THE IMPACT OF CUE FIDELITY ON PILOT BEHAVIOUR AND PERFORMANCE

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ABSTRACT

For almost as long as flight simulators have been used for pilot training, concerns have persisted that the difference in cueing environments between simulation and flight could compromise transfer of training, and therefore the training effectiveness, of synthetic devices. If these differences are intrusive then confidence in the training value of these devices will suffer and, in extreme cases, pilots may actually experience discomfort or feel sick in a way which is unrepresentative of flight. Reduced motion cues and restricted field of view are well-known differences from flight but the effects of simulator delays and harmonisation between motion and visual cues are less well understood. A knowledge of these effects is necessary if deficiencies are successfully to be countered using cue compensation techniques. Such techniques potentially offer either improved training effectiveness through better use of available cues or cheaper training devices through less-stringent cue requirements.

This paper presents the results of a study to assess the effects of inadequate and poorly-harmonised cues on pilot perception (handling qualities, workload and discomfort), pilot control behaviour and task performance. The study showed that a degraded cue environment, in the form of restricted or delayed motion and visual cues, always leads to increased workload and discomfort, modified pilot control behaviour and degraded performance. Adequate and well-harmonised cues have a major beneficial influence on pilot perception and performance, giving considerable scope for cue compensation techniques to make an impact on training effectiveness.

ABOUT THE AUTHOR

The author has worked on simulation-related activities at DRA, formerly RAE, Bedford, UK for 10 years. Work undertaken has included aircraft mathematical modelling, aircraft control law assessment, aircraft handling qualities assessment and advising the UK Ministry of Defence on training simulator issues such as operational requirements and acceptance testing. As an assignment manager within a UK MoD-funded research package he is currently engaged in identifying and refining techniques for improving the training effectiveness of piloted training simulators.

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INTRODUCTION

Background

This paper describes the results from the first in a series of trials aimed at establishing methods of making a simulator appear to pilots to fly like an aircraft in the absence of real-life motion and visual cues. These methods include cue compensation and pseudo-motion cueing. The aim of this first trial was to gain an understanding of the effects of cue disharmony in a variety of cueing environments so that future compensation schemes can be targeted where they are likely to be most effective.

Flight simulators have long been used for training pilots in aircraft handling and mission tasks. Despite this, concerns have persisted over many years about how the different sensations experienced in simulators, compared to flight, might affect pilot training[1]. These concerns arise from reports of pilots recognising discrepancies between their workload and performance of a task in flight and in simulators and, consciously or sub-consciously, modifying their control strategy to achieve more representative workload and performance in simulators. Where the training task involves an element of aircraft manoeuvring, these discrepancies have the potential to alter the workload balance in the cockpit, in some cases to the detriment of training. Where the training task involves aircraft handling as an integral part of the task, the discrepancies may result in a reduction in training value or even negative transfer of training. The psychological effect of such discrepancies on both instructors and trainees should not be under-estimated. The credibility of a training device is likely to be undermined and, in extreme cases, pilots may actually experience discomfort or feel sick in a way which is unrepresentative of flight.

Objectives

Across a wide range of training devices, from part-task trainers to high-fidelity dynamic and mission simulators, there is a need to maximise training value by optimising the effectiveness of cueing devices and by compensating for missing or false sensations. In practice, this means harmonising cueing devices so that the sensations experienced by pilots feel natural and induce aircraft-like control behaviour in response. Where insufficient cueing devices are available it may be possible to modify the simulation in a way which produces more realistic performance, control behaviour and workload balance.

Before any attempt can be made to compensate for poorly harmonised or inadequate cues, an understanding of their effects on performance, control behaviour and workload balance is required. A benchmark, against which future cue compensation or pseudo-motion techniques can be assessed, is also needed. The simulation trial described here was created to meet these requirements.

The specific objective of the trial was to quantify the effects on pilot perception, control behaviour and performance of simulator cueing deficiencies, in particular the effects of insufficient or badly-timed cues. The investigation addressed visual field of view, motion platform constraints and time delays, including the effects of unsynchronised motion and visual cues.

TRIAL PROCEDURES

Introduction

Measures of pilot perception, control behaviour and performance were used to quantify the effects of different cueing environments. Pilot perception was quantified using the Cooper-Harper handling qualities/workload rating scale[2] and a pilot discomfort scale which was created specifically for the trial. Control behaviour was quantified using stick activity measures[3] and performance was judged using objective measures of aircraft response and touchdown proficiency.

A matrix of configurations with different motion and visual delays was assessed in a variety of cueing environments. The matrix was made up of nine combinations, using three motion and three visual delays, which were presented to pilots in a random order.

The cueing environments were selected for their relevance to current and projected training requirements and were as follows :-

- o fixed-base + single-window CGI visual
- o fixed-base + three-window CGI visual
- o conventional platform motion (synergistic platform emulation) + three-window CGI visual
- o full motion cueing + three-window CGI visual (This configuration was included as a reference, as it had been validated against flight[4])

Three experienced test pilots completed an assessment of every cueing configuration in the study. Two of these were familiar with the simulator and one was not.

