ACAH AUGMENTATION AS A MEANS TO ALLEVIATE SPATIAL DISORIENTATION FOR LOW SPEED AND HOVER IN HELICOPTERS[1]

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1. Abstract

This paper is based on the premise that a primary factor in spatial disorientation accidents is that high pilot workload is required for control in low speed and hover in the degraded visual environment (DVE). Numerous flight test and simulation experiments have shown that the DVE has the same effect on rotorcraft controllability as degraded handling qualities. Degraded handling qualities lead to increased pilot attentional demand for aircraft for control, hence reduced excess workload capacity for other tasks and for situational awareness. A regression analysis of pilot rating data shows that the use of attitude-command-attitude-hold plus height hold augmentation (ACAH+HH) could significantly reduce the risk of a spatial disorientation accident.

2. Abbreviations and Symbols

AD	Attentional Demand required for helicopter control
ACAH	Attitude-command-attitude-hold augmentation
DVE	Degraded visual environment
EWC	Excess workload capacity
GVE	Good visual environment
HQR	Handling Qualities Rating from Cooper-Harper Scale
HH	Height-hold augmentation
SA	Situational Awareness
SD	Spatial disorientation (Refers specifically to Type I SD in this paper)
VCR	Visual cue rating
VCR	Visual cue rating for pitch and roll attitude
VCR_x	Visual cue rating for translational rate. Worst of the ratings for horizontal and vertical velocities.

3. Introduction

A review of civil and military rotorcraft accident records reveals numerous accidents that are difficult to explain because they involve collisions with objects that are visible in the pilot's field-of-view, and often occur with experienced pilots at the controls. Many of these accidents occur in an environment where the visual conditions are less than ideal, even though objects are clearly visible. In this paper, such conditions are referred to as the degraded visual environment (DVE). Examples of the DVE are low altitude flight, over snow or water with flat lighting, and at night with vision aids such as night vision goggles or forward looking infrared (FLIR). Many rotorcraft accident reports indicate that collisions with objects or the

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ground resulted from spatial disorientation (SD) while attempting to hover, translate at low speed, or land. The issue is complicated by the fact that helicopter pilots routinely operate in degraded visual conditions, making it difficult to identify what is unique about the spatial disorientation accident scenarios.

The US Army has been working to better understand the nature of spatial disorientation, and to develop measures to minimize SD accidents, e.g., Reference 1. An important innovation resulting from that work has been to create a distinction between two types of spatial disorientation as follows:

Type I SD – Aircrewmembers are unaware that they have an inaccurate perception of their position, altitude, or motion.

Type II SD – Aircrewmembers are aware that SD circumstances exist and must be addressed before safety is irreversibly compromised.

The Type II SD accident nearly always occurs in instrument meteorological conditions (IMC) and is reasonably well understood. It relates to the fact that the human vestibular system is unable to detect which way is up, resulting in a conflict in visual and kinesthetic cues. The solution is to train pilots to ignore vestibular cues and to rely on cockpit instruments. The relatively new category of situational awareness (Type I) has been developed to describe the situation where the pilot can extract which way is up from the outside visual scene, but is unable to accurately detect aircraft attitude and horizontal and vertical drift. For the purpose of this paper spatial disorientation refers to the Type I category.

Essentially all conventional approaches to develop ways to mitigate the risk of spatial disorientation accidents involve deductive reasoning. For example, References 1 and 2 list the potential solutions for Type I and Type II SD accidents shown in Table 1. These are prioritized in order of the frequency where two of the three researchers felt the solution would have been effective. Reference 3 documents a comprehensive analysis of helicopter surface collisions. The six most effective solutions to minimize SD accidents in Reference 3 are summarized in Table 2.

Potential Solution	*Frequency*
Increased crew coordination	45%
Improved scanning	39%
Audio warning on radar altimeter	22%
Night vision goggles head-up display	22%
Hover lock	19%
Drift indicators	14%

Table 1 Recommended Solutions from References 1 and 2

Potential Solution	*Frequency*
Radio altimeter	77%
Improved displays	77%
Automatic voice alerting device	73%
Low height warning	70%
Height hold autopilot	53%
Ground proximity warning system	43%

Table 2 Recommended Solutions from Reference 3

A comparison of the solutions proposed in Tables 1 and 2 indicate similar approaches to the SD accident problem. For example, radar altimeters and height warning devices are suggested. This conclusion is based on reasoning that the pilot's situational awareness of altitude was lacking, and that the logical solution is a better altitude display, or better use of such a display. Most other solutions in References 1 through 3, involve better displays, warning devices, and pilot training.

The present research is based on the premise that better displays, or pilot training to better use existing displays is of little value if the pilot's excess workload capacity is very low. Excess workload capacity is defined here as the workload capacity that is left over from that required to control the rotorcraft. The effects of pilot training and proficiency are not addressed directly. However, all of the evaluation pilots in the supporting flight test experiments were highly experienced, and in most cases were Army or NASA test pilots.

