MULTIMODAL PILOT CUEING FOR 360° SITUATION AWARENESS

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Abstract

The improved agility and flight control augmentation of Future Vertical Lift (FVL) aircraft will allow a variety of mission sets, extending the current helicopter reach to new terrains of operations such as high-altitude desert plateau and the urban canyons of megacities. Operations in megacities will require many of the same aviation capabilities of attack, reconnaissance, assault, and medical evacuation used in operations in less dense terrain, but with considerable constraints. Megacities offer limited landing and pickup zones. Flying close to the ground to provide air support is made more difficult by powerlines, antennas and satellites dishes, and narrow flight patterns between buildings. In this context, it is crucial to develop integrated multimodal interfaces that extend the current operational envelope while enhancing flight safety, providing a 360° SA coverage. Visual displays present inherent limitations due to partial representation of the threat space, because of their limited field-of-view (FOV) or their 2D exocentric perspective. Spatial auditory displays support a natural, ecologically valent, egocentric representation of space where auditory objects behave realistically in terms of direction, distance, and motion. Tactile displays also support a partial representation of 3D space, although with a lower resolution and typically limited to direction and motion.

A study was conducted at the US Army Aeromedical Research Laboratory to evaluate the effectiveness of a trimodal display suite consisting of the Integrated Cueing Environment-Collision Avoidance Symbology (ICE-CAS) blended with the Primary Flight Display (PFD) symbology, an Integrated Collision Avoidance Display (ICAD) overlaying a panel-mounted terrain display (PMD), an Augmented-Reality Spatial Auditory Display (ARSAD), and the Tactile Situational Awareness System (TSAS). Ten UH60M Army evaluation pilots participated in a high-fidelity simulation at the U.S. Army Aeromedical Laboratory (USAARL) in the full-motion UH60 simulator. The results showed that deviations from Commanded Heading were the lowest when the Spatial Auditory Display was used, even more pronounced when the TSAS was activated. This suggests that the Auditory warning gives more time to the pilot to plan the avoidance trajectory. Overall, Exposure Time, which represents the frequency of Time on Task where at least one obstacle was present within the Threat Space (Caution and Warning regions around the ownship), was the lowest when using a combination of Visual, Spatial Auditory and Tactile Displays. Exposure Time to two obstacles (vs. one) was also the lowest with the trimodal Visual-Auditory-Tactile Display combination. When the Tactile Display was activated, the Time of Exposure in the Warning region was lower in the Visual-Auditory-Tactile than in the Visual-Tactile condition, indicating that the spatial auditory information led to a faster avoidance maneuver. These qualitative results validate the previously reported and new subjective data, and demonstrate the substantial advantage provided by multimodal displays for obstacle avoidance. The evolution of the multimodal Display suite and its physical integration for in flight demonstration are discussed in the context of pilot cueing synergies for the FVL multi-role platform.

1. INTRODUCTION

This study was a joint effort between CCDC Aviation and Missile Center (AvMC), the Army Research Laboratory, Human Research and Engineering Directorate (ARL-HRED), the Combat Capabilities Development Command, Data and Analysis Center (CCDC-DAC), the U.S. Army Aeromedical Research Laboratory (USAARL) and NASA ARC.

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In 2018, the US Army released its solicitation for a next generation of Future Vertical Lift (FVL) Attack Reconnaissance Aircraft (FARA) to fly in 2022 and begin fielding in 2028.

The FARA solicitation states: *Army Aviation must operate in highly contested/complex airspace and degraded environments … The Army currently lacks the ability to conduct armed reconnaissance, light attack, and security with improved stand-off and lethal and non-lethal capabilities with a platform sized to hide in radar clutter and for the urban canyons of mega cities.*

Operations in megacities will require many of the same aviation capabilities of attack, reconnaissance, assault, and medical evacuation used in operations in less dense terrain, but with considerable constraints. Megacities offer limited landing and pickup zones. Flying close enough to soldiers on the ground to provide air support is made more difficult by powerlines, antennas and satellites dishes, and narrow flight patterns between buildings.

