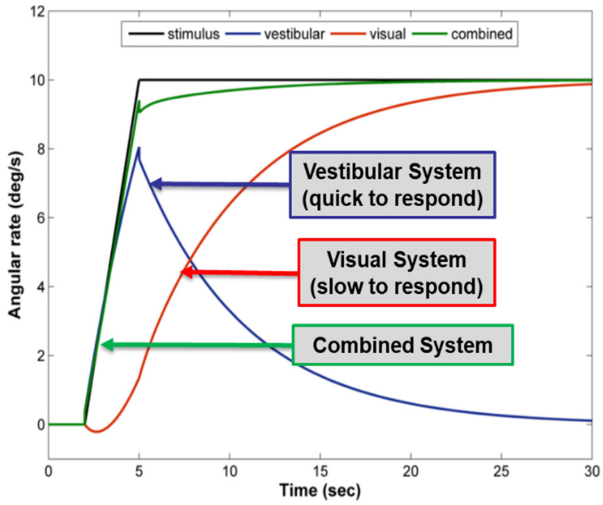

Figure 3: Motion perception response to angular rate stimulus [20]

2.1. Motion Cueing System

Motion platform demands of the flight simulator are produced by the MDA, which typically contain washout filters that tailor the simulator's motion response to provide a return to neutral capability. There are three main types of MDAs used in simulators: classical motion cueing washout algorithm, adaptive washout algorithm and optimal higher order motion drive algorithm. The most commonly used MDA is the Classical Washout Algorithm (CWA) proposed by Reid and Nahon [24], shown in Figure 4. The CWA allows easy analysis of the filter settings and its response due to its linear filtering technique [25] and has been shown to achieve reasonably good results compared with the other two MDAs [26].

The CWA obtains aircraft body states data (specific forces and angular rates) from the flight model and attenuates it to produce simulator motion demands which are then sent to the motion platform actuators.

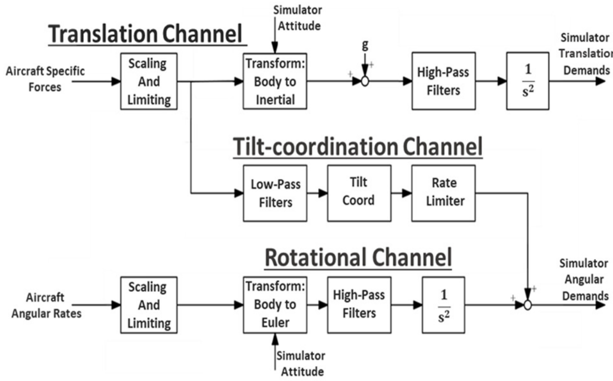

Figure 4: Classical Washout Algorithm

A CWA consists of three channels: translational, rotational and tilt-coordination. Translational and rotational channels each contain three high-pass (HP) washout filters and the tilt-coordination channel contains two low-pass (LP) washout filters. The quantity and quality of the motion attenuation depends upon the tuning of the HP and LP filter coefficients, i.e. gains 'k' and washout or break frequencies 'ω_n', which alter the motion base's response, hence changing the overall behaviour of the motion platform [25]. The combination of these coefficients in all six axes within all three channels forms a Motion Tuning Set (MTS). The specific configuration of the HELIFLIGHT-R CWA can be found in [10].

2.2. Visual Cueing System

HELIFLIGHT-R consists of a 12ft diameter visual dome mounted on a 6-DOF short stroke (24in) Moog hexapod motion system. The simulator incorporates a direct projection system using three high-resolution WQXGA 2560x1600 projectors with a frame rate of 120Hz, providing a horizontal and vertical field of view of 220° and 70°, respectively, Figure 5. VIOSO software is used to warp and blend the three displays using NVIDIA's Mosaic Technology.

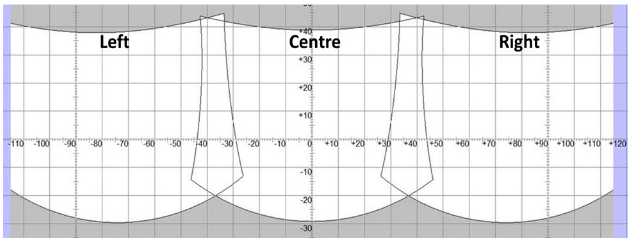

Figure 5: HELIFLIGHT-R simulator Field-of-View (FoV)

The latency associated with the HELIFLIGHT-R simulator between pilot control stick input to the visual movement response is approximately 105ms.

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3. LITERATURE REVIEW

A variety of studies relating to simulator visual-vestibular motion cueing interactions have been presented in the literature for flight and driving simulators. Bos, et al. [27] investigated visual-vestibular cueing using an interaction model to predict and assess the motion perception for a take-off manoeuvre in a fixed and in a motion base simulator for civil aviation applications and in the DESDEMONA centrifuge arm simulator for military aviation applications. In Bos's experiment, it was concluded that the inertial motion becomes more important when the vision is impeded because the physical motion then adds essential elements to the perception of aircraft motion. Moreover, for an accurate attitude perception, vestibular cues are required because visual cues only are not sufficient. Van der Vaart [28], Hosman [29] and Pool et al. [30] conducted a series of experiments at TU Delft to evaluate the effects and use of peripheral visual and physical motion cues in a manual roll-axis compensatory target-following tracking and disturbance-rejection tasks. Tracking performance, control activity and control behaviour were compared for varying task difficulty to understand the effectiveness of the peripheral visual and physical motion, which was found to be less important in a simple tasks [30]. Peterse, et al. [31] conducted a study to measure the interaction effects of different vestibular cues with and without "Out-The-Window" (OTW) visual cues in a yaw-axis target-following disturbance-rejection tracking task conducted in the SIMONA Research Simulator. The effects of varying single-axis vestibular motion cues with and without visual cues on human tracking behaviour were examined and showed that when the OTW visual cues were present the varying vestibular motion cues were less dominant in affecting the pilot's control performance.

Pilot model related investigations have also been conducted to study visual-vestibular motion interactions. Kaljouw et al. [32], Mulder et al. [33] and Lohner et al. [34] conducted a series of experiments on the pilot's use of central visual and vestibular motion in manual control tasks for identification and parameterisation of the multi-loop model of pilots. Zaal et al. [35] used a cybernetic approach to identify the effects of systematic variation of the visual display FoV and vestibular motion cues on the pilot's perception of self-motion in unstructured optical flow environments. In Zaal's experiment, it was found that with an increase in motion cueing fidelity, the visual perception gain increased because the pilot was more confident in using the visual information; on the other hand, when physical motion was decreased the pilot was trying harder to perceive overall self-motion.

Most of these studies have focused upon single/multi-axis land-based tasks, the results of which are not directly applicable to rotorcraft maritime helicopter-ship applications due to the multi-axis disturbances experienced by the pilot while tracking a moving landing spot. Hence, new work is required to understand visual-vestibular fidelity requirements in the complex HSDI task.

Previous research has been undertaken using the HELIFLIGHT [36] and HELIFLIGHT-R simulators at the UoL. Hodge [20] conducted an experiment to investigate visual cueing requirements in HSDI tasks using various visual scenarios at a constant baseline HELIFLIGHT simulator motion configuration. In this study, the effects of varying visual cues only were investigated in different HSDI Wind Over Deck (WOD) conditions. Wang, et al. [9] examined the effects of degrading the visual environment, with and without baseline HELIFLIGHT-R physical motion cues, on the simulated landing of a 'SH-60B like' helicopter model on a Type 23 frigate. One of the primary conclusions drawn from the work was that, in the Degraded Visual Environment (DVE), due to poor visual cueing scenario the workload of the pilot increases and will result in a reduced simulated SHOL envelope. It has been found in the previous phase of the current research [10], that vestibular motion fidelity introduces significant differences in overall simulation perception, control activity, workload and task performance, to an extent that it could lead to a determination of a compromised simulated SHOL envelope when poor vestibular motion fidelity is presented to pilot. Therefore, the impact of variations in both visual and vestibular cueing needs to be analysed to establish overall simulation motion fidelity requirements to determine a new robust simulation fidelity matrix.