4. Quantifying Pilot Workload

For the purpose of this study, it is assumed that 100% of the pilot's workload capacity must be allocated to the sum of the "attentional demand" required for aircraft control (AD) and excess workload capacity (EWC).

$$AD + EWC = 1.0. \text{ (or 100\%)} \quad (1)$$

A review of civil and military helicopter Type I SD accidents shows that, in most cases, the pilot flying was not tending to other tasks, e.g., communicating or navigating. Therefore, it can be assumed that all of the excess workload capacity was being used to maintain situational awareness (SA = EWC). Situational awareness is defined as the comprehension of position, velocity, and attitude with respect to the ground and all objects in the vicinity of the rotorcraft. All items associated with rotorcraft control (ranging from basic stabilization to maintaining torque and rotor RPM within limits) are defined as part of the required attentional demand for control, AD. On the basis of the foregoing,

$$AD + SA = 1 \text{ (or 100\%)} \quad (2)$$

Equation 2 indicates that when the attentional demand required for control is high, the situational awareness is low. When there is insufficient situational awareness, the pilot is said to be "overloaded", and the potential for an accident or incident is high. This is often manifested by experienced pilots making seemingly "foolish" errors.

The basic premise of this work is that an ability to predict AD as a function of visual environment, and helicopter handling qualities in a good visual environment (GVE) allows predictions of the propensity for a Type I SD accident in the DVE. The elements of the functional relationship between AD and DVE are:

1. The Cooper-Harper Handling Qualities Rating (HQR) scale to quantify handling qualities (Reference 4)
2. A pilot rating scale to quantify the degraded visual environment (Visual Cue Rating, VCR, Scale,) from References 5 and 6.
3. An empirical relationship between handling qualities and the visual environment (HQR as a function of VCR).
4. An empirical relationship between HQR and attentional demand (AD)

The first of these is the well accepted and validated Cooper-Harper pilot rating scale. The VCR scale (item 2) was first developed in Reference 5 and refined in flight test and simulation programs to its current form (Reference 6). The empirical relationship between HQR and VCR is developed in Section 4.1. A similar relationship between HQR and AD is presented in Section 4.2.

4.1. Effect of Degraded Visual Environment on Handling Qualities (HQR as function of VCR)

A substantial amount of flight test and simulation research has been accomplished to quantify the effect of the DVE on handling qualities since the late 1970s. That work has resulted in a data-base that is the foundation of the present research. It is described in References 5 and 7 through 9.

The first flight test experiment to quantify the DVE was accomplished in early 1980 under a NASA Small Business Innovative Research Program (SBIR), and is reported in Reference 5. It was motivated primarily by unfavorable simulation vs. flight comparisons of flying qualities of rate damped helicopters in low speed and hover. For example, the UH-60 (rate damping only) was flown in a moving base simulation (NASA Ames Vertical Motion Simulator, VMS) in flight test using identical tasks and pilots. The pilots indicated that the simulator seemed “less damped in all axes”. This was supported by their assigned Cooper-Harper Handling Qualities Ratings, which were 1.5 to 2 ratings worse in the simulator. The VMS employed a four window computer generated display and a large amplitude motion base.

A Visual Cue Rating (VCR) Scale (Figure 1) was developed in Reference 5 to quantify the attitude and translational rate cues in each axis (longitudinal, lateral, and vertical). The VCR scale was adapted for use in the U.S. Army aeronautical design standard for rotorcraft handling qualities (ADS-33), and has been an integral part of that specification since its inception in 1987.