Simulation Environment

The trial was conducted using the Advanced Flight Simulator (AFS) facility at DRA Bedford, an important element of which is the largest motion cueing platform in Europe.

A generic fighter aircraft model was used as the baseline vehicle for the study[4]. The handling qualities of this baseline model for an approach and landing task were 'satisfactory without improvement' in the terminology of the Cooper-Harper rating scale.

The task chosen for the study was an offset approach, followed by an 'S' turn onto the runway centre-line at a height of 150 feet. This task had been used in a previous validation study[4] and was known to generate the kind of high-gain pilot behaviour which is necessary to bring out vehicle or simulator deficiencies.

Since the study aimed to provide information which could be used to assess the effectiveness of future cue compensation and pseudo-motion techniques, it was important to minimise the effects of pilot adaptation. On the other hand, the effects of adaptation were also of interest and the reliability of some measures, such as subjective ratings, was likely to improve with prolonged exposure to each configuration. By way of compromise, pilots flew two approaches for each configuration. On the first run, the reference configuration (representing flight) was flown down to the point at which the 'S' turn evaluation manoeuvre commenced, whereupon the test configuration was smoothly blended in. On the second run, the test configuration was flown for the entire approach. Pilots were encouraged to manoeuvre at the beginning of each run, either to re-acquaint themselves with the reference configuration or to practice with the test configuration.

A visual scene of the DRA Bedford airfield was generated by a Link-Miles Image 600PT CGI system with photographic texture. It was presented to the pilot on three collimated monitors with a field of view of 120° in azimuth and 30° (47° for the side monitors) in elevation. The side monitors were blanked out for single window configurations.

The Large Motion System (LMS) has three rotational and two translational degrees of freedom (heave (±5m) and sway (±4m) in this case). Ultimately, the aim of the work is to make simulators feel and perform as much like aircraft as possible. Since the AFS had already been successfully validated against flight for the approach and landing task[4], a configuration using the full capabilities of the LMS was included in the test matrix to represent the real-flight case. A second motion cueing environment was also included to emulate a conventional 6-dof synergistic platform. This involved increasing the frequencies of the motion drive 'washout' filters to constrain platform movement. Motion gains (or more accurately, attenuations) were set to be the same as the full LMS drive laws. This had the added advantage that any effects measured would be dependent on motion 'washout' frequency only. The absence of a surge degree of freedom was not considered to be significant for the approach and landing task.

GUIDE TO INTERPRETATION OF RESULTS

Measures used in the Assessment

Handling Qualities Rating: The Cooper-Harper Handling Qualities Rating[2] (HQR) scale (Figure 1) provides a subjective measure of aircraft handling qualities and piloting workload which takes into account the task performance and any pilot compensation required to achieve it. A low rating indicates that the handling qualities are satisfactory whilst higher ratings indicate degraded handling, increased workload and poorer performance.

Discomfort rating: A literature survey of reports relating to simulator-induced sickness[5-11] produced useful background material but no questionnaires or rating scales of relevance to this trial. Simulator sickness tends to occur after prolonged exposure and all the rating scales found in the literature relate to well-developed symptoms. Since pilot exposure to each configuration would be severely limited in this trial, the requirement was for a rating scale which would be sensitive to even very minor signs of discomfort. A scale, comprising the two left columns of Figure 2, was created for the trial and used with some success, though it was still not sensitive enough. If discomfort was registered by a pilot it was never greater than moderate and usually only mild with a qualifying comment. Numerical ratings, based on the scale and a review of pilot comments, were assigned later to quantify the level of pilot discomfort.

Pilot control behaviour: Pilot control activity was measured using the root mean square (rms) value and the 'pilot cutoff frequency', based on the stick force signal throughout the formal approach and landing task, ie from initiation of the 'S' manoeuvre to landing. These represent a characteristic amplitude and frequency of the command signal. The pilot cutoff frequency is a measure of pilot operating bandwidth and is defined as the frequency below which half the power in a signal is contained. The measures have been successfully validated by comparing identical vehicle configurations in the AFS and in flight[3].

Aircraft Response: The magnitude of the aircraft response was measured using the rms value of roll rate throughout the task, from 'S' turn to touchdown, to indicate how successfully pilots kept the aircraft under control.

Touchdown performance: The quality of the landing was assessed using a weighted average of several aircraft state variables at the instant of touchdown, expressed as a percentage of nominally 'ideal' touchdown values. These were landing dispersion, aircraft attitude, sink rate and airspeed. The percentages achieved are not in themselves significant: it is the variation in performance caused by changes in the cueing environment that is important. Although the measure is derived at a single point in time, it can reasonably be expected to reflect the pilots' difficulties in controlling the vehicle, provided enough measurements are taken to smooth out the inevitable variability.