4. EXPERIMENTAL ASSESSMENT METHODOLOGY AND DEVELOPMENT

The importance of harmonised visual-vestibular perception to accomplish a high workload task (e.g. deck landings) was demonstrated in the previous phase of this research and reported in [8, 10]. An objective technique known as Vestibular Motion Perception Error (VMPE) was proposed and was utilised to optimise the vestibular motion cueing for deck landing operations in the HELIFLIGHT-R simulator. VMPE integrates vestibular motion perception models with the CWA to quantify the difference, or "error", between the vestibular motion perceived by the pilot in the simulator and simulated aircraft, for a particular task; this error is minimised for the purpose of vestibular motion cueing optimisation using the pilot-in-the-loop simulations.

The VMPE technique was used to optimise the simulator vestibular motion settings for deck landing operations on two different naval ships, the Queen Elizabeth aircraft carrier [8] and a single-spot

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destroyer [10]. Different MTSs of the HELIFLIGHT-R MDA were derived offline using VMPE and then experimentally tested, for landings at different WOD conditions and corresponding ship sea states. It was found that of the two helicopter-ship combinations examined, the single-spot destroyer provided more noteworthy objective and subjective results due to the challenging task-specific characteristics, such as confined ship deck landing space and larger deck heave and rolling motion, up to ±8ft and ±6°, respectively; factors which do not produce severe operational challenges for landings on an aircraft carrier. Therefore, the single-spot destroyer investigation has been extended in the research reported in this paper.

Figure 6 shows some results from the previous flight trial experiment reported in [10] and are utilised here for the visual-vestibular investigations. The Hodge Motion Fidelity Ratings (HMFR) awarded by the test pilot are shown for the two WOD conditions, i.e. relative wind speeds of 15 and 35kts coming from 45° off the starboard (also known as Green 45, or G45 winds) with Sea State (SS) 4 ship motion for the 15kts wind, and SS5 for the 35kts wind, tested using three different simulator vestibular MTSs; 'Benign', 'Intermediate' and 'Optimised', derived using the VMPE in [10]. The importance of the visual-vestibular motion cueing fidelity was demonstrated through the pilot comments. For the Benign MTS case, the pilot commented: "*Visual cues are dominant*" and "*Visual cues are not enough for task performance*". This showed that with the poor vestibular motion configuration (i.e. Benign MTS) the pilot was trying to focus on the visual cues to sense the aircraft motion. This situation became adverse and affected pilot's task performance and workload negatively, particularly at the higher wind speed for which the airwake disturbances are more pronounced and the vestibular motion cueing is even more important. However, when the vestibular cues were improved by using the Optimised MTS, which provided harmonised visual and vestibular motion feedback, the pilot commented: "*Visual and vestibular motion harmonised*" and "*Motion highly harmonised*".

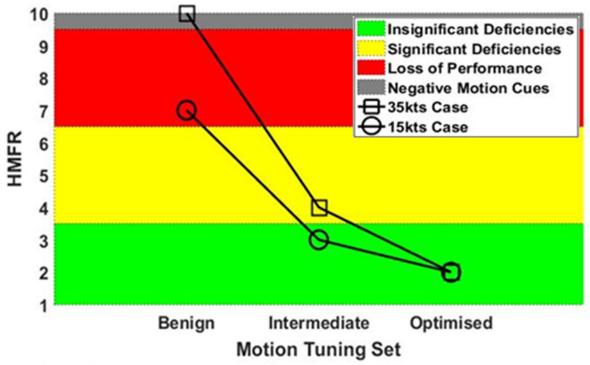

Figure 6: Vestibular motion fidelity subjective assessment results from previous experiment [10]

4.1. Visual Motion Cueing

Three different visual scenarios of the single-spot destroyer have been modelled (high, medium and low visual cueing environment), progressively reducing the textures on the ship model and degrading the visual cueing environment (i.e. visibility), as seen in Figure 7. Guidance on the systematic development of different visual scenarios for providing different Useable Cue Environments (UCEs) was obtained from a previous visual cueing fidelity study conducted by Hodge in UoL's HELIFLIGHT simulator [20].

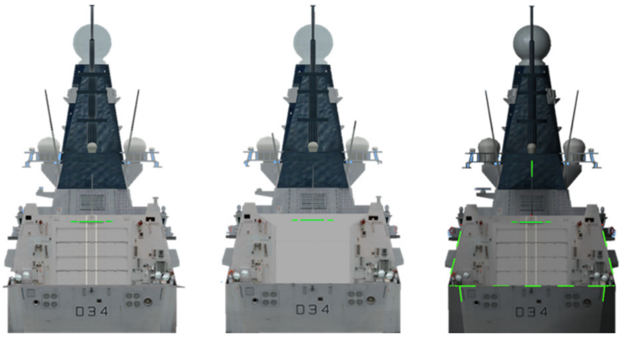

Figure 7: Three visual models for simulated flight trial [Left-Right: High, Medium and Low Visual Cueing]

The three visual scenarios were named as: High Visual Cueing (HVC), Medium Visual Cueing (MVC) and Low Visual Cueing (LVC). In the HVC scenario, a fully detailed model of the ship was used, which included all the deck markings (line-up line, fore/aft line, diagonal lines, deck landing spot and harpoon), deck perimeter netting, roll stabilised horizon bar and hangar door showing vertical lines used by the pilot in the hover and touchdown manoeuvres [20]. The HVC scene also had a high visibility range where the pilot could clearly see the natural horizon and had enough references giving clear and immediate feedback of angular and translational motion, in which aggressive and precise manoeuvring was possible, as per descriptors in [37]. In the MVC scenario, the visibility range was reduced to 1000ft, resulting in the obscuration of the natural horizon, reducing the information available on the relative attitude of the ship, making it difficult for the pilot to distinguish the relative attitude of the aircraft with the horizon. This degraded visual environment resulted in a lack of visual reference of the deck fore/aft line and ship bow. The hangar door was faded in this case so the pilot could not take reference from the vertical lines for lateral positioning corrections. Finally, a night-time LVC scenario was modelled in which the textures and details on the ship were the same as the HVC scenario, however, the natural horizon was completely unavailable along with no reference to the ship's bow, whilst the Horizon Bar (HBar) was active. Electro-luminescent Panels (ELPs) were placed onto

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the ship, along with the floodlighting on the hangar door and deck landing spot. The ELPs highlight the deck edge markings as well as the superstructure outline providing ship motion cues to the pilot.

Figure 8 shows the HELIFLIGHT-R visual scenes for all three cases examined in the trial. In the HVC scenario, visibility is highest with a clear natural horizon and hangar markings. As the visual environment degrades to the MVC scenario, the visibility is reduced due to the lack of a natural horizon reference and visual reference of the deck fore/aft line. Moreover, the lines on the hangar door have been excluded. Further degrading to the night-time LVC scenario, the natural horizon has completely disappeared, which affects the pilot's ability to judge the ship deck motion without additional aids e.g. ELP.