Operations in the Iraq and Afghanistan theaters have determined that flying in degraded visual environments (DVE) pose a significant risk to helicopter operations. DVE can be caused by partial or total loss of visibility from airborne dust, sand, or snow being stirred up by the helicopter's rotor downwash (brownout). DVE can also be caused by clouds, haze, fog, and starless nights. These conditions modify significantly the pilot's capability to use the natural out of the window (OTW) perceptual cues, increase workload and lead to failure to maintain sufficient clearance with the obstacle, and ultimately, collision with terrain (CFIT), natural objects (trees) or erected structures (buildings, poles, towers and wires). According to a recent US Army Aviation accident report [Ref.[1]] from Fiscal Year 2011 through Fiscal Year 2015, 31% of events for class A and 17% of the events for class B were classified as collision related. Among obstacles, wires represent a specific hazard due to their near invisibility. During the 1994-2003 period, US Army helicopters were involved in 1160 accidents, in which 34 were wire strikes (7 fatalities).

Current sensors provide imagery, which is fused with, or overlaid on, enhanced synthetic vision (ESV) three-dimensional (3D) terrain and/or electro-optical/infrared (EO/IR) imagery. The presentation of realistic, fused terrain/obstacle imagery "augments" the natural scene perception through helmet-mounted display (HMD) or windscreen projected "head-up" display (HUD). Combined with abstract, non-conformal two-dimensional (2D) or conformal 3D symbology (3D CS) superimposed on a multi-function display (MFD) or HUD (Head Up Display), it supports guidance and control especially during operations in DVE. Although EVS and synthetic vision systems (SVS) can improve pilot's SA, thus lowering workload, they can also be misleading and produce clutter and attentional tunneling. Given this, they might not provide the maximally effective depiction of the environment around the helicopter. Indeed, visual displays provide only a partial representation of the threat space, because of their limited field-of-view (FOV) or the 2D exocentric perspective representation of space.

Thus, it is necessary to use alternate sensory modalities that can support a natural, ecologically valent, egocentric 360° representation of the environment around the aircraft. Augmented-reality spatial-auditory displays are natural candidates for the task. They allow the creation of a virtual auditory space where auditory objects behave realistically in terms of direction, distance, and motion. Tactile displays also support a partial representation of the 3D space, although with a lower resolution and typically limited to cueing direction and motion. Spatial-auditory cueing can be an effective terrain/obstacle avoidance display alone or in combination with visual or tactile cues. The fundamental question is how the environment needs to be presented to the crew to provide a maximally effective depiction of the environment around the helicopter while keeping the workload within an acceptable range. An earlier version of visual-auditory display was presented by the authors [Refs.[2,3]]. The current work adds a tactile component and a parametric Threat Space model for defining the Caution and Warning cueing regions.

1.1. Visual Displays

The function of enhanced, synthetic, and combined vision systems is to provide a supplementary view of the external scene thereby delivering the crew with an awareness of terrain, obstacles and relevant man-made features such as buildings, towers and wires. Alerting functions can be added. Conformal symbology (CS) [Ref.[4]] can be superimposed on the display image, such as the locus of the landing zone (see Figure 1 Top).

1.1.1. Enhanced Vision Systems (EVS)

An EVS is a real time "electronic means of displaying a sensor-derived or enhanced real-time image of the external scene through the use of external sensor such as forward looking infrared (FLIR), millimeter wave radiometry, millimeter wave RADAR and/or low-light level image intensifying [Ref.[5]]. The image is displayed to the pilot conformal to the outside scene, i.e. the pilot sees the displayed elements the same relative size and aligned with objects outside the aircraft.

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1.1.2. Synthetic Vision Systems (SVS)