Interpretation of Results

The results have been averaged for all pilots and presented as two-dimensional maps, where the horizontal axis represents added visual delay in all cases. Where a configuration includes motion cueing, the vertical axis represents added motion platform delay. Where no motion cueing is present, the vertical axis represents the (reducing) number of visual windows. The convention is that 'up' and 'right' represent a degradation in the controlled elements of the cueing environment, ie an increase in delay or a restriction in visual field of view.

As a guide to interpreting the maps, some examples are given to illustrate what the maps would look like if certain assumptions are made about the relationship between visual and motion cue delays. The maps for the fixed-base results are relatively straight-forward and need not be explained at this stage.

The simplest cases would be to assume that the variable of interest, eg pilot operating frequency or touchdown performance, is sensitive to delays in visual cueing only (Figure 3a) or in motion cueing only (Figure 3b).

If we assume that the variable is solely a function of cue disharmony, ie the difference in delay between motion and visual, then the map will look like Figure 3c. The contour lines join points where the difference in delay is the same and the value of the variable represented by each contour increases as a function of cue disharmony. In other words, the difference in the delays is more important than the absolute delays. The symmetry indicates that the function is not affected by whether motion leads visual or vice versa.

Conversely, if the variable is completely independent of cue disharmony then the contour lines will be perpendicular to the above as shown in Figure 3d. At all points on this map incremental changes to either motion or visual delay have equal effect, eg the variable may be dependent on the average of the motion and visual delays. In this case the absolute delays are more important than the differences between them.

If the variable is influenced by motion and visual delays in proportion to their absolute values then the incremental effect will be equal if the delays are equal but otherwise dominated by whichever is larger (Figure 3e). For example, changes to the motion delay will have little effect if it is small relative to the visual delay and vice versa.

DISCUSSION OF RESULTS

Introduction

Figures 4 to 6 illustrate the results for full motion cueing, conventional motion platform cueing and fixed-base cueing environments respectively. The results presented are based mainly on pilots' first runs, ie before learning could occur. The exceptions are the discomfort ratings and touchdown performance which are based on both runs. These measures required longer exposure and a greater number of samples respectively to produce sensible results. Pilot comments indicated that handling and performance was affected mainly by vehicle characteristics in the lateral axis, and this was confirmed by data analysis, so only the lateral stick activity and aircraft response are shown. Each figure contains three groups of contour plots arranged, from top to bottom, as follows:-

- o pilot perception (handling workload and discomfort)
- o pilot control activity (amplitude and frequency)
- o task performance (aircraft roll rate and touchdown proficiency).

Contour smoothing and interpolation techniques have been used to aid interpretation of the maps. General trends can be established with confidence but fine detail needs to be treated with caution because the maps have been generated from small numbers of pilots and test points.

Full Motion Cueing Environment (Figure 4)

Handling Qualities Rating: With full motion cueing the HQR map resembles Figure 3e. When closely harmonised, incremental changes in visual or motion delay have equal effect but if one delay is significantly larger than the other then incremental changes in the smaller of the two delays have little effect. An interesting difference from Figure 3e is that for small motion delays the HQRs are influenced predominantly by cue disharmony. In this area, at the bottom of the map, an increase in motion delay actually improves the HQR, ie decreases the handling workload. The data suggest that the motion platform delay is less than the visual delay, which is consistent with the simulator's known characteristics. Pilot comments confirmed that an additional motion delay improved cue harmony.

Pilot discomfort: Pilot discomfort can be seen to be almost solely a function of cue disharmony: the greater the differences in delay between visual and motion, the higher the discomfort rating (cf Figure 3c). This might be expected from current theories on simulator sickness, which link sickness to cue conflict[10]. The symmetry indicates that discomfort is independent of whether motion delay is less or more than visual delay. The bias in the vertical direction is consistent with the known difference in nominal motion and visual delays.

Pilot control behaviour: Stick magnitude increases mainly as a function of visual delay for low delays but motion delay becomes more important as the motion and visual delays increase. Motion delay does not appear to have much influence on stick frequency which decreases strongly as visual delay increases. This is surprising given the significant increase in frequency that invariably accompanies motion cues compared to visual cues alone.

Aircraft response: Aircraft roll magnitude shows much the same pattern as the pilots' stick amplitude, with motion delay becoming more influential as the visual delay increases.

Touchdown performance: The variation in touchdown performance is virtually identical to the variation in pilots' handling/workload ratings, indicating that motion and visual delays affect performance in a very similar manner to the way they affect handling qualities.

Conventional Platform Motion Cueing Environment (Figure 5)

Handling Qualities Rating: With conventional platform motion cueing the HQRs are influenced mainly by the visual delay, though large motion delays do have an effect. The small change in the slope of the contours as visual delay increases indicates an increasing tendency to be influenced by cue disharmony, an effect which is most pronounced at the lower right of the map where disharmony is greatest. The ratings are generally better than those for the full motion cueing environment, indicating that the reduced motion cues are conveying to pilots a different perception of the vehicle's handling qualities.