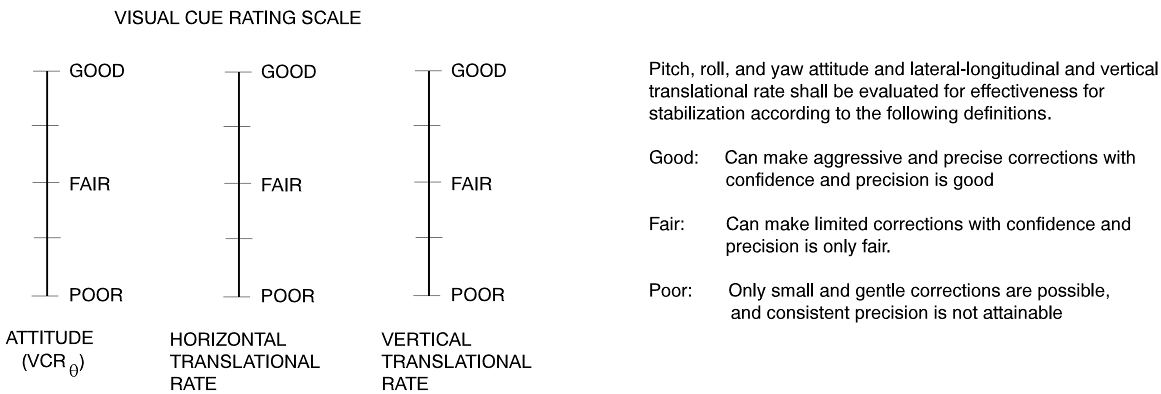

Figure 1 Definition of Visual Cue Rating Scale

A data-base of 93 flight test data points has been compiled where pilots rated both the VCR and the HQR for low speed and hover tasks (less than 45 knots groundspeed) with conventional rate response characteristics. The helicopters used in this data-base consisted of a Hughes 500, variable stability Bell 205, and AH-1S Cobra. The handling qualities ratings assigned by most of the evaluation pilots, in the good visual environment, (GVE) for the hover and landing tasks, were HQR = 3 or better. A multiple polynomial regression fit of that data was accomplished with the following results.

$$HQR = 3.55 - 1.02 VCR_{\theta} + 0.468 VCR_{\theta}^{2} - .084 VCR_{X} + 0.257 VCR_{X}^{2} - 0.303 VCR_{\theta} VCR_{X} \quad (3)$$

Where VCR_{θ} is the visual cue rating for attitude and VCR_x is the worst of the horizontal and vertical translational velocity ratings.

The estimated handling qualities ratings (HQRs) from equation 1 are compared to actual ratings from the data-base in Figure 2. The data indicate qualitatively good correlation between estimated and actual HQR. (= .82). Hence, there is good reason to believe that the results of equation 1 may be used to quantify the effect of the DVE on handling qualities.

Equation 3 applies to any situation where micro-texture cueing is degraded for tasks similar to precision hover at low altitude (several feet above the ground). Degraded micro-texture occurs either due to a natural lack of texture (snow, water, grass at night, fog, etc.), or due to limitations of vision aids such a night vision goggles (NVG), or forward looking infrared (FLIR).

4.2. Effect of Handling Qualities on Workload (HQR vs. AD)

While the exact relationship between pilot workload and handling qualities is not well understood, there are some laboratory data that can be used to quantify what seems intuitively obvious. That is, the attentional demand required to control the helicopter must increase as handling qualities are degraded.

The attentional demand required for aircraft control was experimentally obtained as a function of HQR in References 10, and 11. This multi-axis piloted simulation experiment utilized a technique referred to as the “cross-coupled subcritical task.” The primary task was to track a sum of sine waves in the pitch axis, in the presence of an unstable secondary roll task. The pilot subjects assigned HQRs for the primary task and the AD was determined quantitatively in terms of performance in the unstable lateral task. The resulting relationship between HQR and AD is given as:

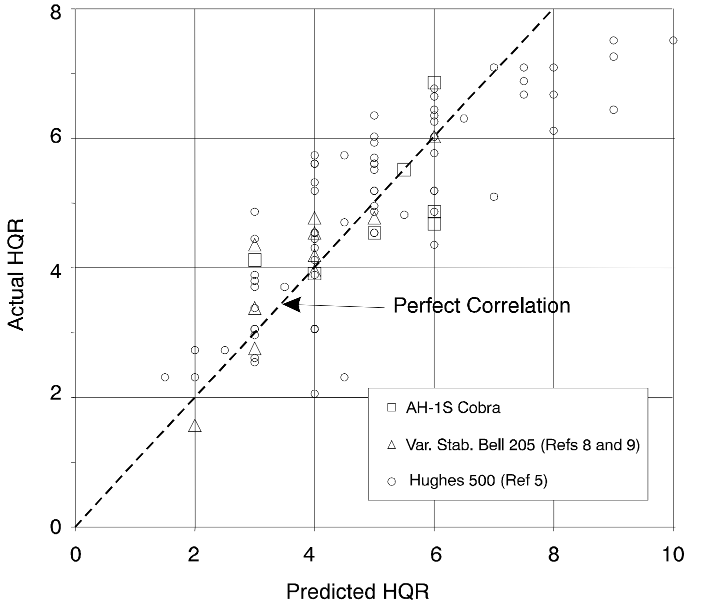

Figure 2 Polynomial Multiple Regression - Rate Response

$$AD = \frac{(HQR - 1)}{8.33} \qquad (4)$$

This important relationship between attentional demand and handling qualities represents the expected trend. However, it must be cautioned that the simplified nature of the experimental “stick and scope” setup is somewhat questionable when compared to actual rotorcraft operations. Certainly more work is necessary to validate or refine equation 4. For the purpose of the present research, this relationship is judged to be adequate as long as the results are interpreted as reasonable approximations.

4.3. Spatial Disorientation Accident Risk

Very low values of AD result in high situational awareness (equation 2) and therefore low risk of having a Type I SD accident, and conversely very high values of AD involve high risk. The risk boundaries, and supporting logic for setting those boundaries are described as follows.