An SVS is an aircraft cockpit display technology that presents the pertinent and critical features of the environment external to the aircraft through computer-generated image of the external scene topography from the egocentric perspective of the cokpit or from an exocentric perspective (the aircraft position symbol is placed on the terrain and obstacle map). SVS are usually displayed in a track-up orientation (rather than north-up) to avoid circular mental rotation and translation cognitive operations required to align the egocentric reference frame (ERF) and the world reference frame (WRF) [Refs.[6,7]]. The displayed information is derived from aircraft attitude, altitude, position and a coordinate-referenced database [Ref.[8]]. Enhanced intuitive views, precise navigation guidance, and hazard detection displays are key elements of SVS. Enhanced awareness is achieved by employing a "look-ahead" function (forward looking terrain avoidance warning). It is also referred to as enhanced ground proximity warning system (EGPWS), or automatic ground collision avoidance system (auto-GCAS). Helicopter terrain and warning systems (HTAWS) displays provide the pilot with alerts (usually color-contouring and aural advisories) of potential wires, terrain, and obstacle conflicts along the flight path [Refs.[9,10,11]). Some of the commercially available systems include Honeywell's HTAWS, Sandel Avionics' HeliTAWS featuring a "WireWatch" capability (provides advance warning of transmission wires whether they are powered or not), the Garmin WireAware Wire-Strike Avoidance Technology that graphically overlays comprehensive power line location and altitude information on the moving map and the AgustaWestland Obstacle Proximity light detection and ranging (LIDAR) System (OPLS) [Ref.[12]] (see Figure 1). These are designed to help the crew avoid main and tail rotor strikes against peripheral obstacles which jeopardize the aircraft's safety during low speed hovering maneuvers in confined spaces. Within these displays, Threat Space representation is usually confined to the use of a circular planar surface, sometimes divided into rings filled with the color corresponding to the proximity to the obstacles such as seen in Figure 1 (Caution = Yellow, Warning = Red).

1.2. Auditory Displays

Auditory displays have been the subject of research for well over two decades [Ref.[13]] and their definition still varies among authors. Here, we refer to an auditory display as any display that uses sound (speech and non-speech) in computational settings to communicate information to users.

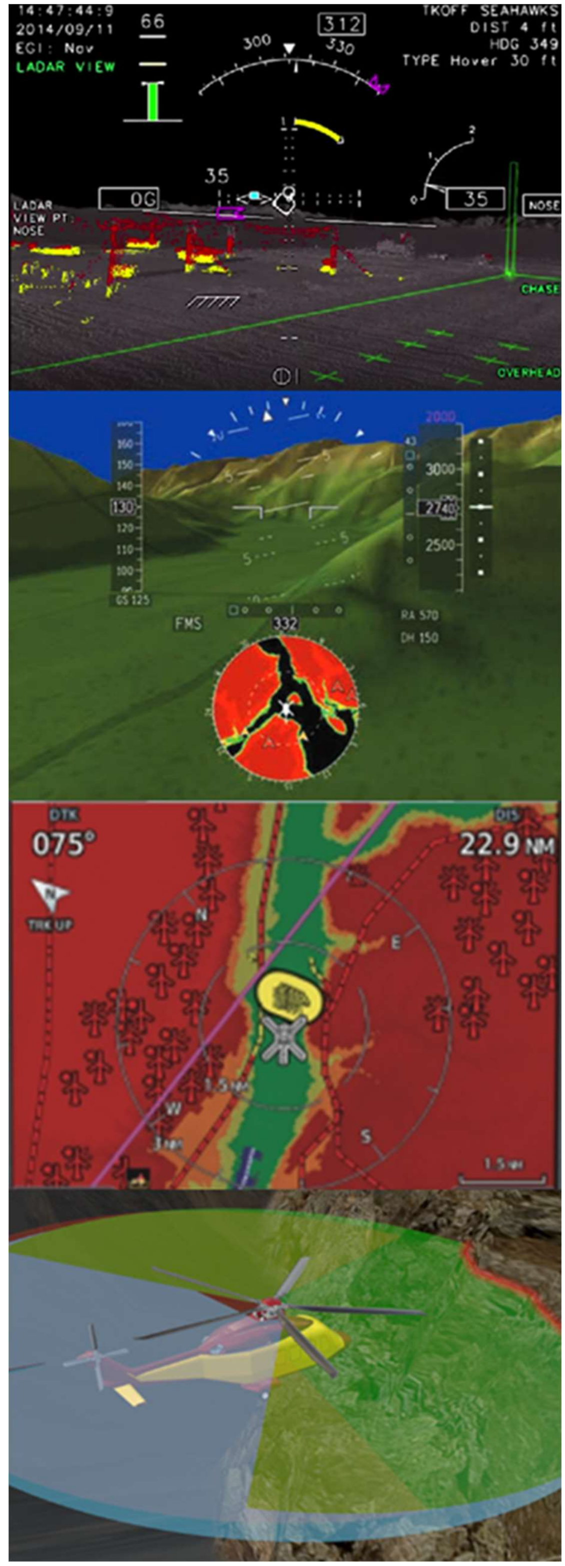

Figure 1. From top to bottom: EVS: ADD LADAR, SVS: Rockwell Collins, Garmin (with WireAware power line avoidance), and Augusta Westland OPLS.

