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Literature Review of Display Research Relevant to the HSCT External Vision System

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1.0 Executive Summary

Aerodynamics dictate that the High Speed Civil Transport (HSCT) have a forward nose section which is considerably longer and more pointed than subsonic transports. The geometry of this forward section, combined with the high angle of attack flown by a delta wing aircraft, causes a partial obstruction of the pilots' forward vision from the flight deck. An electronic external vision system (XVS) consisting of video cameras and large-field-of-view displays has been proposed as a means of providing forward visibility to the pilot without drooping the nose of the aircraft. This report covers the findings of a literature review of research which has examined human performance issues relevant to the design and implementation of an external vision system (XVS) for the HSCT. The primary goals in performing this review were: (1) to identify the extent to which previous research has demonstrated the efficacy of external or synthetic vision systems; (2) to determine which issues have been found to be important in the use of indirect or artificial visibility systems; and (3) to provide recommendations based on this information which can be used to better direct future XVS research within the HSR/HSCT program.

The reports summarized in this document include information on the effects of various indirect vision system parameters on pilot performance, including image field of view, magnification, resolution, collimation, and parallax. While the research reviewed describes a variety of system implementations and simulation studies which used a broad range of research methodologies, two interesting findings emerged which appeared to be relatively consistent across several of the studies. The first general finding indicated that pilots could successfully perform approaches and landings with indirect vision systems which provided relatively limited fields of view (e.g., 17°). One caveat to this finding is that the tests typically involved only straight-in approaches which did not require blind turns onto final. The other notable finding was the tendency of pilots to perceive imagery on displays as being smaller, or perceptually minified, compared to imagery viewed directly through windows. Interestingly, the magnification level of the displayed image was found to significantly affect longitudinal touchdown point in several studies. Some degree of magnification greater than one was typically employed in these systems to counteract this effect.

One research area which has not received much attention is the interaction between a forward indirect vision display and a conventional side window. Only three reports were reviewed which have considered the effects of differences between an indirect vision display and simulated side window display. These differences, which define various types of conformality between the two displays, exist along several dimensions (e.g., image scale, resolution, etc.). Efforts are currently underway to investigate some display conformality differences, but clearly more work needs to be done to follow up on preliminary results and address unresolved issues.

2.0 Introduction

The current baseline for the HSCT XVS uses a video image to provide forward visibility from the flight deck while conventional side windows provide near-forward and lateral visibility. The ability of this combined system to support pilot functions as well as, or better than, a conventional layout of windows must be adequately demonstrated to ensure the successful development and certification of the XVS component of the HSCT flight deck. The research required to fulfill this task is considerable, placing a great importance on leveraging off key findings from relevant work which has been conducted previously. The lessons learned by others who have experimental or operational experience with systems similar to the XVS can serve to both identify important issues to pursue, as well as help in avoiding the duplication of existing work. This report is an attempt to identify the current state of knowledge regarding the efficacy of using video and other imaging techniques to support a range of pilot tasks and performance criteria. In conducting this literature review, papers written over the past 40 years were identified which contain information relevant to current XVS issues. These fell into two broad classes: system implementation studies and simulation experiments. The system implementation studies described the development of indirect vision systems and, to a greater or lessor extent, some form of testing and evaluation of the systems. (The term “indirect vision system” is used as a general referent for systems described in the reports discussed here, while the acronym “XVS” refers specifically to the HSCT flight deck.) The simulation experiments used formal experimental methods to study various indirect vision system parameters. In some cases formal experimentation was conducted in fully implemented systems (e.g., in aircraft).

The papers which described implementations and subsequent testing of aircraft indirect vision systems report generally positive results. Some of these projects were conducted with imaging and display technology which is now over thirty years old. Therefore, it is quite likely that current systems which leverage recent technology advances may offer substantially improved performance over the systems described in this report. While the scope of testing conducted in these indirect vision system demonstrations was necessarily limited, focusing primarily on approach and landing maneuvers, the positive findings support the feasibility of the XVS concept within the domains of the test conditions used, which included a variety of aircraft types, such as light single and twin engine models as well as large commercial transports. Taken collectively, the reviewed studies reported that more than 1000 manual landings have been performed using various external/synthetic vision systems. Most of these research efforts, however, did not focus on a systematic investigation of the parameters involved in displaying an image of the forward view to the pilot, but rather consisted of testing a limited set of system configurations.

The second broad class of research more closely examined the factors which influence the performance of pilots using an indirect vision system to perform a variety of flight tasks, typically using an experimental simulation approach. This work, most of which has been performed within the HSR program, has more specifically identified how system parameters mediate performance, including sensor and display fields of view, image magnification, collimation, resolution and sensor/display parallax. This ongoing work has filled in many of the gaps in knowledge with respect to XVS systems and promises to further refine the relevant XVS design issues.

The organization of this report is based on the XVS issues which have been identified to have known or potential impact on pilot performance (e.g., field of view, image magnification, display resolution, etc.). The literature which addresses these issues is summarized in the respective sections. Most of the studies provide information on several XVS issues, and therefore will be mentioned throughout the report. Brief background summaries of the studies are presented in the first Issues section (FOV), or in the first section in which the study is mentioned. Therefore, it will be helpful to read the first Issues section for details about reports which are discussed for the second time in later sections. Finally, in many cases variables were manipulated together (e.g., magnification was increased, but display size remained constant resulting in a decrease in image or camera field of view). This complicates interpretation of the study's findings, and to some extent requires discussion of both of the variables in the same Issues section.

3.0 XVS System Parameters

3.1 Field of View (FOV)

One of the critical issues in the development of the XVS is the field of view requirements for the image displayed to the pilot. The influence of FOV restrictions in aircraft and ground research vehicles, as well as in experimental flight simulations has been well documented in the literature. However, little formal experimental manipulation has been conducted to assess the effects of varying the FOV independently from image magnification. Field of view, as the term is used in this report refers to the angular extent, vertically and horizontally, of the outside view which is presented to the pilot, regardless of the size of the display device on which (or through which) the image is displayed. This term is different from display FOV, which is the angle subtended by the display at the eye. In most of the system demonstration research reviewed here, image FOV was manipulated by varying the focal length of the lens used to capture the image, while the display size remained constant. This of course resulted in concomitant changes in image magnification which influence the conclusions that can be drawn from the tests. The reports which describe experimental tests using systems that were actually implemented, either in aircraft or in ground vehicles, will be summarized first. Work which has used simulation techniques to examine FOV effects will be discussed subsequently. Within the following sections, the research will be presented more or less chronologically.