Figure 8: Three HELIFLIGHT-R visual scenes; (top) HVC, (middle) MVC and (bottom) LVC

5. PILOTED SIMULATION FLIGHT TRIAL EXPERIMENT

The three simulator MTSs (Benign, Intermediate and Optimised) discussed in the previous section were tested in two different oblique wind conditions (G45 15 and 35kts) with associated ship sea states (SS4 and SS5), operating in three different visual cueing scenarios (HVC, MVC and LVC). The ship motion was modelled for the corresponding ship and WOD condition using a well-validated ship motion potential-flow modelling code, ShipMo3D, developed at Defence Research and Development Canada (DRDC)-Atlantic and made available to the UoL [38].

In the flight trial experiment, the landing procedure was split into three Mission Task Elements (MTEs) using the standard UK forward-facing port-side deck landing procedure [2], Figure 9. MTE 1 consists of a lateral translation from off the port side of the ship across the flight-deck to a position above the landing spot, at a hover height of 30ft. MTE 2 consists of a stabilized hover station-keeping prior to the landing. Finally, MTE 3 is the descent from the hover to touchdown on the flight deck.

Figure 9: Deck landing mission task elements

The vestibular motion fidelity was assessed and rated subjectively using the HMFR scale, Figure 10 [39]. The rating scale is a 10-point decision tree scale which has the same structure as the Cooper-Harper handling quality rating scale. The HMFR scale is separated into three coarse levels of high, medium and low motion fidelity, broadly correlating to three fidelity regions of the Sinacori/Schroeder motion boundaries [40, 41]. These three levels are each further expanded into three more descriptions, which allows the pilot to better describe their perception of the vestibular motion cues, comparing them with real-world motion cues. Moreover, the HMFR scale provides alphabetic suffixes (descriptors) to supplement the numerical ratings to discern any possible motion cueing deficiencies experienced by the pilot.

Visual cueing was assessed and rated subjectively using the ADS-33E-PRF Visual Cue Rating (VCR) scale (Figure 11) [37], which is a five-point rating scale divided into three coarse levels, Good-Fair-Poor. It is used by a pilot to judge their ability to

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perceive translational rates and attitudes of the aircraft during a manoeuvre. The lower the VCR, the more the pilot is able to detect translational rates and attitudes. Conversely, the higher the VCR value, the less visual information a pilot has to detect those states. The VCRs are plotted on a Useable Cue Environment (UCE) chart to determine the overall usability of the environment's visual cues. UCE 1 denotes that all the visual cues to assess the aircraft states are available to the pilot, whilst UCE 3 identifies that the cues are missing and limits the aggression of any manoeuvres. Results from testing are presented on UCE charts in the following section.

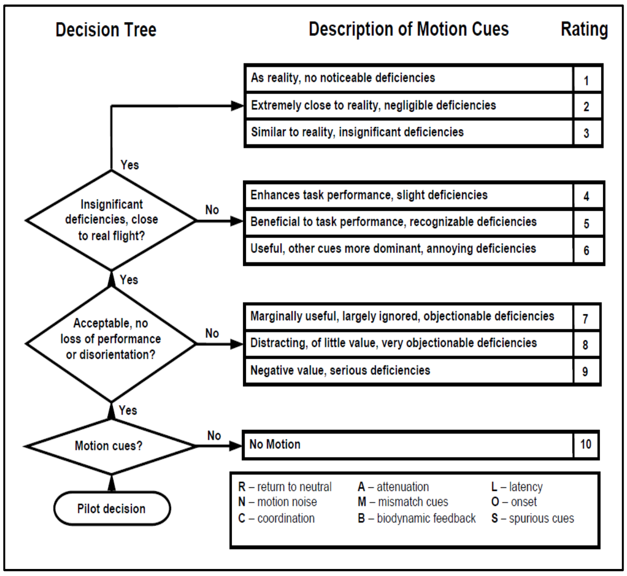

Figure 10: Hodge Motion Fidelity (HMFR) scale [39]

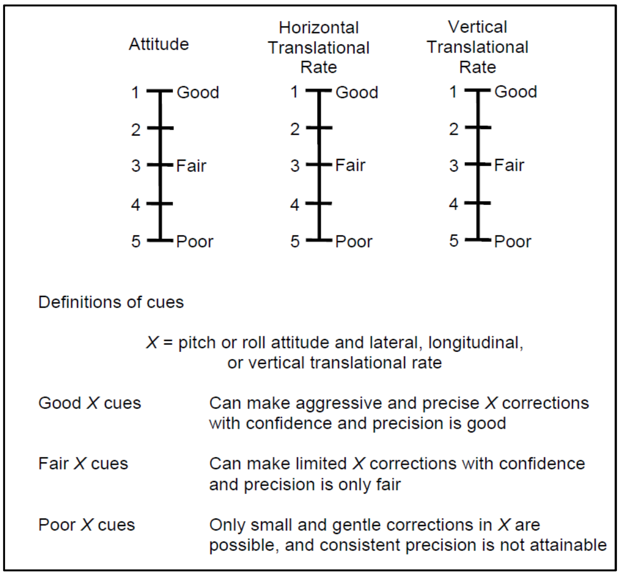

Figure 11: VCR scale [37]

5.1. Results

The simulator trial was conducted to examine the flight simulator visual-vestibular motion cueing fidelity, using the HMFR and VCR scale. Pilot workload/effort was also assessed using the Deck Interface Pilot Effort Scale (DIPES) and the Bedford Workload Rating (BWR) scale. The simulations included unsteady ship airwakes and deck motion for the ship moving at a 12kts forward speed. The piloted simulation flight trial consisted of a test matrix of 18 deck landings at three visual cueing scenarios and three vestibular MTSs at two WOD conditions. The test matrix is shown in Table 1.

Table 1: Flight trial test matrix

WOD Condition	Sea State	Motion Fidelity	Visual Cueing
G45 15kts	SS4	Benign	High Medium Low
		Intermediate	
		Optimised	
G45 35kts	SS5	Benign	
		Intermediate	
		Optimised	

5.1.1. Vestibular Motion Cueing Assessment

Figure 12 shows the flight trial HMFR results for the 18 cases tested. As was found in the previous phase of the research reported in [10], vestibular motion fidelity improved from the Benign MTS to the Optimised, for all three visual scenarios. The Benign MTS was subjectively rated worst and the Optimised as best by the pilot, as reported previously in [10]. However, in this experiment, since the variation in the visual scenarios was undertaken alongside MTSs, additional differences in the HMFRs due to changes in the visual scenarios were observed.

As expected for the Benign MTS, the HMFRs for both WOD conditions remained broadly in the poor motion fidelity region, Level 3-4 (HMFR 8-10) of the HMFR scale, suggesting objectionable motion cueing deficiencies and negative motion cueing, respectively. This is because the pilot was trying to perceive the aircraft motion via the visual cues since the inertial motion was insufficient to provide the appropriate vestibular motion cues. The pilot commented: *"High rate in aircraft responses perceived from the visuals is not matching the motion (vestibular) feedback", "Lack of motion (vestibular) is a deficiency" and "Subliminal motion (vestibular) cueing making it difficult and more reactive as opposed to proactive".* Although small, there was a difference obtained in HMFRs between the three visual scenes, for the Benign MTS case.