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It was suggested [Ref.[14]] that it should also include the user context (user, task, background sound, constraints) and the application context (aircrafts, automobiles, etc.), since these are all quite essential for the design and implementation.

The rationale and motivation for displaying information using sound (rather than visual information) have been discussed extensively in the literature [Ref.[15]]. Because auditory displays exploit the superior ability of the human auditory system to recognize temporal changes and patterns [Ref.[16]], they may be the most appropriate modality when the information being displayed has complex patterns, changes in time, including warnings, or call for immediate action. Sonification, using synthesized non-speech sound, is thereby an integral component within an auditory display system, which addresses the rendering of sound signals that depend on data and optional interaction. Sonification is generally defined as the mapping or transformation of data streams onto auditory dimensions for the purposes of facilitating communication or interpretation [Ref.[17]]. Changes in data values are associated with a change in an associated acoustic parameter, such as sound wave frequency or amplitude. Sonifications are built upon the notion of pre-attentive awareness and exploit the auditory modality's ability to recognize patterns or small changes in an auditory event. Sonification's short information units (as compared to speech) make it well suited for conveying rapidly changing data such as relative distance and orientation. Sonifications promote eyes-free continuous monitoring without startling or disrupting attentional focus [Ref.[18]]. Thus, if sonifications are designed and implemented effectively, human operators may effectively monitor complex systems while adhering to additional responsibilities without having to constantly switch attention from one task to another.

Sonification includes auditory icons, earcons, and audification. Auditory icons represent a sound "image" of the object to which it is referring. This is a direct comparison to visual icons. E.g., a heartbeat sound can be used for monitoring pulse information [Ref.[19]]. Earcons are nonverbal abstract audio messages used in the user-computer interface to provide information to the user about some computer object, operation, or interaction [Ref.[20]]. In contrast to auditory icons, earcons are harder to remember and learn because they have no natural link or mapping to the objects or events they represent. On the other hand, they are highly structured and can easily represent families and hierarchies of objects and actions with very simple audio messages. This type of sonification has better results in desktop interfaces, alarms and warning systems such as vehicle collision detection systems, and immersive virtual environments (VEs). Earcons have been used successfully in advanced driver assistance systems (ADAS) with high priority warnings such as forward collision warnings, lane or road departure warnings, and blind spot and back-up warnings. Lastly, audification is a specific type of auditory data analysis in which data samples are isomorphically mapped to time or frequency domain audio data. Audification is the most direct form of sonification, as all data samples are preserved and spectral features within the original data will be present as timbral components in the resulting sound.

1.2.1. Spatial Auditory Displays

Spatial-auditory displays (SADs) (also referred to as virtual auditory displays) use spatial auditory cues (sounds with spatial positional characteristics) to provide information to a user. SADs create a virtual auditory space where the auditory information can be substitutive or redundant to visual information. Since sensory systems are energy specific, each system provides the organism with characteristic properties that can be either exclusive or, conversely, amodal, i.e., shared by two or more sensory systems. Indeed, color and timbre are modality-specific, while physical location or duration can be equally conveyed by vision and audition.

Different modes for the uses of (spatialized) sound can thus be inferred: substitution, which is the condition in which one modality replaces another modality when the other is not available or degraded, and complementarity [Ref.[21]], where congruent inputs from different sensory channels are combined. For example, spatial auditory displays can be used to alleviate visual workload when the visual channel is saturated (Refs.[22,23]). They can also be developed for use in applications for which visual information provides no benefit, in limited field-of-view (FOV) applications, teleoperation [Refs.[24, 25]] or presenting information to the blind [Ref.[26]]. More recently, Beattie [Ref.[27]] investigated the potential application of spatial earcons for presenting primary driving information in automated vehicles.

