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Towards Determination of Visual Requirements for Augmented Reality Displays and Virtual Environments for the Airport Tower

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ABSTRACT

The visual requirements for augmented reality or virtual environments displays that might be used in real or virtual towers are reviewed with respect to similar displays already used in aircraft. As an example of the type of human performance studies needed to determine the useful specifications of augmented reality displays, an optical see-through display was used in an ATC Tower simulation. Three different binocular fields of view (14°, 28°, and 47°) were examined to determine their effect on subjects' ability to detect aircraft maneuvering and landing. The results suggest that binocular fields of view much greater than 47° are unlikely to dramatically improve search performance and that partial binocular overlap is a feasible display technique for augmented reality Tower applications.

1.0 INTRODUCTION

Augmented reality (AR) is a new visual media technology in which computer generated imagery is optically or electronically superimposed in a spatially conformal way onto users' views of the world. The added information can assist them by providing status and position information about their surrounding environments that is not normally available (Azuma, 1997).

When implemented with an optical see-through mode, AR displays are similar to cockpit head-up-displays (HUD), which provide pilots status and spatially conformal information such as runway symbols. Such displays aid users by substantially reducing the amount of visual scanning needed to integrate various sources of information and can support information formats otherwise unavailable. Initially, the benefits of HUDs were expected to come from users no longer needing to shift their focus in and out of the cockpit, but much of the benefit has been attributed, in fact, to better information integration as compared to standard display formats (Weintraub & Ensing, 1992). Reduced stress on the users' oculomotor system, nevertheless, remained a benefit since visual accommodation (focusing) is a slow response (average time constant ~ 200 to 400 msec). Visual tasks in a Tower which require frequent shifts of gaze back and forth between outside targets and inside displays may be significantly slowed and become fatiguing due to repeated focusing, especially if the controller is more than 40 years old (Neveu, Blackmon & Stark, 1990)

Since congestion at commercial airports has focused attention on new technologies to improve airport efficiency and safety, interest has developed in transferring the benefits of HUD-like displays to air traffic controllers in airport towers. The proposal for such displays in towers, in fact, was first made over 25 years ago by Lloyd Hitchcock of the FAA (Weintraub & Ensing, p.144). He suggested that these displays could provide controllers with status information such as aircraft identification, barometer settings, wind conditions, and runway/gate assignments. More advanced recent proposals (e.g. Redeiss, 1997; Krozel, et al, 1999; Ellis et al, 2002; Ruffner, Fulbrook & Foglia, 2003; Fuerstenau et al, 2004) suggests that spatially conformal information such as aircraft and ground vehicle shapes and airport buildings could be presented on head mounted displays via synthetic vision or computer graphics systems using new image sensors and high precision GPS or radar position. Such AR displays could provide the tower controllers with "x-ray vision," conceivably allowing them to continue operations in weather that would otherwise close the airport or reduce its capacity. They also provide a possible development path for the design of fully immersing virtual environments that could be used for "virtual towers."

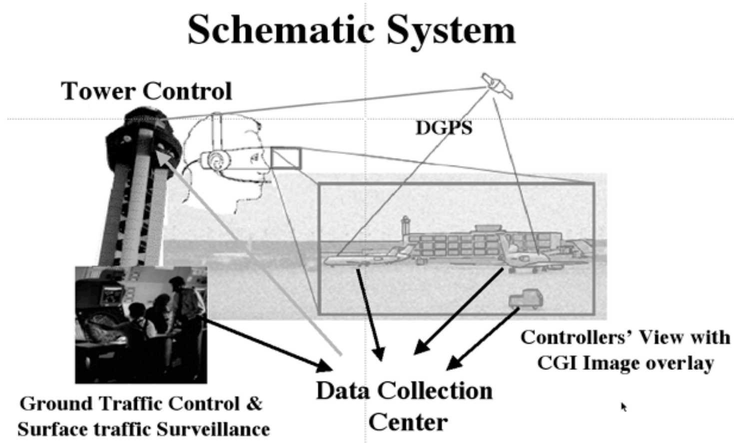

Figure 1. Proposed information flow for an AR display in the airport control tower (after Krozel, *et al.,* 1999)

Many design options are possible for AR displays within a tower, from video mixing systems using existing panel displays which provide electronic windows all the way to head mounted displays (HMD) presenting spatially conformal symbols. The HMD option is the most technologically challenging but also is the form most likely to provide the needed wide field of regard, sufficient visual resolution, moderate cost, small physical footprint, intuitive and rapid view direction control, as well as convenient upgrade path that will make such systems practical.