Using the Cooper-Harper HQR scale semantics (Reference 4), a low risk of inadequate situational awareness for Level 1, is defined for (1 < HQR < 4.5). The semantics for a rating of 5 indicates that “adequate performance requires considerable pilot compensation”, and a rating of 4 is described by “desired performance requires moderate compensation”. From equation 4, HQR<4.5 translates to AD < 0.42.

HQRs between 4.5 and 6.5 are judged to involve high risk because they are defined by adjectives that imply high workload (compensation between “moderate” and “extensive”), but “controllability is not in question”. On that basis, high risk for a spatial disorientation accident is defined when (0.42 < AD 0.66).

For HQRs greater than 6.5 there are “major deficiencies” in handling qualities and the required pilot compensation is maximum for adequate performance. In addition, controllability is an issue for HQR >7. Situational awareness is unacceptably low when the pilot is exerting high levels of compensation or having controllability problems, so the region for HQR> 6.5 is considered to be extreme risk (AD > 0.66).

Based on the foregoing, the risk of a spatial disorientation accident due to excessive pilot attentional demand to control the rotorcraft is defined as follows:

- Low risk exists when AD < 0.42
- High risk exists when 0.42 < AD < 0.66
- Extreme risk exists when AD > 0.66

4.4. Effect of DVE on Workload for Low Speed and Hover Tasks (AD vs. VCR)

Equation 3 provides an empirical relationship between handling qualities and the degraded visual environment (HQR as a function of VCR). Equation 4 provides a relationship between attentional demand required for control and handling qualities (AD as a function of HQR). Using equation 3 in equation 4 provides a relationship between attentional demand and the VCRs for attitude and translational rate.

$$AD = 0.306 - 0.122 VCR_\theta + 0.056 VCR_\theta^{\,2} - .010\ VCR_X + 0.031 VCR_X^{\,2} - 0.036 VCR_\theta\, VCR_X \quad (5)$$

This expression applies to helicopters with good basic handling qualities (HQR = 3). The translational rate vs. attitude VCRs are plotted in Figure 3 for constant values of AD defined above as the Low/High and High/Extreme risk boundaries The following interpretations may be made from those results.

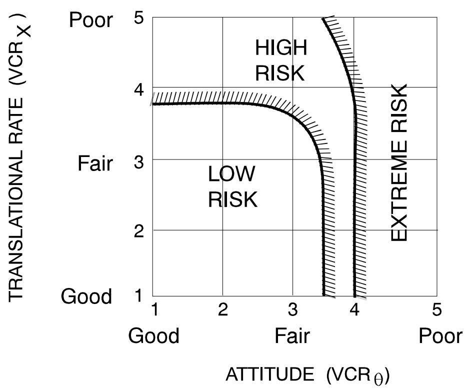

Figure 3 Regions of Low, High, and Extreme Risk - $(HQR)_{GVE} = 3$

- For helicopters with good basic handling qualities, the risk of a spatial disorientation accident increases from Low to High as the visual cue ratings for attitude and translational rate exceed Fair (VCR > 3). Improved attitude cueing (VCR < 2.5) allows a small degradation in translational rate cueing. Similarly, Improved translational rate cueing (VCR_x < 2.5) allows a slight degradation in attitude cueing.
- An Extreme risk of a spatial disorientation accident exists if the attitude cueing is highly degraded (VCR 4), no matter how good the translational rate cues are. This result verifies the intuitive understanding that attitude cues are essential for control i.e., improved translational rate cues cannot make up for degraded attitude cueing
- Fair-to-Poor translational rate cues result in an estimate of High risk, even for good attitude cues. An important interpretation of this result is that adding improved attitude displays will not eliminate the risk of a spatial disorientation accident in conditions where the micro-texture cues are highly degraded. High pilot workload has been, and continues to be, consistently observed on ground based simulators that have good attitude cues (clear and definite horizon), but only fair to poor translational rate cues (insufficient micro-texture). Precision low speed and hover maneuvering on the simulators has proven to be either impossible or requires very high pilot workload, depending on the quality of micro-texture produced by the visual display.

The above results are based on low speed and hover tasks for rate-response helicopters with good basic handling qualities in calm air. For example, if good visual conditions are assumed, (VCR = VCRx = 1), equation 1 results in HQR = 2.9 and equation 5 produces an attentional demand requirement of 22% of the available workload for control (AD = 0.22). The effect of adding augmentation is discussed later in this paper.

4.5. Effect of Turbulence and Degraded Handling Qualities

It is possible to estimate the effect of degraded handling qualities and turbulence by use of the knowledge that both result in an increase in HQR. For example, the HQR for most rotorcraft in a good visual environment, $(HQR)_{GVE}$, in calm air is 4 for precision tasks in the low speed and hover flight regime. Adding moderate turbulence typically adds at least one rating point to the calm air HQR.