3.1.1   XVS Implementation Studies

3.1.1.1 Roscoe, Hasler and Dougherty (1966)

The pioneering work of Roscoe (summarized in Roscoe, Hasler and Dougherty, 1966) represents the most extensive evaluation of an external vision system to date. Although the work was conducted in the 1950s, it remains quite relevant to current XVS FOV and magnification issues. The system employed a periscope mounted directly forward of the left seat in a light twin engine trainer (Cessna T-50). An image of the forward view was focused on a ground glass plate which measured 8″ square. The resulting display FOV was approximately 23.6°, while three lenses produced magnification factors of .86, 1.20 and 2.00. The effects of varying magnification will be discussed in detail in a later section. With respect to image FOV, however, the researchers found that the lens which provided a 25° FOV (mag. = 1.20) supported better performance than did the displays offering 35° or 15° FOV. Using the 25° FOV lens, pilots were able to take off, approach and land effectively in a variety of conditions. The utility of the periscope display was demonstrated in a series of experiments, one of which involved low-time students with no previous twin experience.

An intriguing finding of these experiments with respect to the FOV issue, is that the largest FOV (35°) was found to be inferior to the 25° FOV image. Another way to interpret this is that the costs of image minification were greater than the gains from the additional image FOV. This is an important finding because it shows that when a trade-off was necessary in this particular display implementation, the need for a slightly magnified image outweighed the need for a larger FOV. Potential reasons for the relative importance placed on image magnification over FOV include the fact that the pilot flying likely did not have responsibility for surveillance, considering that their only outside view was through the periscope display and that a safety pilot was always present in the right seat. Additionally, the focus of the research was on pilots' abilities to control the flight path during approach and landing, skills which were supported by the magnified display. The primary conclusion relevant to the FOV issue is that the tasks which were performed in these experiments did not require a FOV larger than 25°. Even with the option for a 35° FOV, other considerations (i.e., image magnification) were found to be more important. What is not clear from this research is whether the relative importance of magnification over FOV would exist in systems which have substantially greater FOVs, such as the current baseline design for the HSCT. Simulation work which addresses this question is discussed later.

3.1.1.2 Kibort and Drinkwater (1964)

Using a television display system mounted in a DC-3, Kibort and Drinkwater (1964) tested three camera lenses which provided respective fields of view of 11°, 23° and 48° from a position in the lower part of the aircraft's nose. An underbelly camera position toward the tail was also tested with the wide FOV 48° lens. The TV monitor offered pilots a 17° display FOV, which resulted in magnification factors of 1.55, .73 and .34 for the 11°, 23° and 48° lenses respectively. Results of approach and landing trials showed that while vertical acceleration at contact was comparable between the TV and control (direct visibility) conditions, the dispersion of touchdown points was somewhat greater using the TV display. With respect to FOV, the 11° image FOV supported the most accurate performance among the TV conditions. Similar to Roscoe's findings, the greater magnification apparently fostered more precise flight path control (possibly through the added display gain). The procedures tested, however, included only straight-in approaches and landings which limit the conclusions which can be drawn from the experiment. What can be concluded is that pilots were able to successfully perform the tasks which they were attempting using a fairly restricted image FOV (11°). Finally, the pilots commented that the TV display was acceptable for approach and landing provided that other critical flight instrumentation was present (specifically, altitude, a/s and vertical rate).

3.1.1.3 Reeder and Kolnick (1964)

Systematic manipulations of FOV were not part of a research effort conducted by Reeder and Kolnick (1964), but their successful testing of a TV visibility system in a single engine trainer offers further support to the feasibility of such a system. A camera mounted under the left wing provided a 21.5° image FOV on a 12″ monitor in front of the pilot. The magnification factor was not explicitly stated in the report, but was likely close to 1. The pilots commented that the "more important" visual cues were provided by the TV image, and that the image FOV was adequate for the task of approach and landing.

3.1.1.4 Hood (Boeing SST, 1966)

As part of the SST research program at Boeing, Hood (1966) reports on the implementation of a TV visibility system on a B707. A camera was installed on the belly, behind the main landing gear, oriented 5° pitch down. Image FOV could be varied between 13° and 53° horizontally by zooming the camera lens, but the report contains no information on the relative advantages of the various camera FOV settings. After several test flights, comments from the test pilots indicated that landings could be made using the TV monitor, provided that other flight information was superimposed on the TV image (i.e., altitude and attitude). This system later evolved into an early version of the electronic attitude director indicator (EADI), which did combine a forward looking TV image with primary flight information.

3.1.1.6 Layton and Dana (1966), Gaidsick, Dana and McCracken (1969)

A binocular optical viewing system was installed in an F-104B aircraft and tested in a variety of approach and landing configurations. The system used two periscopes whose image receptacles were positioned several times further apart than human eyes, resulting in a super-stereo effect. The oculars provided a total FOV of 130° horizontally by 90° vertically, with 50° of overlap from each eye. Although safe and acceptable performance was achieved during all flight phases (daylight visual flight), pilot comments indicated that the lack of a side view degraded performance of circling approaches. On some approaches pilots were allowed to use the conventional side view afforded by the canopy, which was considered very beneficial by the pilots. This finding is interesting in that it underscores how dependent the opinions of those participating in the tests are on the kinds of maneuvers performed. This project utilized a high-performance aircraft to in part simulate power-off approaches from high altitudes using fast approach speeds (300kts). It is likely that these specific maneuvers placed a greater requirement on lateral visibility than straight-in approaches; this is a potential reason that the pilots in this study expressed a desire for greater lateral FOV, while those in the other flight test programs discussed here did not in general find the comparatively limited FOVs to be a problem.