Discomfort rating: Like the discomfort ratings for the full motion cueing environment, those for the conventional platform motion environment are predominantly a function of disharmony. The map suggests that cue harmony would be improved by adding a considerable motion delay, much more than can be explained by the difference in nominal cue delays. The explanation probably lies in the motion drive laws, specifically the 'washout' filter which constrains the platform motions. A side effect of this filter is to distort the dynamic response of the cockpit: the higher the 'washout' frequency, the greater the phase distortion at the low frequency end of the pilots' operating spectrum. This phase lead is the opposite of the phase lag induced by time delays so, for the large-amplitude low-frequency manoeuvres likely to cause discomfort, extra time delay could compensate. The disadvantage of doing so would be poorer high frequency response, which would affect vehicle handling qualities.

Pilot control behaviour: Like the HQRs, pilot control activity is influenced predominantly by visual delay. The stick magnitudes cover a greater range than with full motion cueing and change from being dependent on absolute delays to being dependent on relative delays from top left (maximum motion delay, minimum visual delay) to bottom right (minimum motion delay, maximum visual delay). Note also that the highest control frequencies are at the top left of the map. Both these effects are consistent with the handling qualities and discomfort ratings. Pilot operating frequencies are significantly lower than with full motion cueing, probably due to the additional disharmony effects of the motion washout filtering.

Aircraft response: The aircraft roll response contours follow very similar trends to those of the stick magnitude. The roll rates generated are significantly higher than those generated with full motion cueing, even allowing for the additional stick magnitudes. This indicates that the motion cues are insufficient to induce pilots to use the same high gains that they use when full motion cueing is available.

Touchdown performance: For low visual delays, variation in touchdown performance is similar to the variation in handling quality ratings, ie incremental changes in motion delay are relatively insignificant unless the absolute motion delay is large. For large visual delays, however, motion delays have a significant effect on touchdown performance, unlike the HQRs.

Fixed-Base Cueing Environment (Figure 6)

Handling Qualities Rating: The fixed-base HQR results can most easily be compared with those for the motion cueing environments if the zero added motion delay case is used because the horizontal axis has the same meaning on all graphs. The vertical axis for the fixed-base environment represents reducing visual field of view. Along the horizontal axis the HQRs generally become poorer as we move from full motion, through conventional platform motion, to fixed-base. The three-window configuration produced a larger spread of ratings than the single-window configuration, for the same reason that motion cues normally increase the rating spread, ie the better cues show up deficiencies more clearly.

Discomfort rating: Discomfort levels for the three-window fixed-base environment are relatively low provided the delay is low but increase as the delay increases. Ratings for the single-window fixed-base environment are poor even with no added delay and extra delay makes matters even worse. These results are surprising because past evidence has suggested that wide field of view simulators are **more** likely to induce simulator sickness, not less. The answer may be that early signs of discomfort do not necessarily lead to simulator sickness or that the discomfort in this case is more psychological than physiological. A trial involving longer-duration sorties would be needed to answer this question satisfactorily.

Pilot control behaviour: Pilot stick activity shows that stick magnitude is predominantly a function of delay and that the reduction in field of view does not have a significant impact. Pilot control frequencies are reduced significantly by delay and also by restricted field of view. Compared with full motion cueing, visual delay in the fixed-base environment has a much greater influence on stick magnitude, shown by the more closely packed contours, and on stick frequencies, which are significantly lower.

Aircraft response: Field of view has only a minor effect on aircraft response magnitude compared to the effects of delay.

Touchdown performance: The restriction in field of view degrades touchdown performance. This is not reflected in the HQR results, indicating that pilots did not perceive the degradation in performance.

CONCLUSIONS

The study showed that pilots are likely to require both motion and visual cues, minimum delays and harmonised cues to achieve the same handling qualities, pilot workload, control behaviour and task performance in the simulator as in the aircraft. Inadequate or poorly-harmonised motion and visual cues degrade pilot performance.

Degraded cueing, in the form of delayed visual cues, restricted visual cues, delayed motion cues, distorted motion cues or no motion cues, causes the following:-

- o increased workload as a result of degraded handling qualities
- o increased pilot discomfort
- o larger control movements at lower frequencies
- o poorer performance

Provided the motion cues are adequate and reasonably well harmonised with visual cues, the effects of additional motion and visual delays are similar. However, if the asynchrony between visual and motion cues is large, then incremental changes in the smaller of the two delays has less effect than changes in the larger. With full motion cueing, pilot discomfort increases in proportion to motion/visual asynchrony, regardless of which cue has the bigger delay.

For conventional platform motion cueing, visual delay is the dominant influence. However, a complicating factor here is that the added motion delay counters the phase lead distortion introduced by the 'washout' filters used to constrain the platform. Discomfort ratings actually improve when motion delay is added. In general, this motion cueing environment appears to offer little advantage over the equivalent fixed-base environment and in terms of pilot operating frequency it is worse. This result must be treated with caution because the motion drive laws were not optimised for the vehicle.