If it is assumed that the only impact of degraded handling qualities in the regression equation of HQR vs. VCR is to bias the results, then equation 3 can be rewritten as:

$$(HQR)_{DVE} = (HQR)_{GVE} + 0.65 - 1.02VCR_{\theta} + 0.468VCR_{\theta}^{2} - .084VCR_{X} + 0.257VCR_{X}^{2} - 0.303VCR_{\theta}VCR_{X} \quad (6)$$

Where $(HQR)_{GVE}$ is nominally 3 (the approximate result obtained from equation 3 with VCR $= VCR_x = 1$).

Using equation 4 in equation 6 gives a similar expression for AD.

$$(AD)_{DVE} = \frac{(HQR)_{GVE}-1}{8.33} + 0.078 - 0.122VCR_{\theta} + 0.056VCR_{\theta}^{2} - .010\,VCR_{X} + 0.031VCR_{X}^{2} - 0.036VCR_{\theta}\,VCR_{X} \quad (7)$$

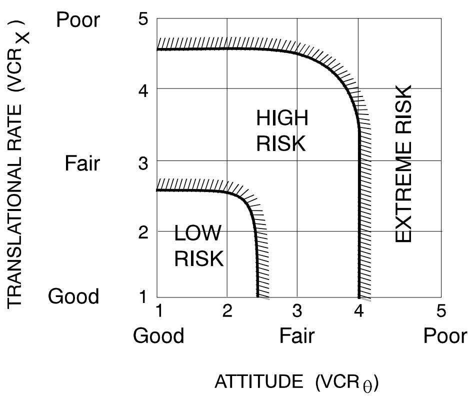

Figure 4 Regions of Low, High, and Extreme Risk - $(HQR)_{GVE} = 4$

The increase in AD due to turbulence and degraded handling qualities can be estimated from equation 7, as long as the HQR in good visual conditions is known. As an example case, the effects of turbulence or degraded handling qualities are illustrated in Figure 4 by assuming that these effects result in $(HQR)_{GVE} = 4$. A comparison with the results in Figure 3, $(HQR)_{GVE} = 3$, shows that the effect of only one $(HQR)_{GVE}$ rating point is considerable. A High risk of spatial disorientation accident is predicted when the attitude and translational rate cueing exceeds only Fair (VCR > 2.8). Fair-to-Poor attitude cueing is seen to result in Extreme risk. If these result seem overly conservative, recall that the basis for estimating extreme risk is that the HQRs are in a region where controllability is in question.

5. Use of Stabilization to Decrease Type I SD Accident Risk

5.1. Handling Qualities Flight Test Results

Flight tests and simulations have consistently shown that the combination of attitude-command-attitude-hold (ACAH) and height hold (HH) augmentation has a significant favorable impact on pilot workload for low speed and hover tasks in the DVE. The primary validation of this conclusion is found in a series of variable stability flight tests conducted using the National Research Council of Canada Flight Research Laboratory (NRC) variable stability Bell 205A. The DVE was simulated in these experiments by using night vision goggles with daylight training filters, and by defocusing to simulate a moonless night. These tests were conducted over a period from 1985 through 1995 in support of the ADS-33D-PRF army flying qualities specification for rotorcraft. A summary of the results is shown in Figure 5, where it is seen that the HQRs for ACAH+HH are significantly improved over the more conventional Rate response for a wide variety of maneuver aggressiveness.

Testing has shown that both attitude command and height hold are required to achieve the decreased workload, and that height hold is primarily required for maneuvering tasks.

Based on results such as shown in Figure 5, ADS-33 includes a methodology to formalize the distinction between rate and attitude "Response-Types". For the purposes of this paper, a Rate Response-Type exists if the helicopter attitude continues to increase following a step stick input. An ACAH response is defined when the attitude following a step stick input is constant. Translational-rate-command is defined when the response to a step stick input is a constant velocity. These "Response Types" are defined in detail in ADS-33D-PRF (Reference 6).

In addition to formalizing the aircraft response, ADS-33 also specifies regions of the VCR_x vs. VCR grid, which are defined as the “Useable Cue Environment” (UCE) as shown in Figure 6. The UCE 1/2 boundary was established based on maintaining Level 1 (HQR 3.5) in the DVE, and therefore the UCE 1/2 boundary in Figure 6 consists of a line of constant HQR = 3.5. A UCE 2/3 boundary is also specified to represent the transition from Level 2 to Level 3 (HQR 8.5). Rate Response-Types are allowed for UCE = 1, and ACAH + HH is required for UCE = 2. Translational rate command is required for UCE = 3.