3.1.1.7 Gee and Carr (1978)

A TV visibility system was implemented in a light twin-engine aircraft to study the requirements for landing a remotely piloted vehicle (RPV). In the first phase of experimentation, the system was comprised of a 9″ (diagonal) monitor mounted in the instrument panel. The display subtended 16.5° horizontally and 13° vertically at the pilot's eye point; the camera lens setting selected after initial testing provided a 14°(h) X 11°(v) image FOV, resulting in a display magnification factor of 1.2. The camera was aligned 5° down in the vertical dimension. Image FOV settings were not formally manipulated, but pilot comments indicate that the FOV selected was optimal for the conditions which were present in the evaluation. The tasks included a series of shallow and steep approaches and landings. The pilots also commented that they felt proficient after about 10 landings, and that a safety pilot would likely not be required after approximately 30 landings. The second phase of the project involved controlling the aircraft from a ground station which duplicated many of the instruments on the aircraft's panel.

Interestingly, in the absence of many of the perceptual cues present in the aircraft (e.g., vestibular, auditory, etc.), the pilots requested that a slightly larger (11″) monitor be used in the ground station instrument set-up. Apparently, the pilots felt that a larger FOV compensated, at least partially, for the information lost due to the remote nature of controlling the aircraft from the ground. This hypothesis is supported by the general finding that landing using the TV image involved higher workload levels than landing by using conventional transparencies.

3.1.1.8 Rowles (1990)

More recently, Rowles (1990) reported results from a project using a helmet-mounted display to provide video imagery of the forward view from NASA's TSRV, a modified B737. Two cameras mounted in the nose of the aircraft provided a total field of regard of 80°(h) X 30°(v). The vertical positioning of the camera coverage was shifted down such that the top of the coverage area was 10° above the aircraft's waterline, while the bottom of the image was 20° below the waterline. An image processing system was interfaced with a head-tracking system to shift the imagery displayed to the pilots in order to compensate for head movements. The tests involved a series of landings using the external visibility system as well as control trials consisting of "normal" visual landings. Results indicated that the helmet mounted video display supported landing performance that was very similar to that found for the conventional landings. The pilots did report higher workload in the experimental condition, attributing this to the relatively low resolution of the displays. Further comments indicated that update rates and image stability could be improved. However, given that much of the hardware was "off-the-shelf," the conclusions drawn from this work are encouraging. The image FOV was not considered a problem.

3.1.1.9 McGovern (1990)

McGovern (1990) summarized work carried out on the development and testing of a variety of teleoperated ground vehicles at Sandia National Labs. In one of the tests described in the report, a 40° FOV camera system mounted on a Jeep Cherokee was found to be inadequate to support turning corners under most conditions. The addition of two cameras, which increased total coverage to 120°, resulted in "easier" operation. However, further improvements were noted with the development of a steering-slaved camera system, while effectiveness was enhanced even more when the steerable camera could be forced further through the independent control of the operator. Although performance with the 40° FOV camera was considered suboptimal, it must be noted that no side view was provided in the systems, other than the eventual ability to pan the camera to the side.

3.1.2 Simulation Studies

Several flight simulation experiments conducted at NASA's Ames and Langley research centers have explicitly studied the effects of varying FOV independently of image magnification. Work at Boeing has addressed the effects of limited inboard FOV (caused by obstruction from the non-flying pilot's XVS display) on performance. Because of the greater experimental control present in the simulation paradigm, this work offers valuable information not available from the implementation work discussed above, which was necessarily constrained by specific system limitations. Additionally, work conducted at the TNO Human Factors Research Institute in the Netherlands has addressed the display FOV issue in a driving simulation.

3.1.2.1 Brickner and Foyle (1990)

Using a desktop workstation which displayed a low-fidelity computer generated scene, Brickner and Foyle (1990) studied the effects of different display FOVs on pilots' abilities to fly through a slalom course defined by pylons. Helicopter dynamics were used for the control model. Display magnification was held constant at unity, while FOV was either 25°(h) x 19°(v), 40°x30° or 55°x41°. Results indicated that performance in the widest FOV (55°h) was best, followed closely by the 40°(h) FOV, with the 25° FOV associated with the worst performance. Interestingly, the FOV factor was found to interact with airspeed which was either 82kts or 109kts. The higher speed reduced, but did not eliminate, the differences in performance between the FOV conditions.

3.1.2.2 Batson, Harris and Houck (1992)

A series of simulation experiments were carried out at NASA's Langely research center, and are summarized by Batson, Harris and Houck (1992). The authors used a desktop system which displayed a high-fidelity computer generated image to investigate a number of system parameters, including FOV. The flight model approximated B737 dynamics. The task involved approaches and landings from 5mi out with up to 4° random heading error present at the start of trials. A wide range of FOVs were tested: 5°x5°, 11°x8°, 14°x11°, 30°x24° and 60°x48°. A number of dependent measures were collected, including an index of flair performance, sink-rate, lateral position and airspeed at touchdown, as well as heading error on approach. In most cases the largest FOV (60°x48°) supported the best performance, followed by the next largest FOV (30°x24°) condition, with few if any differences between the three smallest FOVs. The authors concluded that the wider FOVs provide sufficient visual cues to support the accurate timing of flare initiation, but that additional cues are necessary to precisely control the flare maneuver.

3.1.2.3 Boucek, Kimball and Braune (1996)

Using a full-mission simulation paradigm (including a second, non-flying pilot), Boucek et al. studied the effects of the baseline HSCT's inboard FOV obstruction on flight and ground operations tasks. While an overall horizontal FOV of 200° was provided by the simulator's visual system and window geometry, in the experimental condition an area representing the obstruction created by the first officer's XVS display was blocked by inserts positioned in the simulator's windows. The 45° obstructed area extended from 20° to 65° inboard with respect to the captain's eye reference point. Pilots performed a series of tasks including circling approaches which required turns toward the blocked inboard FOV area in both the experimental (reduced inboard FOV) and control conditions. The results indicated that pilots were able to compensate for the blocked inboard FOV and perform as well in the experimental condition as in the control condition. The compensatory behaviors included a greater reliance on available information from the forward window and navigation display, as well as increased communication with the non-flying pilot (when inter-pilot communication was permitted) who was able to monitor the FOV blocked to the captain. Pilots did report that ground operations were more difficult in the experimental condition. The need to avoid numerous ground obstacles combined with the non-flying pilot's many responsibilities other than monitoring for obstacles, raised concerns about maneuvering in the crowded ground environment. Overall performance, however, was equivalent for all tasks in both the obstructed and control conditions when communication was permitted between the captain and first officer.