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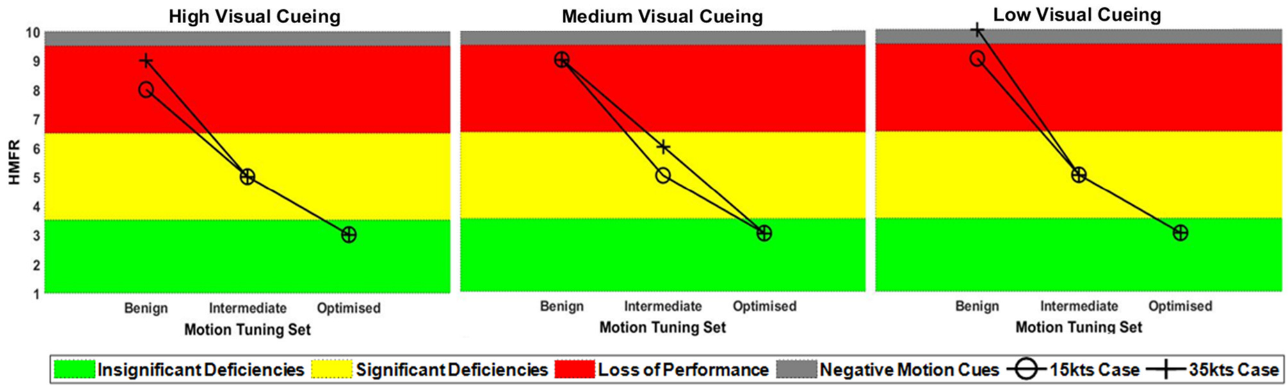

Figure 12: Flight trial experiment subjective HMFR results

For the Intermediate MTS, which improved the motion fidelity, the dependency of the pilot solely onto the visuals to perceive aircraft motion feedback reduced due to the improved vestibular motion cues complementing the visuals. Using the Intermediate MTS, the HMFRs improved to Level 2 (HMFR 5-6) suggesting no loss of performance and beneficial motion cueing. The pilot commented: "*Received warning of movement due to airwake from the motion (vestibular) as well now, which has been missing previously*", "*Motion (vestibular) is not crisp but better than before*" and "*Visual cues definitely less dominant but still depending on it*". This suggests that as the increased vestibular motion fidelity contributes more to the overall motion cueing system, the dependence on the visual cues decreases, making the fidelity of the overall motion cueing more representative of the real world.

When the same WOD conditions were tested using the Optimised MTS, in all three visual scenes, the HMFRs decreased to an overall 3 (Level 1) suggesting good motion cueing, similar to the real world. The deficiencies experienced by the pilot in the Intermediate MTS were further reduced and aided the pilot in perceiving the content of the HSDI scenario more accurately (especially the airwake). The pilot commented: "*The aircraft response feedback is shared by the motion (vestibular) cueing accurately now along with visuals (in HVC scenario)*", "*Feeling the content of airwake in sync with the visuals*" and "*Felt the pressure-wall alongside on the port side (traverse MTE)*".

The impact of the variation in the visual cueing scenarios on the HMFRs was significant in the Benign MTS case, where it can be seen that the HMFRs increased from the HVC to the LVC scenarios. The poor vestibular motion was less objectionable in HVC scenario since the pilot was able to accomplish the task using visual motion cues only, however, the HMFR increased to 10 (Level 4) in the LVC scenario because the required vestibular cues were not provided by the motion platform and the visual cues were reduced as well, leading to poor overall motion cueing. Overall, for the three visual and two WOD cases, the Optimised MTS was rated as the best.

5.1.2. Visual Cueing Assessment

Alongside HMFRs, the pilot also provided VCRs for each of the 18 test points to evaluate the visual cueing scenarios. Figure 13 shows the VCRs plotted on the VCR Translation Rate vs Attitude UCE graph for the two WOD conditions, G45 15 and 35kts.

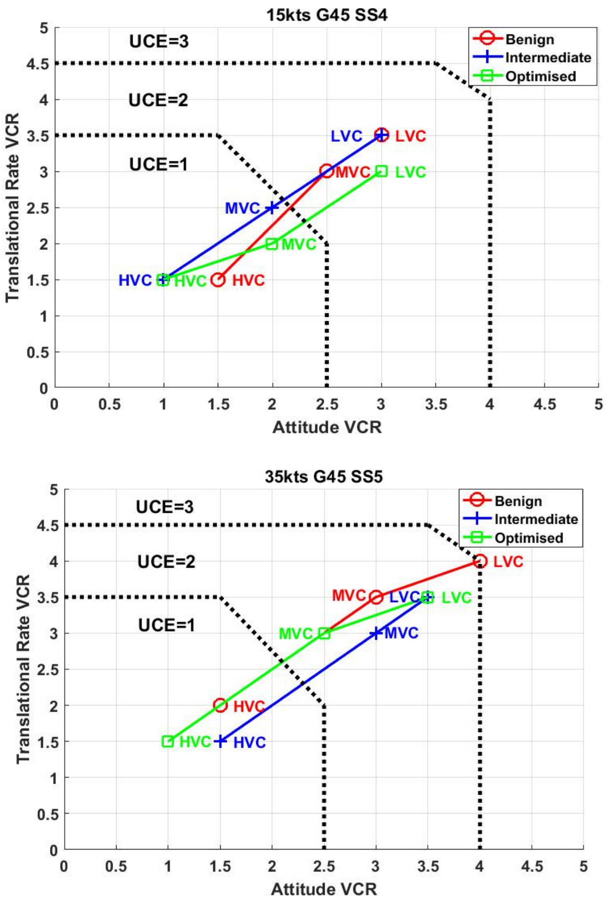

Figure 13: Flight trial subjective VCR results

Examining the results in Figure 13 for the three visual scenes, it can be seen that for the HVC scenario the

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VCRs awarded by the pilot for both WOD conditions were well within the UCE 1 region (VCR 1-2) suggesting Good to Fair visual cueing scenario with the pilot commenting that *"Visuals are beneficial for the task completion, whilst poor motion (vestibular) fidelity"* and *"Clear view at the natural horizon is beneficial to perceive aircraft attitude disturbances"*. For the HVC scenario, although the VCRs obtained for all the three MTSs were low in the UCE 1 region due to good visual cues, differences in the fidelity ratings and workload for the different vestibular MTS conditions were obtained.

As the visual scene was degraded to the MVC scenario, the VCRs for both WOD conditions increased to 2-3.5 (UCE 1-2 region) suggesting overall fair visual cueing scenario. The effect of the WOD condition was more apparent in the MVC scenario. For the 15kts WOD SS4 condition, the VCRs awarded were around the UCE 1-2 boundary as the performance and the workload were less affected by the smaller airwake disturbances and deck motion. The pilot, in this case, commented: *"Can finish the task with the visuals for the lower WOD condition" and "Reduction in the natural horizon is not a significant problem since the deck is not moving a lot"*. When the WOD was increased to the 35kts SS5 condition, the VCRs degraded to VCR 3-3.5, well within UCE 2 region, in which consistent precision is not achievable. The pilot commented: *"Difficult to hold the hover position due to large ship motion along with degraded visual cues"*.

In the LVC scenario, greater differences were observed in the ratings awarded to the lower and higher WOD conditions due to the degraded visual scene. The VCRs degraded from the fair to poor visual cueing condition (VCR 3-4), up to UCE 3. In the 15kts WOD condition, the VCR remained in the middle UCE 2 region. However, in the 35kts WOD condition, the VCR for the poor vestibular motion fidelity case (i.e. Benign MTS) reached UCE 3, where a VCR 4 was awarded by the pilot; this was the worst test point in terms of workload and task performance, discussed in the following sections. In the 15kts SS4 case the pilot commented: *"Ship bow and bow wake are not visible along with the natural horizon"* and *"Utilising HBar now, but not sufficient in pitch tracking"*. For the higher WOD 35kts SS5 condition the pilot commented: *"Inaccurate alongside, difficult to hold due to no natural horizon and bow visibility"*, and *"Pitch tracking is difficult due to no cues for it visually"*.