By every measure, fixed-base cueing environments produce poorer results than a full motion cueing environment. In particular, pilot control activity is markedly greater, showing larger control amplitudes and much lower operating frequencies. Discomfort is higher than in either of the two motion cueing environments.

The study showed that an adequate, well-harmonised motion and visual cueing environment has a major beneficial influence on pilot perception, control behaviour and performance. There is therefore considerable scope for cue compensation and pseudo-motion techniques to make an impact on training effectiveness, particularly for fixed-base simulators and part-task trainers. Work is currently underway on both these techniques.

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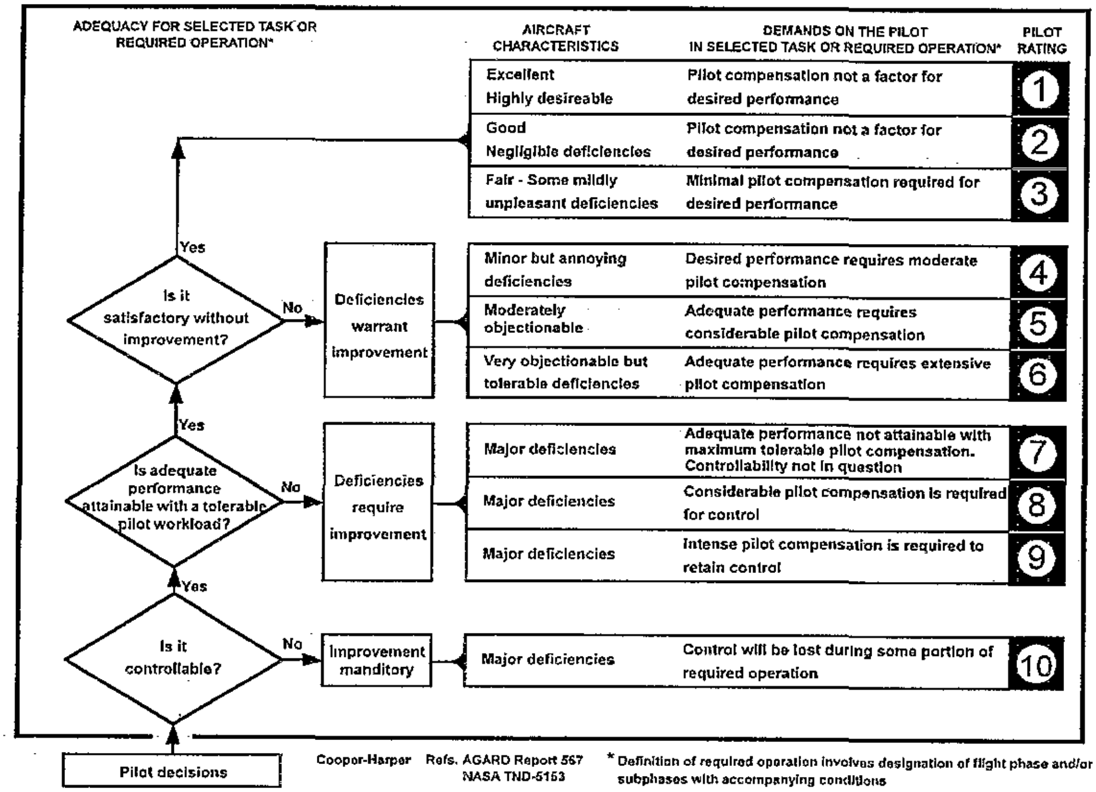

Figure 1 Cooper Harper handling qualities rating scale

Symptoms	Discomfort	Rating
No unpleasant sensations or discomfort experienced.	None	0
Unpleasant sensations detectable but easily disregarded. Feels slightly uncomfortable.	Mild	3
Unpleasant sensations moderately intrusive. Feels uncomfortable.	Moderate	6
Unpleasant sensations very intrusive. Feels very uncomfortable.	Severe	9
Extremely unpleasant sensations. Discomfort intolerable.	Unacceptable	12