3.1.2.4 Erp, J. B. F. van (1995)

In a driving simulation paradigm in which a monitor was positioned above the steering wheel, van Erp studied the effects of varying the display FOV, as well as magnification, on a series of driving maneuvers. The display FOV was either 50° or 100° (measured diagonally). Results showed that use of the camera view (the experimental conditions) did not greatly impair driving ability with respect to a control condition in which the drivers viewed the simulated scene directly on a 120° by 40° cylindrical screen. The author noted that FOV was important in influencing performance, but only in some of the tasks. Best overall performance was found in the 100° FOV condition.

3.1.3 Field of View Summary Comments

Considering the work described above, it is clear that while larger FOVs appear to benefit performance in certain tasks (as evidenced by the flight simulation studies and ground-based remote driving evaluations), pilots can quickly learn to land aircraft using displays which provide an extremely restricted FOV, assuming the approaches are relatively straight and the final legs are sufficiently long. As some of the flight tests showed, restrictive FOV systems were effective even when moderate cross winds were present. The research which leads to this conclusion has focused primarily on the task of controlling the aircraft during approach, landing, and in some cases take-off and horizon reference maneuvers. However, these programs have for the most part not addressed the task of surveillance, an issue which was not critical in the implementation studies because of the presence of a safety pilot. Restricted FOVs posed the greatest problem in the ground vehicle studies, where very wide FOVs were required to negotiate the sharp turns required for driving. This finding underscores the extent to which a wide horizontal FOV is necessary for ground operations, and it places further importance on the need to support effective gaze transitioning from the XVS to the side window and vice versa. The results from the flight test programs suggest that this need is not as critical for aircraft control during the approach and landing phases of flight operations. Clearly though, more research is needed to fully assess the requirements for a more complete suite of tasks other than flight path control during approach and landing. Most prominent among these is the task of surveillance, which, with the exception of the study by Boucek et al., was not addressed in the reports reviewed here. Importantly, the work by Boucek et al. suggests that when the non-flying pilot can view areas of the FOV blocked to the captain, the non-flying pilot can communicate important information about the presence and position of aircraft that cannot directly viewed by the captain, thereby compensating for the effects of the reduced FOV.

In summary, the FOV issue remains a critical area for further investigation. The available research suggests that for flight operations involving aircraft control during approach and landing, pilots can effectively use display systems which provide only narrow FOVs, in some cases as narrow as 11°(h). However, substantially larger FOVs appear necessary for ground operations as well as some types of approaches (i.e., high-speed circling approaches). An interesting divergence in the findings of the flight/ground tests and the simulation studies is the importance placed on FOV with respect to magnification. In several of the flight and ground test paradigms, image FOV was compromised in order to increase magnification to values which were typically greater than 1. The work of Roscoe suggests that the increased magnification was necessary to match the perceived size of objects seen through the imaging system with their normative size as they are typically seen through conventional transparencies. The source of this effect is not well understood, however, and the extent of the minification bias has not been thoroughly examined in systems which have larger display FOVs. It is possible that with a display FOV of 40°x50° (i.e., the current HSCT XVS baseline) there may be no tendency for perceptual minification.

Finally, the presence of a side window may also interact with FOV requirements. Unfortunately, relatively little information is available on the use of external visibility systems with side windows. Only one of the flight test programs addressed this issue; in one condition of this study pilots were given the opportunity to utilize side views (out the canopy in the F-104) in addition to the forward looking optical system which provided a 130° horizontal FOV (Layton and Dana, 1966). Pilots' comments indicated that the added visibility was quite beneficial for circling approaches, but that transitioning between the optics and the side window was somewhat cumbersome due to the restricted exit pupil of the optical system. An interesting note here is that the pilots found benefits from using the side window even though the forward-looking optics provided a 130° FOV, a finding which is important in the context of much of the previously discussed work which has shown good performance in systems with considerably smaller FOVs and no side windows. One conclusion which can be drawn from these different findings is that larger FOVs may support better performance in some flight path control tasks, but that comparatively smaller FOVs can offer performance which is quite good. With respect to surveillance, the necessary work required to address the issue has not yet been carried out.

3.2 Image Magnification/Minification

3.2.1 XVS Implementation Studies

3.2.1.1 Roscoe, Hasler and Dougherty (1966)

Perhaps the most important finding from Roscoe's work was the tendency for pilots to perceive the imagery on the periscope display as being smaller than it actually was. This perceptual bias required that the image be magnified somewhat to provide what the pilots felt was a veridical representation of the outside view. This conclusion is based on converging evidence from both informal testing prior to experimentation as well as from the empirical results of the study. Three magnification factors were examined: .86, 1.20 and 2.00. When using the minified display (.86 mag), pilots were biased towards approaching high and landing long, beyond the target touchdown point. The 2.00 magnification factor had the opposite effect of inducing lower approaches and short landings. The 1.20 magnification supported landing performance which was not biased in either direction. After considerable practice, performance in both the .86 mag. and 2.00 mag. display conditions indicated smaller, but still significant bias effects, while the 1.20 mag. display continued to support very accurate, unbiased landings. The practice effects in the .86 and 2.00 conditions indicate compensatory behavior which suggests that the biases associated with these displays can be overcome, given sufficient familiarity with the condition.

It’s important to emphasize that the pilots’ only contact visibility was through the periscope display; continual adjustments between unity magnification from imagery viewed out a side window and imagery seen on the XVS was not required. It is not at all clear how the biasing effect found in Roscoe’s work would be influenced by the presence of a side window view. One speculation is that the side window could have an anchoring effect, thereby reducing the bias of the XVS display. That is, with an available source of accurate information to compare with the imagery on the XVS, the minification bias would be attenuated. An alternative possibility is that a mismatch in perceived size between imagery on the XVS (assuming unity magnification) and imagery viewed out the side window would cause some level of disorientation. These questions can only be answered with more selectively directed research.