SADs for Aviation

SADs can be used in complex dynamic tasks such as urban combat simulations, flight simulations, air traffic control, and military command and control. Potential applications include monitoring multiple radio communication channels [Ref.[28]], navigating waypoints, locating threats or system malfunctions, and teleoperation of unmanned vehicles [Ref.[24]].

In cockpit applications, with helmet or head-mounted visual displays with limited field of view, spatial audio can be used to direct the attention to critical events outside the FOV.

DVE is another condition in which spatial auditory displays can provide complementarity or substitution to the visual information. Several flight simulator studies have investigated the use of 3D audio for the aural Traffic alert and Collision Avoidance System (TCAS) warning, which is installed in most commercial aircraft [Ref.[29]]. All studies showed that out-the-window visual search time for the intruding aircraft was reduced with 3D audio, compared to monaural warnings. Bronkhorst [Ref.[22]] examined the application of 3D audio to indicate the location of a target jet in a fighter intercept task. They observed that the fastest target acquisition times were obtained with the combination of the visual head down display (HDD) and the 3D auditory display. No difference was found between the conditions with only the visual display or the 3D auditory display.

The application of 3D audio can also be extended to other types of auditory signals in the cockpit. For instance, Haas [Ref.[29]] used 3D audio as a warning display for system malfunctions in helicopters, where the spatial source of the 3D audio warning corresponded to the location of a system malfunction of the aircraft or to the location of a visual indicator light inside the cockpit. The results showed faster warning response times when they were presented with 3D audio (i.e., 3.6 sec on average) compared to the condition when only visual warning signals were present (5 sec). Bastide [Ref.[30]] uses spatial sound to create a multimodal command and control interface for the Rafale aircraft.

In critical domains such as low-level flight where unintentional drift, changes in altitude, and sink rates require immediate counteractive measures to avoid flight into terrain, auditory cues can capture pilot's attention and elicit orientation responses regardless of head position or eye fixation [Ref.[31]]. Novel uses for sonifications have been suggested for the depiction of obstacle location during a simulated helicopter drift during a hover in DVE. Using two earcons (pulsed frequency-modulated waveforms with square-wave modulators, and looming effect), Godfroy-Cooper et al. [Ref.[32]] demonstrated that a single dynamic obstacle presented in the frontal hemifield in the horizontal median plane could be localized, under optimal conditions [individualized head-related transfer functions (HRTFs), best sonification type and continuous presentation] with an average auditory target accuracy of 3.3° and an average precision (response repeatability) of 4.2°.

1.2.2. Ecological Psychoacoustics

The accurate and precise determination of the spatial location and path of objects in the environment is crucial for navigation and object interaction. Unlike the visual system, for which there is a relatively isomorphic correspondence between spatial position in the environment, position in the retina (retinotopic coding), and organization along the visual pathway, auditory spatial information is not directly represented at the level of the sensory receptor. Instead, the sound source location is estimated by integrating neural binaural properties interaural level differences (ILDs) and interaural time differences (ITDs) (for azimuth, defined by the angle between the source and the sagittal plane) and frequency-dependent pinna (external part of the ear) filtering (for elevation, defined by the angle between the source and the horizontal plane containing the listener's ears) [Ref.[33]]. As a result of these differences in coding spatial information in the visual and auditory systems, vision spatial resolution is superior by up to two orders of magnitude [1 min of angle (minute of arc, MOA)] [Ref.[34]], compared to the auditory domain [minimum audible angle (MAA): 1° to 2° for frontal positions, 6-7° for rear] [Refs.[35,36]]; while the temporal resolution of the auditory system exceeds that of the visual system [Ref.[37]]. Thus, the two systems complement each other. Some of the deficits of the visual system due to environmental or physiological factors, for example, not being able to perceive 360° of azimuth simultaneously, or to sense through obstacles are compensated for by the auditory system (in contrast to light, sound is generally able to travel around and/ or through occluding objects). Furthermore, audition plays a key role in guiding locomotion by the central nervous system (CNS) when vision is not available, for which an accurate internal representation of the distance between the organism and the target is essential. The two principal dimensions of egocentric (observer as origin) auditory spatial perception are direction and distance of the sources.