Overall, for the three different visual scenes, the VCRs decreased when the vestibular motion fidelity was improved from Benign to Optimised, as did the HMFRs discussed in the previous section. Moreover, as observed for the HMFRs, the impact of the WOD condition was also apparent in the VCRs. The effect of the visual and vestibular fidelity on task performance and workload is examined in the next section.

5.1.3. Pilot Workload Assessment

The pilot also evaluated workload for each of the 18 test points examined during the simulated flight trial experiment, using the BWR scale [42] for each MTE and the DIPES for the complete landing task [2]; the two scales are included in the Appendix.

Figure 14 shows the DIPES and BWRs for the 15kts WOD case. Broadly, it can be seen that as the motion fidelity and the visual cueing scenario was degraded to the Benign MTS and LVC condition, respectively, the DIPES and the BWRs increased and the opposite was true when the motion and visuals were both improved. However, the effect of an increase in one and decrease in another and vice versa was also observed on the workload ratings and associated comments. The DIPES ratings are for the complete deck landing task whilst the BWRs are shown for the three MTEs 1, 2 and 3. Moreover, the coloured region on the BWR plots specifies decision tree regions from the BWR scale shown in the Appendix.

In the Benign MTS and LVC scenario (B&L), the workload ratings provided by the pilot were highest at DIPES 2, suggesting significant compensation required, and BWR 4-4-4 (Level 2) suggesting insufficient spare capacity. The pilot commented: "*Hover alongside is more difficult since the bow of the ship and natural horizon is not visible*" and "*Motion (vestibular) is useless*". The pilot also gave DIPES descriptors: V (Visual cues), F (Fore/aft positioning), A (Aircraft attitude), L (Lateral positioning) and H (Height control). As discussed above, the HMFRs and VCRs were highest in this case as well, confirming an overall poor simulation motion fidelity. Using the Optimised MTS and LVC case (O&L), the DIPES rating remained the same at 2 but the BWR improved to 3-3-4 (Level 1-2), suggesting a lower workload than the previous case due to improved vestibular motion cueing. However, due to the low WOD condition, the impact of the poor visual cueing scenario was not significant. The pilot commented: "*The workload is majorly due to the visuals only, previously it was visuals and motion (vestibular)*" and "*Not a lot of workload though due to lower WOD*". DIPES descriptors provided by the pilot were: F (Fore/aft positioning) and L (Lateral positioning).

When the visual scene was improved to the HVC with the Optimised MTS (O&H), the DIPES decreased to 1, suggesting slight to moderate pilot effort, and BWR improved to 2-2-2 (Level 1) suggesting low satisfactory workload. The benefit of the reduction in the workload was mainly obtained from the improvement in the visual cueing scenario, compared with the (O&L) case. The pilot commented: "*Overall workload low, motion (vestibular) and visuals are in a correct sense"* and *"Workload is due to the deck motion only now"*. The pilot awarded DIPES descript-

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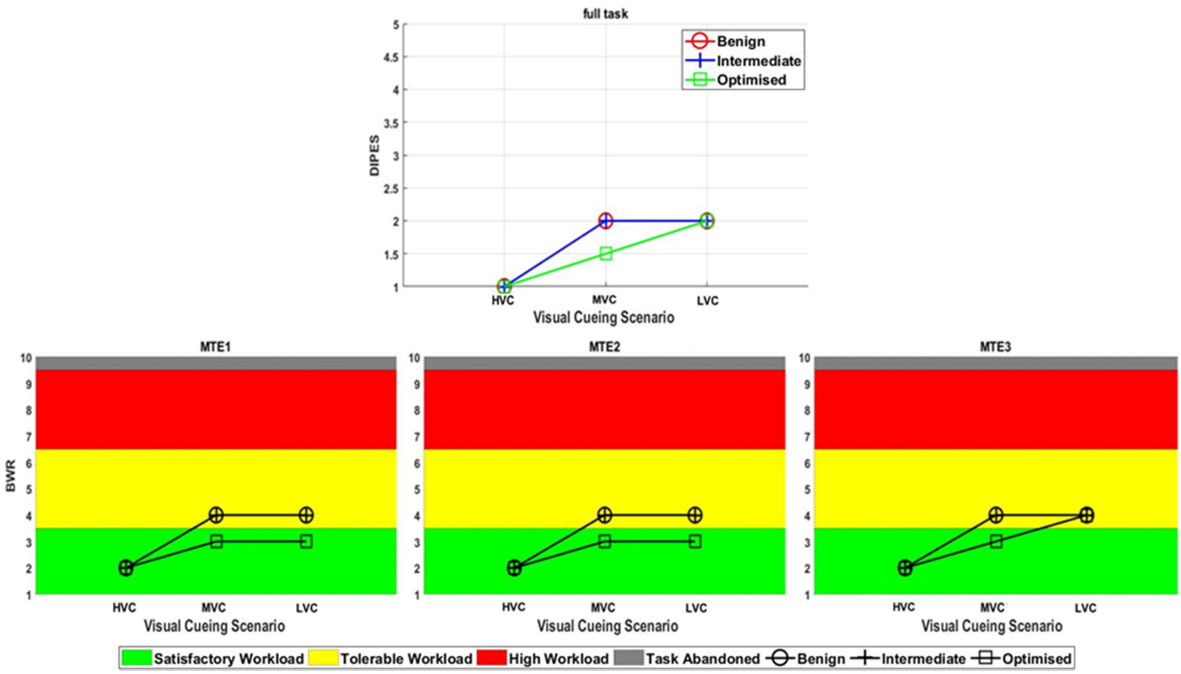

Figure 14: Pilot workload ratings (DIPES and BWR) for 15kts WOD

-or D (Deck motion) only, which suggests that the vestibular and visual motion cues were harmonised and provided sufficient combined motion cues to the pilot. It is likely that the workload is due only to the HSDI task characteristics itself and not to any degradation in the visual and/or vestibular motion cueing fidelity. For the Benign MTS HVC (B&H) case, the DIPES and BWRs remained the same as the (O&H) case because, at this low WOD condition, the vestibular motion degradation did not affect the workload significantly. However, the simulation did not feel realistic to the pilot and resulted in the increased HMFR and VCRs discussed in previous sections. The pilot commented: *"The performance could have been better if better motion (vestibular) cueing was provided"* and *"The workload is low due to low WOD condition, but it doesn't feel real"*. This is because although the visual cues were sufficient for the pilot to perform the task and the workload rating was low, the pilot felt a deficiency in overall simulation fidelity due to lack of accurate physical feedback of the airwake disturbances.

In the higher 35kts WOD condition, the effect of the different vestibular and visual cues on pilot workload is found to be more pronounced than in the 15kts case, due to the task being more challenging, Figure 15, which is consistent with the observed HMFRs and VCRs discussed in previous sections.