While a number of explanations have been proposed to account for the minification bias found in Roscoe’s work, there is still no generally accepted explanation for the effect. Roscoe proposed that the near accommodation necessary to focus on the relatively close display provided proprioceptive feedback cues which conflicted with the knowledge that the information on the display was considerably more distant. Regardless of the underlying factors which contribute to the minification bias, it’s influence is further emphasized by similar findings in related studies discussed below.

3.2.1.2 Kibort and Drinkwater (1964)

The research conducted by Kibort and Drinkwater (1964) also suggests the benefits of magnifying the XVS image. In their study of landing performance in a modified DC-3, image magnification factors of .34, .74 and 1.55 were tested. Better performance in the form of more precise approach and roundout control was found in the 1.55 mag. condition. The next closest magnification factor, however, was .73 which represents a considerable minification of the image. The large reduction in the size of detail in the image may have contributed to the poorer performance in the minified conditions. Interestingly, the authors did not mention any tendency for pilots using the magnified display to undershoot the approach or land short of the target touchdown point, suggesting that the magnification factor was well within the range of what the pilots considered acceptable. This magnification factor is somewhat greater than the 1.20 factor found to be most effective in Roscoe’s studies; however, the display FOV in the DC-3 was only 17°, while in Roscoe’s periscope display the FOV was 23.6°. It’s possible that greater magnification is required to make imagery in smaller displays appear normally sized, however this explanation is only speculative. Finally, as was the case in Roscoe’s work, the pilots did not have a side window view, which may have affected their use of the TV display in unpredictable ways.

3.2.1.3 Cosley and Peal (Boeing SST, 1973)

A summarization of Boeing’s early work on the electronic attitude director indicator (EADI) for the SST, this report describes one experiment in which three camera lens settings were evaluated for their effect on landing performance. Lenses providing vertical fields of view of 19°, 31° and 45° were tested. Because display FOV was not altered, the lens manipulations resulted in corresponding magnification changes, although the specific image magnification values were not provided. The results indicated that touchdown longitudinal error was lowest in the 31° condition; the 45° vertical FOV appeared to induce touchdowns well beyond the aimpoint, while the 19° lens led to landings considerably short of the aimpoint. These findings are consistent with the work of Roscoe et al., in which image magnification was shown to be inversely related to longitudinal touchdown point.

3.2.1.4 McGovern (1990)

McGovern and his colleagues discuss the negative effects of image minification in the operation of a variety of experimental ground vehicles. The minification factors ranged from .4 to .7, and had the expected effect of causing overestimations of distance to objects represented on the display. This phenomenon contributed to a number of vehicle accidents as the operators collided with objects which were perceived as being further away than they actually were. An additional effect noted by the authors was the tendency for novice teleoperators to overcontrol the vehicle. This was likely due to image minification, which reduced the display gain to a level which required operators to make large control inputs in order to see the resulting effect of control through the display. After some minutes of practice with the system, operators were able to adjust their control input gain in response to the reduced display gain, so that they used lower amplitude inputs to achieve smoother vehicle operation. This finding is important because it highlights the potential effect of image mag/minification on manual control, however it also points out the adaptability of operators to systems which do not employ unity image magnification.

3.2.2 Simulation Studies / Basic Experimental Research

3.2.2.1 Batson, Harris and Houck (1992)

As was discussed in the previous section, the desktop flight simulation paradigm of Batson, Harris and Houck (1992) specifically studied the effects of display FOV and image magnification on approach and landing performance. Unlike the display FOV manipulation, however, the magnification levels studied were not factorially combined with FOV; this confound resulted in smaller display FOVs for greater image magnification levels. Therefore, the results must be tempered by the limitations of the experimental design. The experimental findings show that for each of the dependent measures recorded, the largest magnification factor (1.5) supported the best performance; however, this often did not differ dramatically from the next two magnification factors of 1.15 and 1.0. These findings are consistent with those reported by Roscoe et al. (1966), and suggest that for the tasks studied, increases in image magnification had a more pronounced positive effect on performance than did any negative effects associated with the decreases in image FOV. It is not clear whether the positive effects found with the greater magnification levels were associated with the perceptual minification bias, resulted from improved display gain (as was suggested by the comments of McGovern), or were influenced by a combination of the two factors. In summary, the results from the FOV experiment indicated better performance with larger FOVs, while the findings of the image magnification manipulations show better performance with magnified imagery, even though the more magnified images restricted image FOV. These two findings suggest that displays which can provide large image FOVs and can also display magnified imagery would support the best performance. However, the presence of a side window view might affect the perceived size of objects on the XVS (as well as cause object misalignment, as with the horizon line), thereby reducing or eliminating entirely any advantages for image magnification beyond unity. This remains very much of an open issue.

3.2.2.2 Erp, J. B. F. van (1995)

In addition to manipulating FOV in a driving simulation experiment, van Erp also studied the influence of two magnification levels, .5 and 1.0, which were manipulated independently of FOV. The results showed that magnification affected performance in all of the driving tasks, with advantages found for the 1.0 magnification level over the minimized image.