All designs, however, have in common the need to adequately present the purely visual aspects of the information used by the Local and Ground controllers in the Tower. The following discussion will extend earlier visual analyses (Ruffner et al., 2003) by first reviewing the visual elements of the major control tasks required of the Local and Ground controller and considering their implications for system performance. This review will be followed by a description of a design study investigating one of the visual display parameters, binocular field of view (FOV). This study provides an example of the kind of human performance studies needed to determine and evaluate the specifications for such systems.

Simple trigonometry and data on airport dimensions and aircraft sizes and shapes allow calculation of the visual angles subtended by targets that controllers must see from their Tower stations. Ruffner, for example has noted that important targets, e.g. aircraft, ground vehicles, ramp workers, etc., visual subtense may vary from ~40 arcmin (~12 mrad) down to approximately 1 arcmin (~0.3 mrad), depending on the target and aspect. Transport aircraft generally are larger than about 3.4 arcmin (1 mrad) for typical viewing distances when under tower control.

Subtended visual angle, however, does not completely define the visual task that the Tower personnel accept. Depending upon weather and lighting conditions the visual contrast of the targets varies substantially with consequent degradation in the controllers' ability to detect, identify, discriminate, and estimate range of their required targets. In addition to specific relative altitude, depth and distance estimates between pairs of aircraft, controllers are required to maintain a "big picture" spatial visualization of their existing pattern of controlled aircraft, of the incoming aircraft which they will need to accept, and of the departing aircraft which they will seek to hand off.

Job Task	Job Subtask
1. Separation	1. Separation is ensured and maintained at all times. * 2. Safety alerts are provided.
2. Coordination	1. Performs handoffs/point-outs. 2. Required co-ordinations are performed.
3. Control Judgment	1. Good control judgment is applied. 2. Priority of duties is understood. 3. Positive control is provided. 4. Effective traffic flow is maintained.
4. Methods & Procedures	1. Aircraft identity is maintained. * 2. Strip posting is complete/correct. * 3. Clearance delivery is complete/correct and timely. 4. Letters of Agreement (LOAs)/directives are adhered to. 5. Additional services are provided. 6. Rapidly recovers from equipment failures and emergencies. 7. Scans entire control environment. * 8. Effective working speed is maintained.
5. Equipment	1. Equipment status information is maintained. 2. Equipment capabilities are utilized/understood.
6. Communication	1. Functions effectively as a radar/tower team member. 2. Communication is clear and concise. 3. Uses prescribed phraseology. 4. Makes only necessary transmissions. 5. Uses appropriate communications method. 6. Relief briefings are complete and accurate.

Table 1. FAA Air Traffic Control Tower on the job training job task and subtasks. Tasks with primary visual component indicated by *.(after Ruffner, 2003; FAA, 2006). Note that the visual subtasks are described in terms of goals and not of specific visual features to be observed. A principled design of a visual environment to support these goals will require determining the specific visual information needed to meet them.

The overall situation awareness that the controller is expected to maintain is the result of the integration of a wide variety of information sources, including radio and telephone communication, local airport radar and transponder systems, intra-Tower and inter-station controller communication, printed matter such as flight data strips, and the view out the Tower window of the airport. This out-the-window view clearly contains some of the visual components of the Tower controllers' task as identified in the FAA analysis of the air traffic control tower task description (Table 1): However, the exact visual affordance of the specific visual task is not necessarily described in the general training material. The Local Controller in the Tower, for example, may give a clearance for take off to aircraft holding at the end of the active runway and then be required to verify compliance by noting the onset of the take off roll. This function requires not just adequate visual acuity but also visual motion discrimination. The parameters of this discrimination need to be established so that any synthetic view of this situation may adequately represent the visual image normally seen. Many of the visual requirements for such display have been determined for head-mounted systems used in aircraft (Rash et al., 2006) but the specific visual cues used by controllers for Tower operation as well as the visual display parameters needed for virtual or augmented Tower displays are not all identified.