As with the 15kts WOD case, the workload ratings provided by the pilot for the Benign MTS and LVC (B&L) scenario were highest at DIPES 3, the highest tolerable effort and boundary limit of the Acceptable/Unsatisfactory workload and simulated SHOL envelope [12], and BWR 5-6-6 (Level 2 upper boundary) suggesting little spare capacity/unsatisfactory workload. The pilot commented: "*Difficult alongside position-keeping (inaccurate)*" and "*Lack of motion (vestibular) with degraded visuals making it more difficult*". The pilot awarded DIPES descriptors: V (Visuals cues), F (Fore/aft positioning), A (Aircraft attitude), L (Lateral positioning), H (Height control) and D (Deck motion); the HMFR and VCR for this case were highest amongst all the points tested. With the Optimised MTS (O&L), the workload reduced to DIPES 2/2.5, suggesting a considerable pilot effort, and BWR to 4-4-4 (Level 2) suggesting insufficient spare capacity. The pilot commented: "*Motion (vestibular) is good, but the night scenario making it difficult*" and "*Difficult to judge the ship motion due to poor visuals*". The DIPES descriptors provided were: D (Deck motion), F (Fore/aft positioning) and L (Lateral positioning). This shows that the improvement in the motion has affected pilot workload positively compared to the former (B&L) condition, however, poor visuals still play an important role in pilot workload.

As the visual scene was improved to HVC with the Optimised MTS (O&H), the DIPES rating reduced to 2 and BWR to 2-3-3, suggesting the best cueing scenario as observed in the 15kts WOD case. The workload related pilot comments were the same as the ones in the 15kts (O&H) case and the pilot awarded DIPES descriptors: D (Deck motion) for the same reason as specified in the 15kts case and a small R (Roll motion). Using the Benign MTS with the HVC scenario (B&H), DIPES 2/2.5 and BWR 3-4-4 were awarded. The increase in the workload is because of the decrease in the vestibular motion cueing fidelity which made the landing task for the pil-

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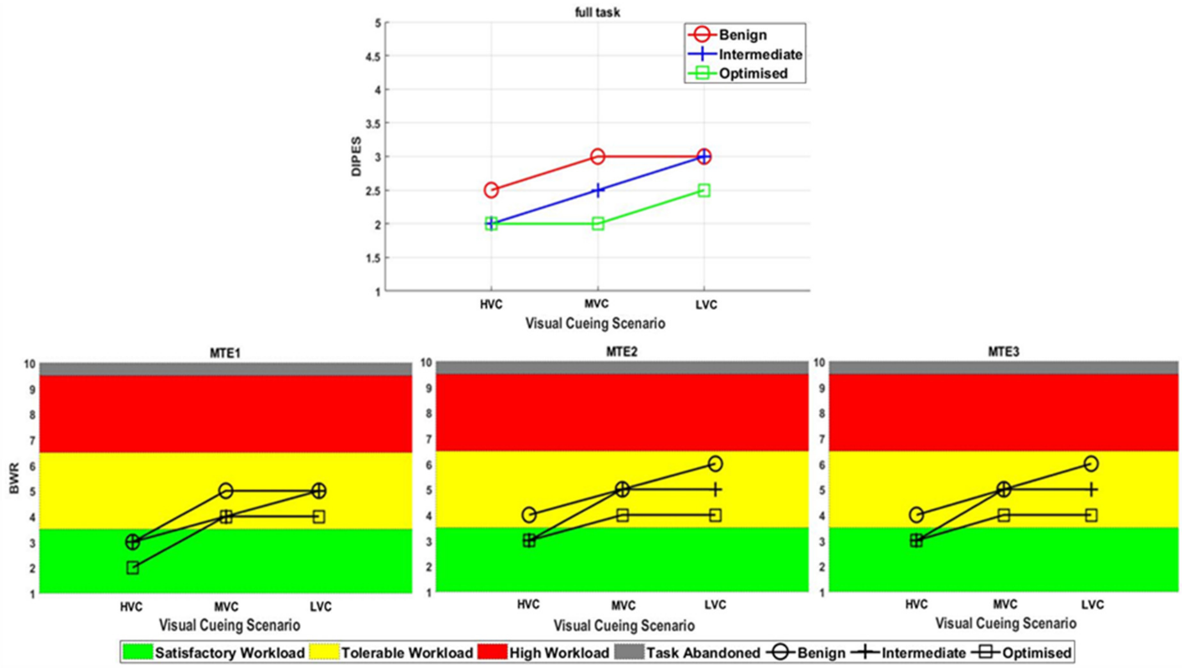

Figure 15: Pilot workload ratings (DIPES and BWR) for 35kts WOD

-ot more challenging overall. The pilot commented: "*Motion (vestibular) is making the task largely inappreciable*", the DIPES descriptors provided were: F (Fore/aft positioning), L (Lateral positioning) and H (Height control).

In the higher WOD condition, the workload ratings were higher and more sensitive to the changes in the cueing environment because at the higher airwake disturbance conditions the pilot requires more information via visual and vestibular motion cues compared with the lower WOD condition. As in the 15 kts wind, the workload increases as the visual scene is degraded, and it decreases as the motion tuning is improved from Benign to Optimised; however, the overall workload is higher in the higher wind speed. Again, these results are consistent with the HMFR and VCR assessments discussed in previous sections.

Further evidence of the effect of vestibular fidelity and visual cueing scenario on the pilot's experience in the simulator was seen in the cyclic control activity and aircraft trajectory (spatial deviations) during the landing task, as discussed in the following sections.

5.1.4. Control Activity

Figure 16 shows the cyclic control activity of the pilot for the six 35kts SS5 WOD cases, i.e. Benign and Optimised MTS in High, Medium and Low visual cueing scenario, for the hover MTE only. The central plot in each graph shows lateral (XA) vs longitudinal (XB) control activity whilst the outer plots show respective time histories. Broadly, for the three visual cueing scenarios the control activity in the Benign MTS case is noticeably larger than in the Optimised MTS case. Moreover, the control activity shows an increase in its scatter as the visual scene is degraded from HVC to LVC, due to the poor cues provided to the pilot when station-keeping over the ship's deck and tracking its motion, whilst compensating for the airwake disturbances.

For the HVC scenario, using the Benign MTS (B&H), the pilot commented: *"Took longer to pick up the change in the aircraft drift leading to large reactive control inputs".* The lateral control range was 25.3% and longitudinal was 23.1%. In the Optimised MTS case (O&H), the pilot commented: *"Accurate control inputs, not hard work as before"* and *"Obtained feeling of the airwake leading to accurate control"*. The lateral control range reduced to 19.2% and longitudinal control input to 13.6%.

For the MVC scenario, using the Benign MTS (B&M), the cyclic control scatter increased compared with the HVC case due to the reduced visual information being less beneficial for the task performance. The pilot commented: "*Larger control scatter, lack of attitude cues*". The control ranges were 27.1% and 26.4% in lateral and longitudinal, respectively. Using the Optimised MTS (O&M), the control ranges reduce significantly to 22.9% and 16.8%, respectively, and the pilot commented: "*Accurate workload*" and "*Easier over deck*".

When the visual scene was degraded further to LVC with the Benign MTS (B&L), the control activity range further increased, and the pilot commented: *"Trouble keeping lateral position accurately"*. The control ranges were 32.3% in lateral and 25.3% in

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longitudinal, the largest scatter amongst all the six cases. The workload was highest in this case, consistent with HMFR/VCRs discussed earlier. Using the Optimised MTS case (O&L), the control activity decreased with the pilot commenting *"Good motion (vestibular) and feeling airwake content making it easier to hold the position over deck".* The control ranges reduced to 20.4% in lateral and 16.8% in longitudinal.