3.2.2.3 Randle, Roscoe and Pettit (1980)

Randle et al. (1980) used an open loop computer-generated landing simulation to further explore the nature of the minification bias noted by Roscoe and his colleagues. The authors used collimated and uncollimated displays, and manipulated the magnification of the displayed images as well as pilots' visual focus demand (in an attempt to assess the effects of visual accommodation on aimpoint judgments - overshoot versus undershoot of the aimpoint). Results indicated that the magnification factor of the image did affect pilots' tendencies to predict either an overshoot or undershoot of the landing aimpoint; imagery that was magnified fostered relatively fewer undershoot judgments, while minified imagery had the opposite effect. The authors also found that measured accommodation was reliably less than the focus demand of the optics across all experimental conditions. While increases in focus demand in the uncollimated condition were correlated with the proportion of undershoot judgments, accommodation itself was not associated with aimpoint judgment tendencies. This finding offers only partial support to the hypothesis that the near-accommodation response might have induced a bias toward perceiving undershoots of the landing aimpoint (an explanation which has been proposed as a possible cause of the minification bias). However, focus demand had no effect on aimpoint judgments in the collimated display condition. The authors suggest that for this reason, collimated displays should continue to be used in flight simulators. It should be noted, though, that performance in the two display conditions did not differ dramatically overall. Furthermore, regression analysis indicated that both display conditions would require image magnification to support unbiased judgments 10sec prior to touchdown, with the collimated display requiring 10% more magnification than the uncollimated display. The results of this study clearly show the influence that image magnification can have on pilots' perceived situation on final approach with respect to landing aimpoint. However, given that the pilots had no control over the simulation, it is difficult to determine how these results relate to pilots' performance in a more realistic setting. While suggesting a possible cause of the minification bias, the findings do not point to ways to counteract the effect, other than to adjust image magnification.

3.2.2.4 Meehan and Triggs (1988)

Meehan and Trigs (1988) investigated the imaging display minification bias in a non-aviation context. The authors measured judgments of perceived size made using a single-lens reflex camera in a task which required matching the size of an image as seen through the camera to the size of the scene when viewed directly. Participants matched the image size by adjusting a zoom lens on the camera, and were permitted to compare the camera view with the direct view as many times as they wanted. Monocular and binocular conditions were also tested in which direct views were either restricted to one eye or not (all views through the camera were monocular). Consistent with the results of Roscoe et al., size judgments made through the camera were biased toward magnified settings. The size of the overestimates were smaller than those found by Roscoe et al. (5%-10% compared with the 20% noted by Roscoe et al.), and were also affected by the content of the scene which was judged. Images containing more depth information (e.g., more foreground objects in addition to farther objects) were biased less than scenes which had more homogeneous content (e.g., an open field). Additionally, the bias was smaller in the monocular viewing condition, which is not surprising given that scenes are typically perceived as being smaller when viewed monocularly. The results of this study support the general finding of a minification bias when using imaging displays, however the authors do not mention whether display FOV was controlled. This raises the question of whether the findings were confounded by uncontrolled FOV differences.

3.2.3 Magnification Summary Comments

Taken together, the research which has considered the issue of image magnification, either through formal experimentation or informally through system evaluation, has generally found benefits for magnifying the displayed image. These benefits are seen in both a reduction in error variability and reduced biases in judging position on approach to landing. As was discussed above, there is no generally accepted explanation for this phenomenon. Possible explanations include the conflicting proprioceptive cues (e.g., from the near accommodation response, and convergence cues); however another possibility is the need to resolve fine detail on the display which doesn’t provide the high resolution image offered by standard out-the-window views. Still another potential factor is the relatively small display FOV present in most of the systems tested, which may affect the judged size of, and distance to displayed objects in ways which are not presently understood. What is not clear from the work reviewed here, however, is how the presence of side window views would affect the perception of size/distance on the XVS display. None of the flight test or simulation studies reviewed here manipulated the magnification of a forward display while also providing a side window view. The basic psychophysical study by Meehan and Triggs (1988) suggests that even when virtual and direct views can be compared consecutively, there still is a tendency to perceptually minify the virtual image. However, it is impossible to determine how the simultaneous viewing of two relatively wide field of view scenes would be affected by the perceived minification of the virtual scene.

The need to match XVS display magnification to the side window’s magnification (i.e., unity magnification) seems to be, on the surface at least, a fundamental requirement. A mismatch in the size of objects (as well as the displacement of features, such as the horizon, due to scaling) between the side window and the XVS has generally been considered to be undesirable by the HSR/HSCT XVS team. However, it’s possible that the perceptual minification bias could influence the processing of information on the XVS even with the side window view available to the pilot. Alternatively, the presence of the side window might have an anchoring effect, causing the perception of the XVS display to be unaffected by the minification bias. Also, larger, higher resolution displays might not be affected by the minification bias, obviating the need to consider image magnification as a way to counteract the bias. Finally, even if unity magnification does induce a tendency to perceptually minify the XVS image, any scale changes will affect the conformality between the two scenes in potentially unacceptable ways. More research is needed to assess the effects of image magnification on performance in the context of an XVS-side window configuration. Upcoming flight tests using the TSRV (737) may provide insight into whether a minification bias exists in the current system (although image scale will not be manipulated during this experiment).

3.3 Spatial Resolution

The resolution of the XVS camera-display system must be capable of supporting all piloting tasks as well as or better than conventional windows. One of the obvious limitations of current display systems is their relatively low resolution, but it is unclear how much system resolution is required to provide pilots with sufficient information to perform their tasks. One solution to this issue is to require eye-limiting resolution (approximately 1 to .5 minutes of arc), which presumably would support the perception of fine detail quite well (although a number of other factors may be equally important, including the range of brightness and color values, contrast capabilities, etc.). This approach, however, may not be technically feasible in the near term, and in fact does not answer the question of how much resolution is needed to adequately support piloting tasks. To date, very little work has been done which has specifically examined the effects of different external scene resolution levels on pilot performance, and these studies have been constrained by the technical limitations of the available systems. A few studies have compared various types of weather/night-penetrating sensor imagery which differ in their resolution levels (see, for example, Burgess et al., 1993; Foyle et al., 1990). This work has generally found millimeter-wave radar imagery to be difficult to use because of its inherently low spatial resolution, while the relatively high resolution provided by thermal imaging systems can support night operations reasonably well. The relevance of this work to the XVS task, however, is questionable, and therefore will not be discussed further here. Those studies in which image resolution was specifically manipulated in a controlled setting are described below.

3.3.1 Simulation Studies

3.3.1.1 Batson, Harris and Houck (1992)

Batson et al. (1992) manipulated image resolution in addition to the other display variables discussed above in their comprehensive desktop simulation study. Two resolution settings were compared in two different FOV conditions: a resolution of .01° per raster line was compared to .08° resolution for the 11° by 8° FOV condition; .04° per raster line was compared to .08° resolution in the 30° by 24° FOV condition. In the .01° versus the .08° comparison, the higher resolution supported significantly better lateral touchdown error, however no other differences were observed between the resolution conditions. Some pilots noted subjective differences between the .01° and .08° resolutions, one commenting that the flare maneuver was easier with the higher resolution, another suggesting pitch control was more precise with the higher resolution.