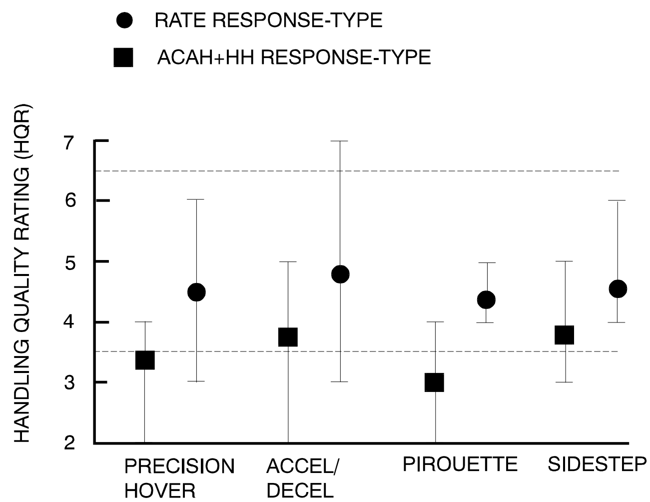

Figure 5 Comparison of HQRs for ACAH + HH with Rate Response-Type in the DVE (Variable Stability Flight Test Results)

A comparison between Figures 4 and 6 shows that the UCE boundaries are similar to the spatial disorientation boundaries when $(HQR)_{GVE} = 4$.

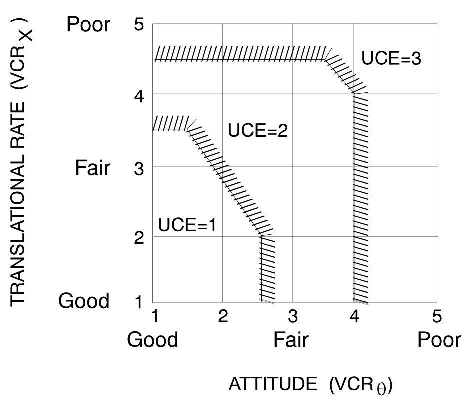

Figure 6 Definition of Useable Cue Environment in ADS-33D-PRF (Reference 4)

Attentional Demand for Control with ACAH + HH

To interpret the benefits of ACAH + HH in terms of attentional demand, a regression fit to the flight test data was accomplished for cases where such augmentation was employed (16 cases).

$$(HQR)_{ACAH} = 1.696 + .022\,VCR_\theta + 0.370\,VCR_X \tag{8}$$

As with the rate response (equation 4), good agreement was achieved between estimated and actual HQR (= 0.64).

Using equation 4, this can interpreted in terms of attentional demand as:

$$(AD)_{ACAH} = 0.084 + 0.0026 VCR_\theta + 0.044 VCR_x \tag{9}$$

This equation indicates that there are no combinations of VCR and VCR_x that result in a prediction of high risk for a spatial disorientation accident; the maximum possible AD = 31.7% of the total workload capacity. However, caution should be exercised in applying this result to the extreme ends of the VCR scales (near 5) since there is little data for that region.

Equation 9 also indicates that with ACAH the effect of the loss in attitude cues on pilot rating is negligible. For example, VCR = 5 (worst possible rating) results in a degradation in AD of only 1.3%. This indicates that with ACAH, even a “perfect” attitude display would not substantially reduce the risk of a spatial disorientation accident.

These results are somewhat non-intuitive. Why should additional stabilization be so much more effective than a high quality attitude display for reducing the required attentional demand for control? The underlying principle for this result is discussed in the following section.

5.2. Effectiveness of Displays vs. Augmentation

The advantage of ACAH over Rate lies in the amount of equalization that is required by the pilot to stabilize the rotorcraft during low speed and hover tasks. This can be shown by a simple analysis of the pilot as an element of a closed loop system as illustrated in Figure 7 . This loop closure assumes that the pilot is using position error and horizontal velocity for stabilization in a hovering task. As shown in Figure 7, the Rate system includes three integrations between the stick and horizontal position, whereas the ACAH system has only two. Assuming the same pilot equalization ($T_{LX}s + 1$) for both cases, the Rate system is unstable and the ACAH system is stable. The instability of the Rate system is due to the additional integration (90 degrees of phase lag) that is inherent to this type of response.