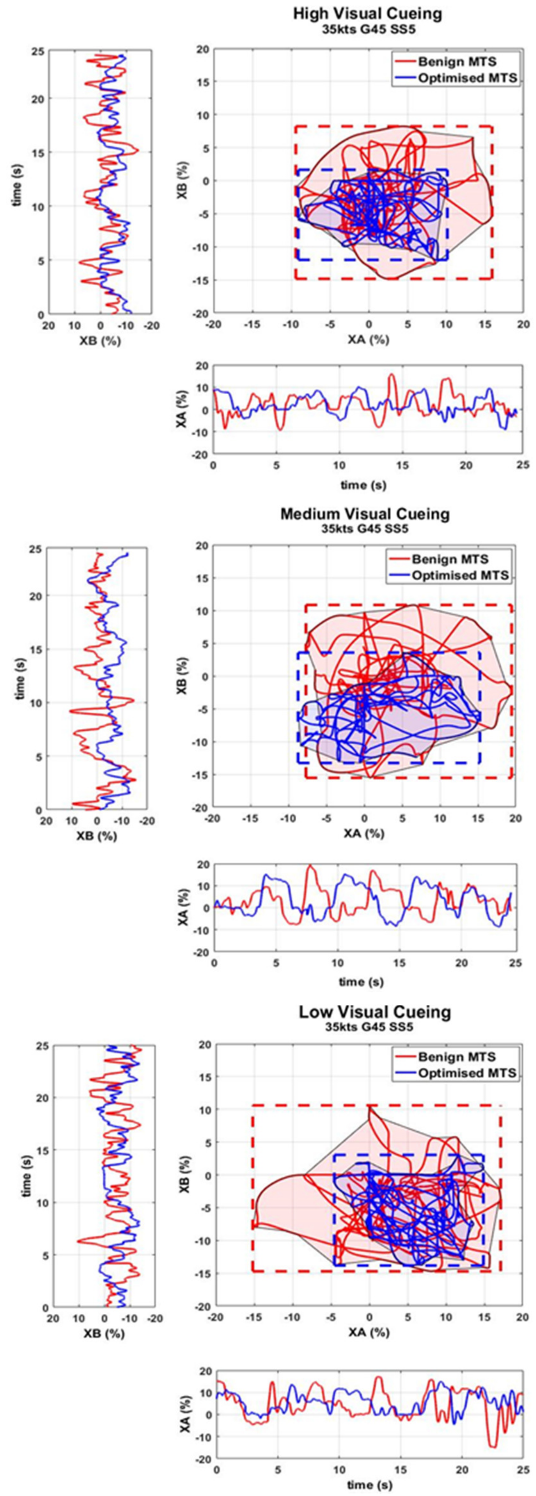

Figure 16: Pilot control activity (trimmed reference)

The cyclic control activity results demonstrate the overall effect of the motion and visual cues on the pilot's strategy. With appropriate synchronised cueing for the motion-visual-airwake response coupling, the pilot can proactively compensate for the airwake perturbations. The lack of appropriate synchronised cues delays the pilot's corrective input, leading to poor performance.

5.1.5. Aircraft Spatial Response

Figure 17 shows the comparison of the position keeping over the ship's landing deck for hover MTE for the six 35kts WOD conditions. The spatial deviation scatter with the Benign MTS is larger than with the Optimised MTS. Moreover, the deviation appears to increase from the HVC to the LVC scenario, especially in the Benign MTS case. These observations are consistent with the control activity discussed above.

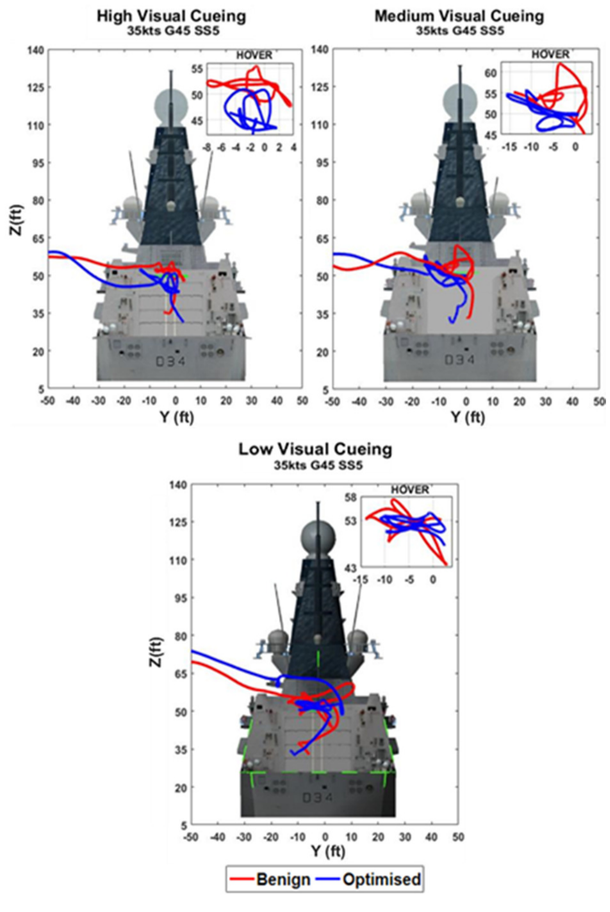

Figure 17: Flight trial deck landing trajectory

With the Benign MTS in the HVC case (B&H), the pilot commented that it "*Took longer to pick up the lateral drift and correct it*" and "*Stayed longer in hover for better attitude cues from visuals*". The overall effect of poor vestibular motion cues was consistent with higher HMFR, VCR and workload ratings discussed earlier. Using the Optimised MTS (O&H), the spatial

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deviation has decreased, and the pilot was able to perceive the airwake disturbances better and subsequently compensate in time to reject the disturbances well before the aircraft drifted from the position. The pilot commented "*Improved tracking accuracy over the deck*".

In the MVC case using the Benign MTS (B&M), the deviation in Figure 17 seems to increase due to the degraded visual scene, and the pilot commented: "*Lateral position keeping is a problem, more scatter*" and "*Motion (vestibular) is not helpful over the deck making it difficult*". As observed in LVC case, using the Optimised MTS (O&M), the task performance improved as the pilot was provided with appropriate vestibular cues helpful for the tracking accuracy over the deck even though the visual were degraded. The pilot commented: "*Motion (vestibular) is providing positioning accuracy*".

With the lowest visual cueing scenario, LVC, using the Benign MTS (B&L), the deviation in the trajectory increases further, consistent with the control activity discussed above, and the pilot was working hard to cope with the degraded visual cues. The pilot commented: "*Motion (vestibular) cueing has nothing to offer, even at large excursion*" and "*Overall position keeping is inaccurate*". Similarly, with the Optimised MTS (O&L), the deviation has reduced, and the pilot commented: "*Feeling content of airwake making it positive for task performance*" and "*HBar is matching with the motion cues response which is realistic*".

It was observed that in the degraded visual environment with poor motion cueing, the pilot was purposely hovering higher to avoid the heaving deck getting dangerously close to the landing gear. Moreover, alongside the port edge during the traverse MTE, using Optimised MTS, in all three visual scenes, the pilot commented positively regarding his ability to detect the pressure wall effect via the vestibular motion cues, which was very realistic and important in the oblique winds (detailed in [43]), helping the pilot to avoid drifting off in the translation.

6. CONCLUSIONS

The results from a simulation trial in which a pilot landed a representative SH-60B helicopter to the deck of a single-spot destroyer have been presented. The simulator was tuned using a range of MTSs, the fidelity of the visual cueing environment was varied, and two WOD conditions were applied. The main aim of the research has been to establish overall motion fidelity requirements for the construction of a high-fidelity helicopter-ship dynamic interface simulation environment; this is key to their use in supporting future FOCFTs and deriving SHOLs. Following are the key conclusions drawn from this work:

1. A correlation between the visual and vestibular motion cueing was observed in the flight trial experiment. When the pilot was provided with high-fidelity vestibular motion cueing for the three visual cueing scenarios, the VCRs and HMFRs were reduced. This is because whilst using the poor vestibular MTS, the pilot was solely focusing on the visuals to capture the aircraft motion, but when the Optimised MTS was used the pilot was able to capture the aircraft motion from the vestibular and visual cues, leading to improved simulation motion fidelity and task performance, which reduced the VCRs ratings.