For example, the desired binocular FOV for head-mounted systems used for general operations in the cockpit, i.e., not simply weapons targeting, is thought to be 60°. This recommendation is based on the assumption that visual resolution is not sacrificed (Rash, 2006). Similar requirements for Tower displays such as HMDs supporting visual acquisition have not been established. The study outlined below gives some initial information on this question and also provides an example of the kind of human factors research needed to establish appropriate visual requirements (Ellis *et al*, 2002).

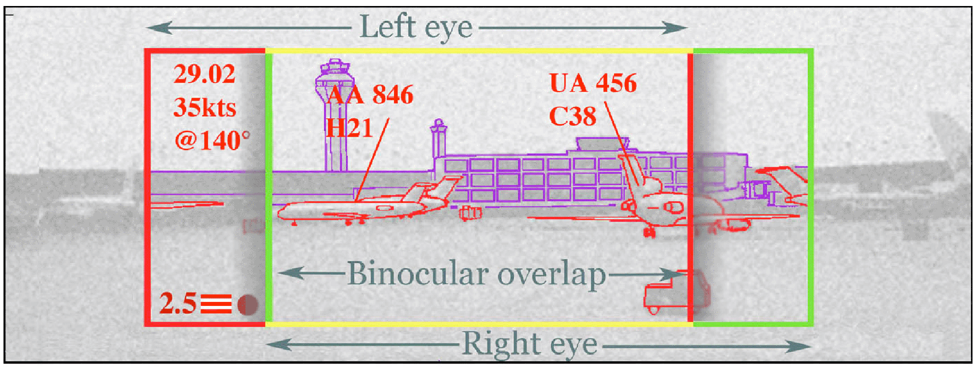

Figure 2. Illustration of the use of partial binocular overlap imagery in an augmented reality display to achieve a wider FOV without sacrificing of visual resolution. The example includes notional text overlay symbology and assumes that the display system does not introduce significant visual occlusion allowing substantial see-around capability. Regions of visual suppression due to binocular rivalry (luning) are shown along the shaded flanks of the region of binocular overlap. The illustrated suppression almost hides a ground vehicle in the center left of the image.

Because of the very wide field of regard required for operators in the tower, existing widely available see-through HMDs displays with sufficient visual acuity might be inadequate for the application. They typically have binocular FOVs varying between ~30° and ~40°. In contrast, consider for example that Local Controllers in a tower at San Francisco International Airport require at a minimum a 120° field of regard for their immediate task. Indeed, their potential required field of regard could extend to 360° for unusual circumstances.

Accordingly, the following experiment examines the effect of several FOV on aircraft detection by subjects using an AR display in a simulated tower environment in which the required aircraft search task encompasses at large field of regard. While intuition clearly suggests that restriction of the FOV should degrade performance, the extent of this degradation varies substantially with such tasks. Some studies suggest that the degradation is marked and performance equivalent to unobstructed vision requires FOV of at least 60° (Hatada, Sakata, & Kusata, 1980), while others suggest that the degradation can be less pronounced and depends upon the subjects' task load (Wells & Venurino, 1990; Eggleston et al,, 1997). The following study examines the effect of FOV restriction in an AR display for task loads and tasks similar to those faced by tower controllers. It also examines whether the visual suppression associated with partial binocular overlap degrades users' ability to detect visual targets in the context of a tower simulation.

2.0 METHODS

2.1 Subjects

Forty-two subjects ranging in the age from 18-59 participated in the study (18 female, 24 male). Participants were selected from laboratory personnel, college students and from the paid participant pool of NASA Ames Research Center maintained by the Ames Contractor Raytheon. Participants needed no prior experience in Air Traffic Control or simulated environments, but they did need normal or corrected vision. Subjects were blind to the specific experimental hypotheses. Several subjects were general aviation qualified pilots who were distributed approximately evenly across the separate groups. Subject gender was also balanced across groups. Neither of these classifications were used for analysis.