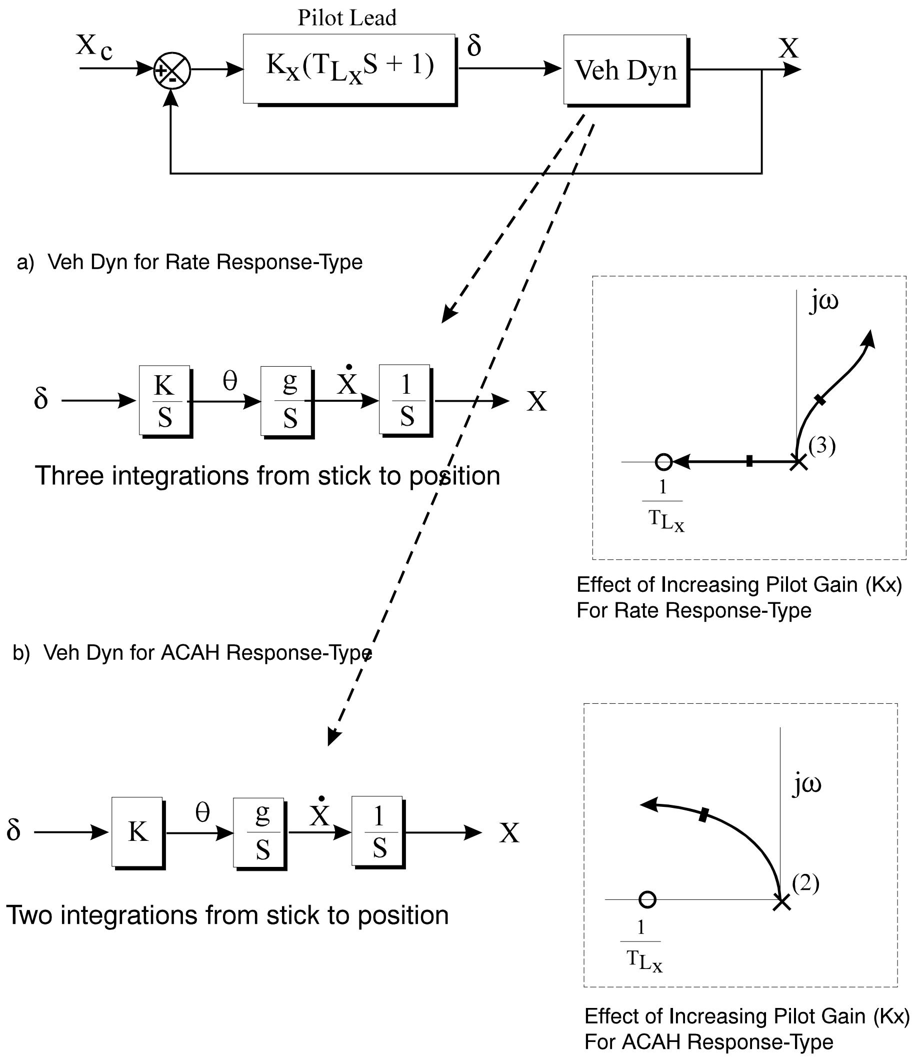

Figure 7 Why ACAH is Better Than Rate for Hover in the DVE

It is hypothesized that in conditions of good visual cueing, the pilot is able to increase his or her equalization by sensing and feeding back small changes in longitudinal acceleration, thereby stabilizing the response for the Rate system. As the cueing conditions degrade, the ability to sense these very small accelerations is degraded. While there is no concrete proof, it is strongly suspected that the important cues for small changes in longitudinal acceleration result from “streamers” emanating from the micro-texture (e.g., blades of grass). As the micro-texture is degraded, experienced pilots learn to search out other cues with rapid eye movements across the visual scene. This activity is suspected to be the primary reason for the high values of attentional demand in the DVE.

A pilot flying in the DVE is faced with a serious dilemma: 1) spend a large percentage of time on helicopter control, or 2) back off from the control task to improve situational awareness. The latter activity is likely to result in undetected drift because of the inherently unstable task.

As discussed in the introduction (Tables 1 and 2), the logical and most commonly recommended solution to spatial disorientation accidents has been to provide displays and warning systems that directly cue the pilot However, adding an improved attitude display does not affect the number of integrations between stick and position, which explains why improved VCR is not an effective solution when VCR_x is degraded. Based on the Figure 7 analysis, the only display solutions that would be predicted to work, would provide lead information, such as an acceleration vector (e.g., Apache PNVS). The problem with such symbology is that it is only effective as long as the pilot is “actively in the loop”. That is another way of saying that high attentional demand is required.

The use of Night Vision Goggles on an ideal full moon night has been shown to provide adequate micro-texture. However, under only starlight conditions, the visual cue ratings are in the Fair-to-Poor range. Forward looking infrared (FLIR) provides excellent macro-texture cues, but is lacking in resolution of the micro-texture, and exhibits Fair-to-Poor VCRs even in ideal conditions. For these reasons, the most advanced U.S. Army helicopter (AH-66 Comanche) is required to have ACAH for operation in the DVE.

Warning devices (e.g., GPWS) and additional instrumentation in the field-of-view (e.g., radar altimeter on helmet mount display) do not address the fundamental problem. In fact they could require additional attentional demand.

In recognition of the value of ACAH for operations in the DVE, the U.S. Army has accomplished significant effort to determine if retrofitting a limited authority ACAH + HH to existing rotorcraft would provide the necessary workload relief. The results to date are very encouraging.

6. Summary

The conclusions from this study apply to low speed, low altitude operations where the pilot is flying with respect to outside visual cues. It is assumed that there is sufficient visibility to see and avoid objects and the terrain, but a degraded visual environment exists because fine grained texture is not visible. This can either be due to natural phenomenon (e.g., whiteout), or degraded performance from vision aids such as night vision goggles.