Figure 2 Discomfort rating scale

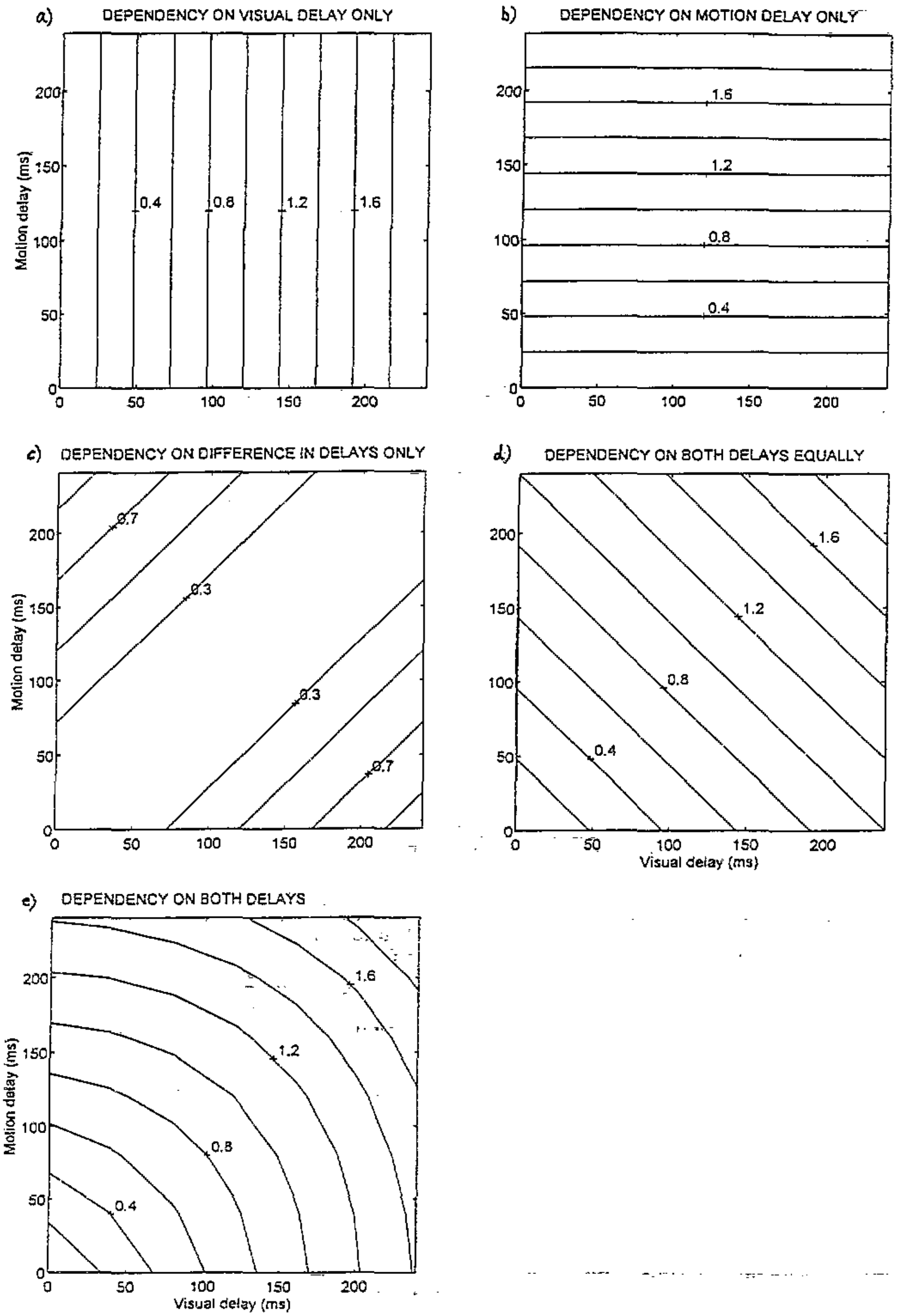

Figure 3 **Examples of function contours assuming a variety of dependencies on motion and visual delays**