2.2 Apparatus

2.2.1 Head mounted display

A custom-made see-through HMD was used in this study. It was adapted from a Virtual Research V8, 50% see-through optics from Virtual Vision and a custom bright back-light allowing presentation of virtual objects with maximum luminance up to ~40 cd/m^2. Michelson contrast of display elements varied between 0.4-0.7. This system allowed focus, interpupilary adjustment and binocular overlap (15% to 100%). The monocular fields of view could be adjusted by replacing the combining optics with alternative elements of differing focal length and field stops such that binocular FOV could be changed keeping visual resolution close to 2.5'/pixel. When on a users head and attached to its cables, the system is well-balanced and weighs < 1.3 kg depending somewhat upon the specific optics and cabling. A FasTrak head position sensor was used with custom, very high performance driver software sampling head position at 120 Hz using a predictive filter (Jung, Adelstein, & Ellis, 2000) so that the effective system latency was reduced to less than 15 msec. In contrast to most other HMD virtual environment implementations, the resulting imagery appears essentially fixed in space during head movements, removing one of the most common deficiencies in VE implementation.

2.2.2 Simulation environment

The virtual airport environment based on the Dallas-Ft. Worth (DFW) West Tower was created using World Tool Kit software on an SGI ONIX graphics computer with RE-2 graphics. Graphics complexity and systems overhead was managed so that the simulation could maintain a stable 60 Hz update rate.

Simulated aircraft activity was based on data collected through the Center TRACON Automation System (CTAS) connected to a live data source on March 16th 2000 from DFW during heavy load. The airline flight identities used for the experiment were permuted but the actual flight activity was based on real traffic (Figure 3). Pre-recorded data for thie experiment allowed replication of actual flight patterns for every subject.

The file of aircraft trajectories was edited to produce separate training and experimental files having comparable numbers of displayed aircraft. Runs based on both files preserved the general directions and location of aircraft using different aircraft identifications and sequences to minimize learning of specific aircraft maneuvering.

To take into consideration that the participants were not professional controllers, only two landing aircraft were required to be monitored at any time. This was in addition to their concurrent task of detecting up to 4 appearing aircraft.

The experiment was conducted within a laboratory room cleared so that the room were generally visually blank. The visual superimposition of the virtual imagery presented by the display made these walls appear transparent as the subjects perceived the virtual aircraft and runways to be approximately at their correct distance of several miles. The resolution of the display, however, precluded precise stereo calibration of the visual imagery for the distances needing to be displayed.

2.3 Design and Procedure

Three binocular FOVs of 14°, 28° and 47° were tested with three independent groups of subjects, (9, 9, 8 subjects respectively) using different optics. The 14°, 28° were presented with 100% binocular overlap. However, divergent partial overlap of 33% was needed to achieve the 47° field (e.g., Figure 2). In a subsidiary investigation, two additional experimental groups of eight subjects each were used to compare 14° and 28° binocular FOV achieved with divergent partial overlap (46%) against corresponding fields of view achieved without partial overlap.

Reaction times (RT) for two events (appearance and landing of aircraft) were measured as two separate dependent variables. The full overlap conditions were tested in a one-way analysis of variance. The partial overlap conditions were evaluated in a separate two-way analysis of variance restricted to the 14° and 28° conditions and the partial and full overlap conditions. Log transforms were used for statistical purposes to correct for skew in the RT data.

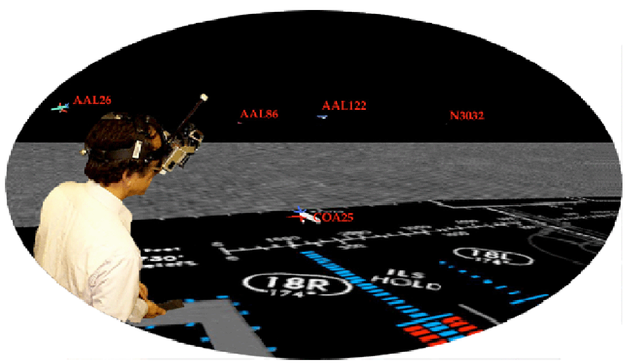

Figure 3. Graphic montage illustrating a subject watching approaching traffic from the DFW western ATC Tower. Aircraft data tags were restricted to identity only, i.e. AAL86 for American Airlines Flight 86. The imagery shown in this figure was seen "through" the wall of the lab, which to some extent appeared transparent during the testing.