2. As the visual scene was degraded from HVC to LVC, the HMFRs increased together with the VCRs, especially in the Benign MTS case. The pilot comments suggested that when the visual cues were degraded and the vestibular motion does not provide sufficient information on the aircraft states and airwake disturbances feedback, the overall simulation fidelity system became unrealistic, leading to the highest workload and poorest fidelity ratings.

3. The impact of the vestibular and visual cueing fidelity was more significant at higher WOD conditions. At a lower WOD condition (i.e. 15kts SS4), differences in the perception of simulation fidelity, workload and task performance were not significantly affected by the visual cueing and vestibular fidelity. However, as the WOD was increased to 35kts SS5 the pilot workload and fidelity ratings were more sensitive to the variations in the cueing conditions. In the worst simulation fidelity scenario (i.e. Benign MTS and LVC) the BWR and the DIPES were highest, approaching to the boundary of the simulated SHOL envelope. However, for the best fidelity scenario (i.e. Optimised MTS and HVC) the BWR and DIPES reduced to their lowest values. This confirms that high-fidelity simulations are more important at higher WOD conditions and poor simulation fidelity can impair the prediction of the simulated SHOL boundary.

4. The impact of the visual and vestibular cueing fidelity was also apparent in the pilot's control behaviour and task performance. It was found that using the Benign MTS, when the visual scene was degraded to MVC and then to LVC, the control scatter increased, as did the airborne spatial deviations. This was reflected in the pilot subjective ratings and comments, suggesting that in the poor fidelity/cueing scenarios the pilot's strategy was reactive as opposed to proactive, leading to poor position control. However, for the Optimised MTS, the degraded visual scene did not show a similar range of pilot ratings as good vestibular cues were being provided to enable a more interactive response from the pilot.

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5. It is interesting to note that, in the LVC night-time scenario, although the pilot was presented with the high-fidelity ship model equipped with the deck ELPs and floodlighting, and illuminated roll-stabilised horizon bar, the pilot rated it as the worst of the three visual scenarios due to overall poor visual environment, which resulted in increased workload and degraded task performance.

ACKNOWLEDGEMENTS

The authors would like to thank the industrial sponsors, QinetiQ and Dstl for funding the project under QinetiQ-Dstl Technology Fund. The authors would also like to thank Dr Sarah Scott ex-researcher at the UoL, for access to the ship airwakes and an ex-Royal Navy pilot, who conducted the flight simulator trials. The authors would also like to acknowledge Presagis for their support in academic licensing of the visual software.

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Presented at 45th European Rotorcraft Forum, Warsaw, Poland, September 17-20, 2019.

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Appendix: Pilot Workload Rating Scales

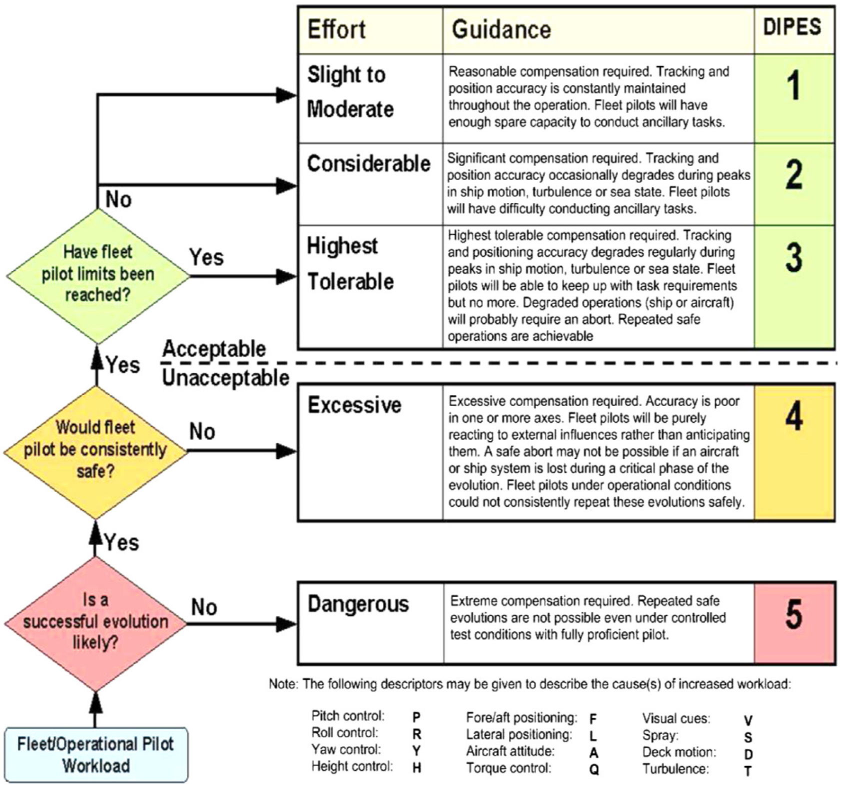

Figure A1: DIPES rating scale [2]

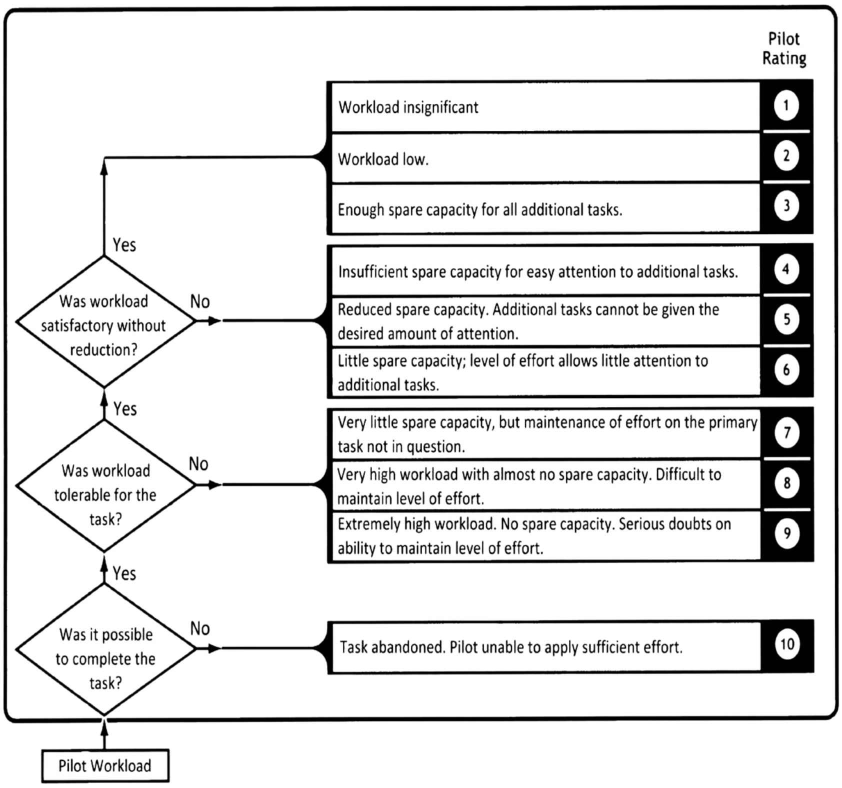

Figure A2: Bedford Workload Rating scale [42]

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