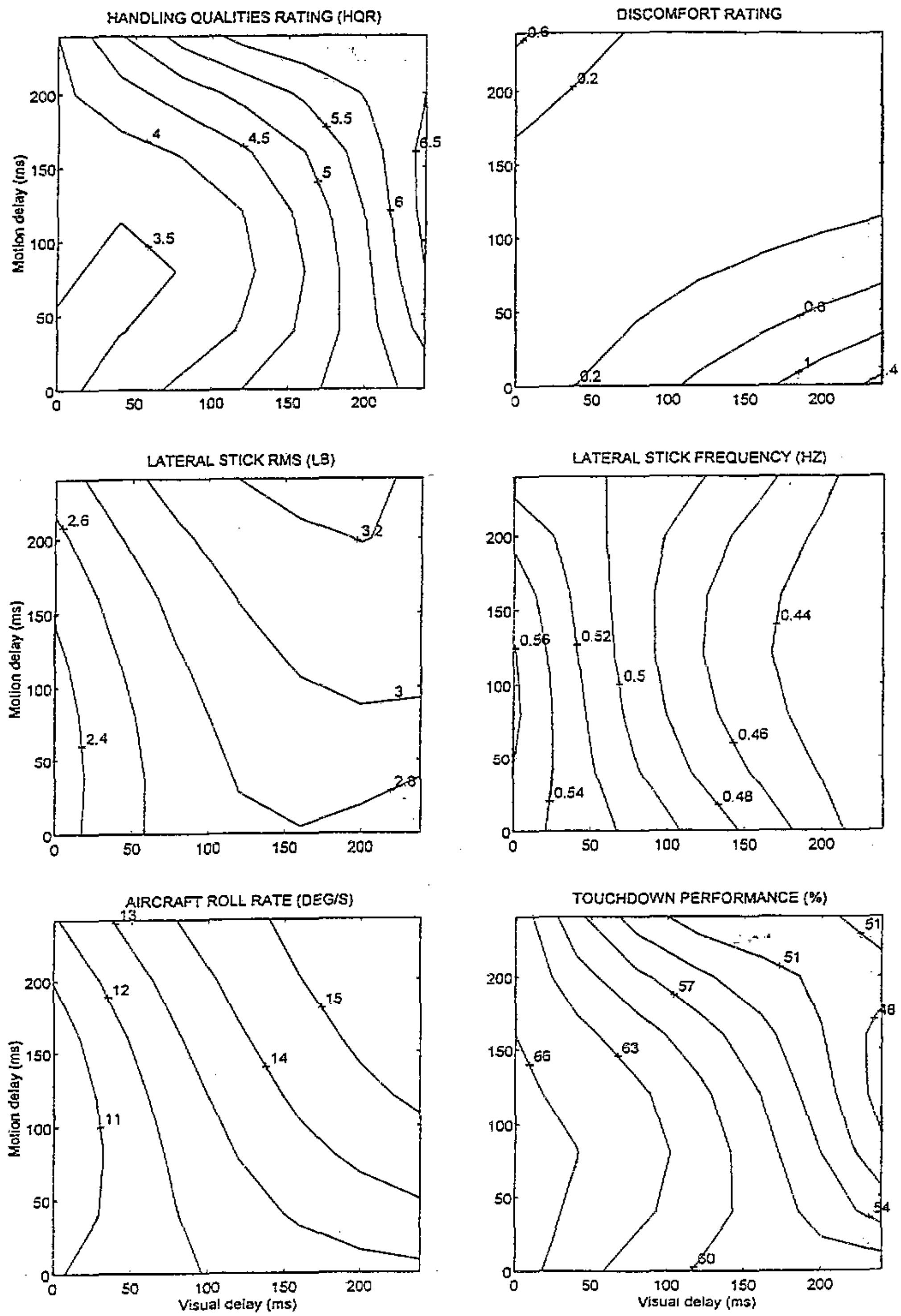

Figure 4 The effects of motion and visual delays in a full motion cueing environment