The experimental task was designed to represent a visual part-task of Local Controller in a tower. Subjects performed the task in a 25 min training-run followed by a 25 min experimental-run. Participants were familiarized with the equipment and a virtual environment of the airport Dallas Ft.-Worth. A texture map of the runways was superimposed to aid subject orientation (Fig 2). Aircraft appeared within an approximately 200° subject-relative horizontal angle. Subjects were instructed to identify two events by button press: 1) the appearance of designated aircraft within their field of regard (Detection Task) and 2) the landing of specific approaching aircraft (Landing Report Task). The display presented 16 aircraft targets with data-tags for identification in apparent real-time. Thirty-two targets were presented for landing reports. They were imbedded in evolving traffic patterns of from 12 to 25 aircraft. A system of paper flight strips similar to those used in a Tower was used to identify the aircraft that subjects needed to monitor. Reaction times between the displayed events and the subjects' responses were measured. Pre- and post-experiment Simulation Sickness Questionnaires (Kennedy, Lane, Berbaum, & Lilienthal, 1993) were given to all subjects.

3.0 RESULTS

Figure 4 (left) plots a significant FOV effect for detection calculated in a one-way ANOVA, ($F(2,23) = 3.908$, $p < 0.035$; log transformation: $F(2,23) = 3.835$, $p < 0.037$). Figure 4 (right) shows a similar significant effect of the FOV conditions on the Landing Time Report calculated with a one-way ANOVA for the FOV ($F(2,23) = 16.511$, $p < 0.001$; log transformation: $F(2,23) = 37.04$, $p < 0.001$).

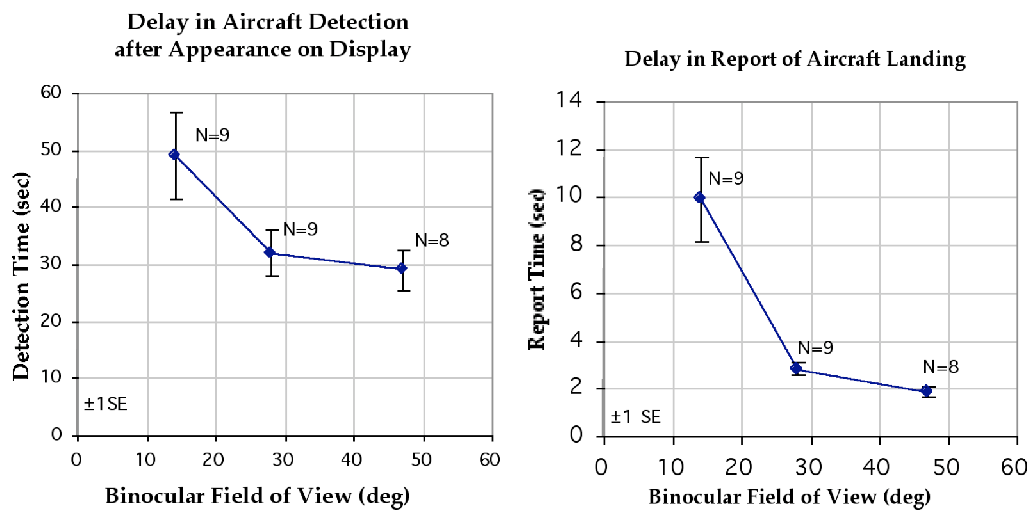

Figure 4. The two tasks tested in this study resulted in significant FOV effects on performance measured by reaction times.

A 2-way ANOVA was calculated for Aircraft Detection with 14° and 28° FOV using either full or partial overlap (Table 2). The FOV effect remained significant ($F(1,30) = 5.667$, $p < 0.024$; log transformation: $F(1,30) = 6.047$, $p < 0.020$). Aircraft Detection data for full vs. partial binocular overlap conditions did not differ significantly ($F(1,30) = 1.294$, $p < 0.264$; log transformation: $F(1,30) = 1.231$, $p < 0.276$). No significant results were found for the interactions FOV and binocular overlap in this task ($F(1,30)=0.00$, $p < 0.991$; log transformation: $F(1,30) = 0.05$, $p < 0.824$).