3.3.1.2 Mann (1987)

Using a flight simulation paradigm, Mann (1987) compared the resolution of simulated radar imagery projected on a HUD with higher resolution computer generated imagery. The three resolution settings were 47 lines (simulated 35GHz radar), 174 lines (94GHz) and 400 lines for the out-the-window CGI scene. Results favored the higher resolution settings, with best performance in the 400 lines condition. Given the comparatively low resolution levels for all of the conditions in this study, however, the implications of the findings to the current HSCT baseline system are unclear. (The goal of Mann's study was to investigate radar wavelength sensor imagery which, as was mentioned previously, cannot currently offer the high resolution supported by visible wavelengths.)

3.3.2 Resolution Summary Comments

Compared to the issues of image field of view and magnification, there is relatively little empirical data on the effects of varying levels of resolution in the ranges that are being considered for the HSCT baseline system. However, given the results reported in many of the implementation studies, there does not appear to be difficulty in controlling flight path on approach and landing with resolutions which are equal to or above the NTSC standard. Clearly though, the task which will be most dependent on very high resolution is object detection, and the studies reviewed here did not address this issue. As was mentioned above, one approach to meeting certification requirements is to require eye-limiting resolution in the camera-display system. Even with these resolutions, though, the other limitations inherent in current camera and display technology (e.g., reduced color and brightness range, relative to human vision) may require greater spatial resolutions from the system in order to compensate for these other limitations, in supporting adequate object detection performance (i.e., equal to the eye-window system). Work currently underway within the HSR program is seeking to quantify certain aspects of human object detection/identification capabilities in a relatively high fidelity simulation environment using stimuli presented at very high resolutions (McDonnell Douglas). This work will help to identify the resolution requirements for specific tasks such as see-to-follow and see-and-avoid, but more research will be required to ensure that the resolutions supported by the XVS display concepts can satisfy all other flight and ground operations requirements.

3.4 XVS Display-Side Window Conformality

As has been mentioned throughout this report, very little research has been conducted which has specifically considered the design of an XVS system which includes both a forward-looking display and a side window view. Differences between imagery displayed on the forward XVS and scenery viewed through the side window exist on a number of dimensions, and little is known about how these two information sources will influence each other as they are integrated to support piloting tasks. The degree to which the two views conform to one another, in terms of viewing orientation, collimation, resolution, etc., is a source of considerable interest within the HSR program. However, only three studies reviewed have addressed issues related to XVS-side window image conformality. These simulation studies were conducted by members of the HSR team at NASA-Langley Research Center and McDonnell Douglas. The first two reports described below deal with vertical translations of the XVS display, which might result from camera alignment errors or vertical head movements of the pilot. The third study compared performance using collimated and non-collimated XVS displays with a collimated side window display.

3.4.1 Comstock, Busquets, Foernsler and Rudisill (1996); Batson and Harris (1996)

Two simulation experiments compared non-conformal Y-axis translations of the XVS (vertical displacement of the XVS image with respect to the side window view) to a conformal XVS-side window arrangement. The first experiment tested landing performance with the forward display either conformal with the side window display, or shifted 4 or 8 degrees up or down with respect to the side window display, resulting in a non-conformal position of the horizon line and flight symbology. No significant differences were found in touchdown sink rate between the conditions, but the touchdown point in the non-conformal conditions was typically found to be further down the runway and at a slower speed, suggesting the pilots were somewhat uncertain about when to initiate the flare maneuver. This effect was significant when comparing the 8 degree non-conformal condition with the conformal display. Subjective comments indicated a preference for the conformal display condition by most of the pilots. A second experiment which studied taxi performance with conformal and 4 degree non-conformal displays did not indicate significant performance differences between the display formats, although pilots commented that they were aware of the non-conformal conditions. One pilot also mentioned the possibility of motion sickness with the non-conformal horizon. Although the findings from these two studies are preliminary, they suggest that small vertical displacements of the forward display (from a conformal position with the side window) will not affect performance under certain conditions. However, greater displacements (i.e., 8 degrees) might adversely affect performance of some maneuvers. These findings are important but only begin to address this issue, and certainly warrant further study which is currently underway in the TSRV (737) aircraft.

3.4.2 Summers, Dwyer and Norman (XVS Telecon, Jan 1997)

Another critical conformality issue is the question of whether a collimated forward display is necessary for physiological, psychological or other performance needs. Preliminary findings from a simulation study of collimated and non-collimated forward vision displays were reported by Summers, Dwyer and Norman (XVS Telecon, Jan 1997). In this full motion simulator study, pilots flew circling approaches to land and performed taxi maneuvers. The side window view was always collimated, while a forward view was presented in either a collimated or non-collimated format (a within subjects design was used). Only pilots' subjective comments were available at the time this report was obtained. A majority (5 of 8) of the pilots reported experiencing significant problems using the non-collimated display, one pilot found the non-collimated display to be somewhat problematic, while two pilots reported having no problems with the non-collimated condition. Some of the problems reported with the non-collimated display included: a difficulty in visually accommodating between the two displays; nausea; headaches; eye discomfort; difficulty judging the trajectory of traffic; and problems lining up with the runway. Many of these comments suggest the presence of 'simulator sickness' symptoms, and raise considerable concern about the potential for physiological and psychological discomfort when using a non-collimated forward display with a collimated side window view. However, it is unclear at this point what exactly contributed to the undesirable effects noted by some of the pilots. It's possible that some aspect unique to this particular implementation of a non-collimated forward view caused the problems cited above. Interestingly, comments from pilots on recent flight tests in which a non-collimated forward image was used with a real side window, do not support the findings from this study, suggesting that an artifact of the simulation set-up may have been responsible for the adverse effects noted by some of the pilots in this study. Certainly more investigation is needed before general conclusions can be drawn about the characteristics of non-collimated forward displays and collimated side window systems. Upcoming work should help to further clarify these results.