The conclusions in this paper are based on a methodology for quantifying the DVE through the use of a visual cue rating (VCR) scale. They are also based on making connections between handling qualities ratings (HQRs) and pilot attentional demand (AD) required for control.

The relationship between HQR and AD is based on a simplified laboratory experiment, and is in need of further refinement for more accurate estimation of pilot workload. However, it is judged to be sufficiently valid to support the conclusions presented below.

The risk of a spatial disorientation accident is linked to the attentional demand required for control as follows. High risk is defined when attentional demand exceeds 42% of the total available workload capacity. Extreme risk is defined when the AD exceeds 66% of the available workload capacity. For the purpose of this study, the total pilot workload capacity is considered to be the sum of attentional demand and situational awareness, and is always equal 1 or 100%. (AD + SA = 1).

The attentional demand for rotorcraft control in the DVE depends on two factors, 1) the basic handling qualities in the GVE, and 2) the Response-Type (Rate or ACAH + HH). The relationship between these factors is summarized in Figure 8, where the attitude VCR and translational rate VCR are assumed to be equal (VCR = VCR_x = VCR) to simplify the presentation of the effects. These results illustrate that as the visual environment is degraded: 1) the use of ACAH+HH is highly effective in minimizing the increase in AD, and 2) helicopters with a Rate Response-Type (conventional) suffer a rapid increase in AD. Any

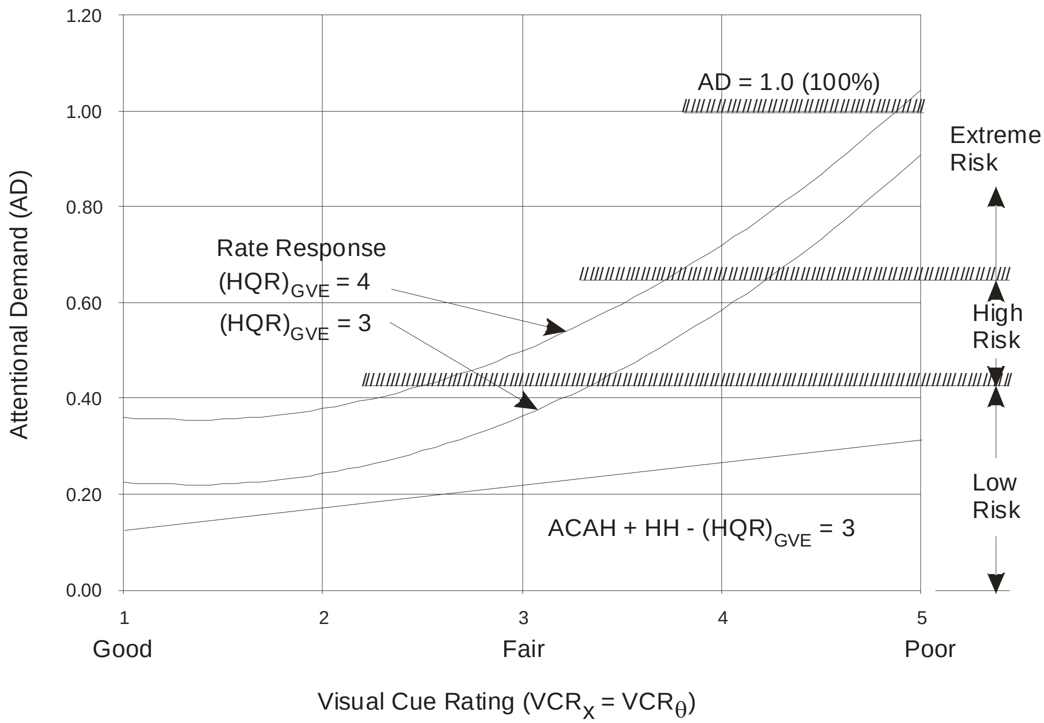

Figure 8 Summary of the Effect of the DVE on Attentional Demand

factor that degrades the HQR in the GVE (e.g., marginal basic handling qualities or turbulence) exacerbates the second result.

7. Conclusions

The conclusions are summarized as follows.

- The estimated risk of a spatial disorientation accident is high if the attitude and translational rate cueing is between Fair and Poor for a helicopter with a Rate Response-Type..
- Attitude Command Attitude Hold with Height Hold (ACAH+HH) augmentation has been shown to significantly reduce the risk of a spatial disorientation accident in the DVE.
- An advanced display of aircraft attitude (e.g. helmet mounted or head-up display) is not an effective alternative for ACAH + HH, nor is it predicted to reduce the risk of a spatial disorientation accident when ACAH+HH augmentation is available. However, basic attitude cueing is essential to maintain Low risk or to avoid Extreme risk (VCR   4) with a rate Response-Type.
- The risk of a spatial disorientation accident for a Rate Response-Type in the DVE is significantly increased if the $(HQR)_{GVE}$ is degraded (e.g., marginal basic handling qualities, or for operations conducted in the DVE with turbulence.)

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