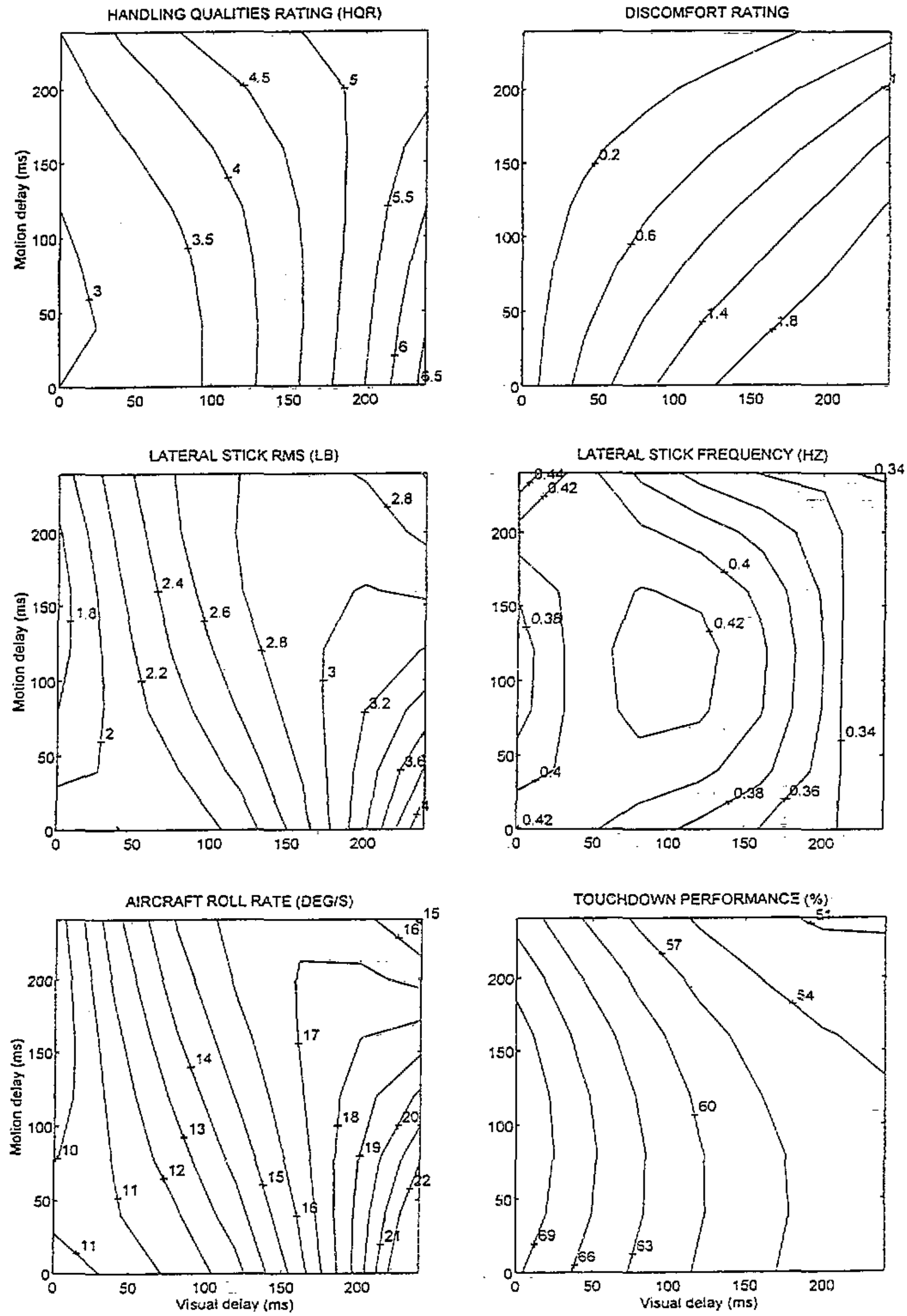

Figure 5 **The effects of motion and visual delays in a conventional platform motion cueing environment**

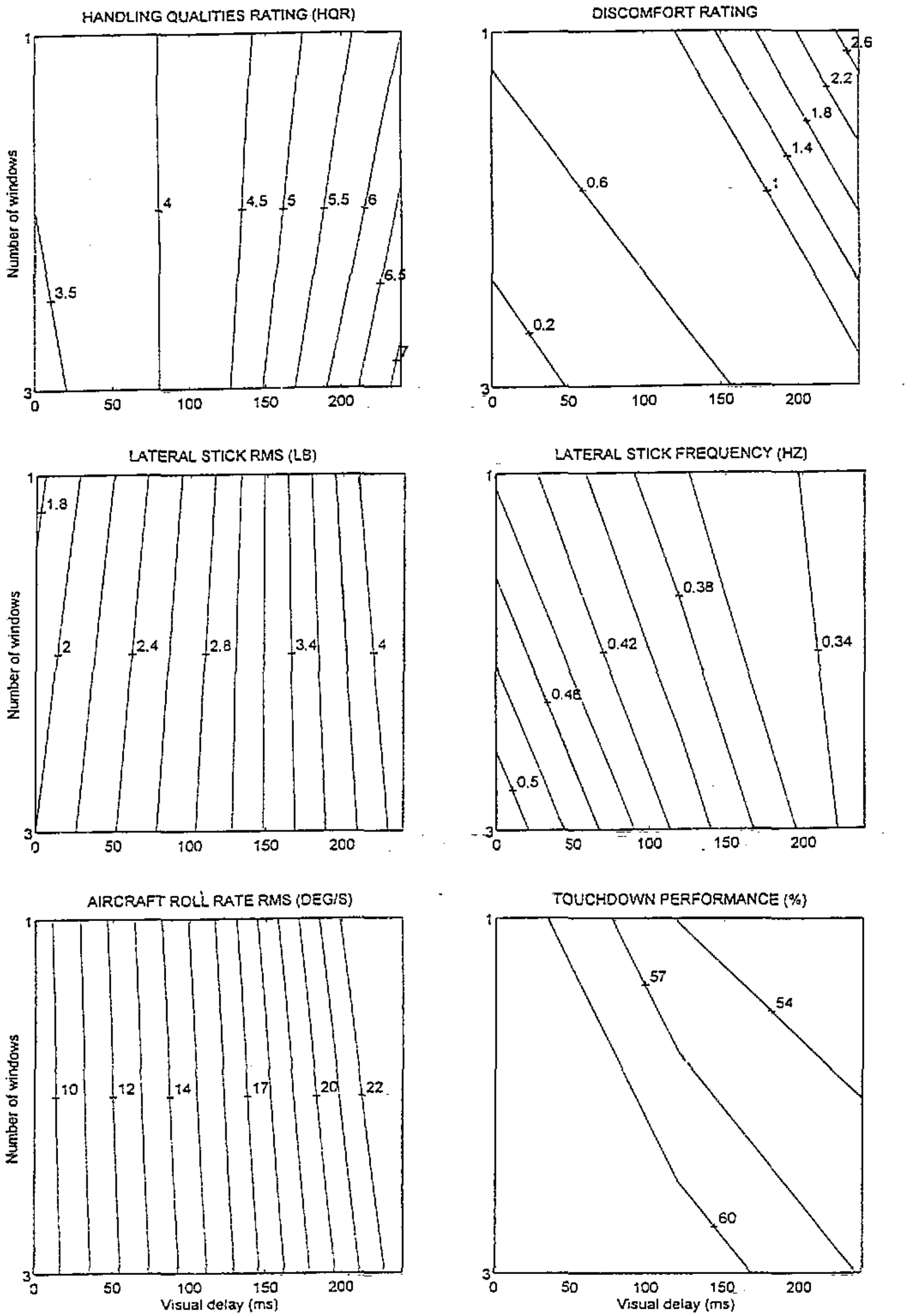

Figure 6 The effects of visual field of view and delay in a fixed-base cueing environment