A 2-way ANOVA was calculated for Landing Time Reports for 14° and 28° FOV with full and partial overlap (Table 2). The results for the FOV effect were significant ($F(1,30) =16.142$, $p < 0.001$; log transformation: $F(1,30) = 23.579$, $p < 0.001$). Data for full vs. partial binocular overlap did not differ significantly ($F(1,30) = 0.367$, $p < 0.549$; log transformation: $F(1,30) = 0.004$, $p < 0.95$). Before the log transformation, no significant interactions were detected. However, after the log transformation a marginally significant interaction was found ($F(1,30) = 4.0$, $p < 0.052$; log transformation: $F(1,30) = 5.065$, $p < 0.032$). Because the interaction suggested a benefit to partial overlap and is not consistent with the detection results, we believe it may be spurious.

Simulator induced side effects were evaluated by the Simulation Sickness Questionnaire (SSQ). No statistically significant effects were found for the FOV or binocular overlap conditions. Nevertheless through out the experiment a low level of simulator sickness could be observed. Of the 45 subjects beginning the experiment, three subjects failed to complete it due to discomfort.

4.0 DISCUSSION

The field of view effects measured for both aircraft detection and landing reports suggest that performance will to become asymptotic somewhat after 50°. The predictability of the traffic pattern probably contributes to this restricted FOV requirement. Such a field is easily achievable with existing head-mounted see-through displays, particularly if a partial overlap system is used.

Reaction Time for Aircraft Detection (sec.)			
FOV		14° FOV	28°FOV
		53.0	36.0
Overlap		Full overlap	Partial overlap
		40.6	48.8
		Full overlap	Partial overlap
FOV x overlap	14°	49.2	57.2
	28°	32.1	40.3

Reaction Time for Landing Report (mean sec.)			
FOV		14° FOV	28°FOV
		8.4	3.6
Overlap		Full overlap	Partial overlap
		6.4	5.7
		Full overlap	Partial overlap
FOV x overlap	14°	9.9	6.8
	28°	2.8	4.5

Table 2. Mean reaction time data for ANOVA discussed in the text.

The subsidiary experiment comparing full with partial overlap systems did not find any consistent performance difference between the 100% and partial overlap conditions. This failure to discriminate the two conditions could mean that the visual suppression of binocular rivalry, luning, (Velger, 1998, p.56-58) associated with the partial overlap conditions did not materially affect performance for the overlap used. One reason the visual suppression may not have effect visual detection is that the constant motion of the eye and head insures that any suppression is just a short transient. A second reason is that in the see-through conditions used, the partially overlapping fields were not completely filled with graphic objects, especially in the view above the airport where only small bright, moving aircraft and data tags were displayed. Thus, the frequency of conflicting binocular contours was reduced. In any case, luning does not seem to introduce major visibility problems due to visual suppression for the application we examined. Consequently, it is suggested that designers consider partial overlap systems to achieve the approximately 50° binocular FOV probably needed for the present application.

The SSQ results appeared to be idiosyncratic showing some base-line effects but no effects of experimental variable. Furthermore, the researcher administering the questionnaire noted that subjects appeared inconsistent in their responses, i.e., subjects who actually appeared to be suffering simulation sickness symptoms sometimes choose low scores while other subjects who did not appear to have such symptoms sometimes choose high scores. Accordingly, we have decided to defer further use of the SSQ until we can improve its administration to obtain results with better face validity (cf., Young, Adelstein & Ellis, 2006).

Field of view is only one of many parameters that need to be evaluated for augmented reality displays that may be used in the airport Tower. Performance testing of other display characteristics may be conducted after further functional analysis of the visual aspects of the controllers' task. Since the visual environment of the Tower resembles that of the aircraft that use the airport, the required specification for see-through HUDs give researchers a substantial head start on particular basic visual specifications. These established specifications include usable values for effective luminance, contrast, semi-silvered mirrors and visual resolution. Specifications remaining to be determined in general relate to the dynamic fidelity with which visual information is presented, i.e. visual stability, latency, and dynamic spatial accuracy. Though not an issue for virtual environments, for augmented reality applications the impact of visual occlusion of the real world introduced by the HMD is another important design factor. To determine these values further analysis and research must be conducted to identify all the visual affordances related to user and aircraft motion that virtual tower displays must support.

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