3.5 Conformality Summary Comments

Indications of the effects of two types of conformality on pilot performance are offered by the reports described above. While it appears that modest (i.e., 4 degrees) vertical shifts in the XVS image may not cause problems for certain types of tasks, the description of negative physiological effects experienced by some pilots using a non-collimated forward display with a collimated side window suggest a potentially serious problem with that particular form of non-conformality (although findings from recent flight tests do not indicate that collimation non-conformality is a problem). Given the divergent findings, the studies need to be replicated in some form (e.g., 737, TIFFS) to support more confident recommendations for the program. Other types of conformality have not been examined, including: brightness, color, contrast, resolution, scale, vibration, stereoscopy, motion parallax and temporal (transport) delays which might exist in the XVS image can also be considered a form of conformality with the side window. Examination of conformality effects for these dimensions probably does not warrant a parametric investigation in each case. However, where there is reason to believe there might be problematic issues, more formal studies will have to be carried out.

4.0 General Discussion and Conclusions

The research reviewed in this report raises a number of interesting questions about the nature of the influences that different XVS parameters may have on pilot performance in the HSCT. As expected, because of the great variety in the types of systems tested in the implementation studies and the various paradigms used in the simulator experiments, the often inconclusive findings make it difficult to draw general conclusions about how the individual XVS parameters affect performance. This is complicated further by the presence of only a few studies (most of which were conducted within the HSR/HSCT program) in which parameters were experimentally manipulated in a controlled way. Despite these limitations, there appear to be several factors which have been shown to influence performance or subjective impressions in similar ways across different test platforms or experimental paradigms. The most consistent finding, particularly from the flight tests, is the apparent minification of the image displayed on the XVS. This effect has been found in systems which used both television cameras as well as indirect optical lens/mirror arrangements. While the source of this effect is not generally agreed upon, its influence on pilot performance has been documented in several experiments (see, for example, Kibort and Drinkwater, 1964; Roscoe et al., 1966). Based on the findings from these studies, it is difficult to predict how or even whether the bias would be expressed when using the HSCT XVS. The biasing effect was found in systems which used displays considerably smaller than that which is proposed for the HSCT. Even less clear is how the minification bias might be influenced by the presence of a large side-window view. None of the reports reviewed here addressed this issue, and it is certainly possible that the bias might be attenuated to the point of being inconsequential in such an arrangement. However, the minification bias might not result in performance decrements per se, but could effect the ease with which information from the two image sources is processed or integrated, resulting in perceptual discomfort. Because of the limited amount of available data on XVS-side window interaction, the potential effects of minification should be addressed in future experimentation.

With respect to image field of view, several of the flight tests indicated that relatively limited FOVs (e.g., 20 degrees horizontal) could support adequate approach and landing performance given some constraints (e.g., straight-in, relatively long final legs). However, the parametric simulator studies conducted within the HSR program showed performance benefits with larger FOVs (e.g., 40+ degrees horizontal). The additional optic flow information provided in larger FOV displays will likely support pilots in performing landings and ground maneuvers. The findings of the studies reviewed here suggest that the FOV dimensions which are being considered for the HSCT XVS (i.e., 40 X 50 degrees) are sufficiently large to adequately support flight path guidance tasks. The XVS display FOV appears to be more constrained by specific industry regulations for visibility (e.g., AS-580B) and by the allowable space in the flight deck than by human performance issues. Less is known about target detection performance with varying FOVs. A reasonable assumption is that larger XVS FOVs would enhance visual object detection performance, assuming that the additional displayed area was not gained at the expense of image scale (i.e., unity magnification was maintained). Finally, the interaction between the XVS display and the side window may greatly affect how pilots use the XVS for object detection. If there are large differences in the pilot's ability to detect targets displayed on the XVS and targets visible through the side window, there might be a tendency to focus more attention on one image source than the other. Some of these issues will be addressed in upcoming flight tests, but more experimentation will mostly likely be required to sufficiently answer these questions.

The effects of image resolution on pilot performance are only beginning to be explored within the HSR program. The few studies conducted so far have shown modest performance advantages for higher display resolutions over lower resolutions (described in section 3.3), however these findings must be considered in the context of the available technology. That is, the resolution levels proposed for the HSCT XVS are substantially higher than those tested in the papers reported in this review. One implication of this is that tasks requiring high spatial resolution, such as object detection, might benefit considerably more from future display technology than from current systems. More research needs to be done to assess the required levels of display resolution to match performance in conventional aircraft, but this kind of research is difficult to perform given the uncertainty about how well pilots currently detect objects. Closely related issues which may interact with resolution to affect target detection include the color, brightness and contrast capabilities of the XVS display. Despite their potential impact on human performance these issues have yet to be adequately addressed. As higher resolution camera-display systems become available, more relevant studies can be conducted to explore resolution issues, including the interaction between XVS resolution and the side window view (i.e., resolution conformality).

XVS-side window conformality is perhaps the most important issue facing the XVS program because of the lack of available data on its potential influence on human performance. The XVS display differs from the side window view in numerous ways, and these differences may have various unknown effects on how the pilot transitions between and integrates the two views. For example, results from a simulator study suggest that a non-collimated forward display combined with a collimated side window view may cause serious physiological distress; however, recent flight tests have not revealed problems with collimation non-conformality. The conflicting findings might be due to specific artifacts of the simulated side window view which are not present with a real side window. These findings must be corroborated in future studies, but it points out one dimension of conformality which may be extremely important for efficient integration of the two external views. Other dimensions may be equally sensitive to XVS-side window differences, including brightness, color, contrast, motion parallax, position parallax, image scale (magnification), and resolution. In fact each XVS display parameter has two potentially interacting effects on human performance: one in using the XVS display by itself, and one with its coordinated, or simultaneous use with the side window view. This certainly complicates evaluation of the parameters' possible influences, and challenges the XVS team to examine their effects in an efficient, yet controlled way. This can be done primarily through further simulation studies and flight test evaluations. Based on the results currently available, the effects of collimation, motion parallax, and brightness differences are high on the list of issues which need attention.

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