Direction

The localization of an auditory stimulus in the horizontal dimension (azimuth) results from the detection of left-right ITDs and ILDs [Ref.[38]]. To localize a sound in the vertical dimension (elevation) and to resolve front-back confusions [Ref.[39]], the auditory system relies on the spectral cues provided by the detailed geometry of the pinnae. Pinna features cause acoustic waves to diffract and undergo direction-dependent reflections [Refs.[36,40]]. The two different modes of indirect coding of the position of a sound source in space (as compared to the direct spatial coding of visual stimuli) result in differences in spatial resolution in these two directions. Indeed, auditory localization performance is “direction-dependent”. Localization precision and accuracy is greater in azimuth (horizontal median plane, HMP) than in elevation. For a sound source located on the sagittal median plane (SMP), precision varies between 2º and 3º in azimuth, 4º to 9º in elevation. For accuracy, Makous & Middlebrooks [Ref.[41]] found similar variations: 1.5º in azimuth, 2.5º in elevation. Auditory localization precision is maximum in the SMP and remains relatively constant outside this plane. Auditory localization accuracy is the greatest for sound sources located 10º to 23º (“auditory horizon”) above the visual horizon (0º elevation) and is characterized by a symmetrical undershoot around this plane, resulting in a compression of the auditory space in this dimension.

Distance

Auditory distance perception plays a major role in spatial awareness, enabling location of objects and avoidance of obstacles in the environment. Sound localization in this third dimension is not nearly as accurate as that in the horizontal and vertical dimensions. Much as with the perception of visual distance, there are several sources that listeners can use to determine the distance of sound sources. Two of the most informative cues are intensity change (i.e., sound level arriving at the listener’s ears), and direct-to-reverberant (D/R) energy ratio [Refs.[42,43]]. The relative importance of these cues varies widely across conditions. The intensity cue arises from the physical attenuation of a sound with distance. Given a point sound source in anechoic conditions, sound intensity arriving at the listener will decay by 6 dB with every doubling of the distance; the rate of decay is lower in reflective surroundings or if the source is directional. The range over which distance cues are operable varies, and some cues are only useful within peripersonal space (sounds that are within reaching and grasping distance, <1 m from the listener), a region where internal representations of distance are based on both auditory and tactile information [Ref.[44]]. Listeners may be particularly sensitive to auditory distance for near sources, potentially because nearby auditory events may require immediate motor responses, especially if the signal is threatening or particularly interesting. Also, there are spectral cues for near-field sources that don’t occur for far-field sources as a function of distance. Note listeners tend to underestimate distances that are greater than 1.5 m and tend to overestimate distances that are less than 1.5 m [Ref.[45]]. Distance judgments are also generally more accurate for lateral sounds than for sounds near the median plane, both for far and for nearby sources. Finally, non-perceptual factors, including the importance of the auditory event to the listener, also can affect perceived distance.

Auditory Looming and Time to Contact (TTC)

Visual looming refers to the rate of change in the size of an approaching object’s retinal image. A corresponding auditory "looming effect" [Ref.[46]] exists supported by monaural loudness changes, interaural time differences, and to a lesser extent, Doppler effect. Both ITDs and monaural intensity change have salient physical characteristics that mark the point of closest passage for a sound source. The Doppler shift (change in frequency) has not such salient characteristics. For a constant frequency approaching source, the frequency that arrives at the observation point (perceived as pitch by the listener) is initially higher than the frequency that is emitted by the source. The observed frequency remains initially constant, rises at a successively increasing rate as the source approaches, and finally drops at a successively decreasing rate as the source recedes. The magnitude of the frequency drop depends on the speed of the source. However, despite the frequency drop, listeners tend to report hearing a rise in pitch as acoustic sources approach. The apparent paradox between falling frequency and perception of a rising pitch has been termed the “Doppler illusion” [Ref.[47]]. The pattern of perceived rising intensity produced by an approaching sound source is particularly salient information on source approach. It has been termed “acoustic tau” [Ref.[48]] in reference to the visual tau (τ) variable that specifies the time to contact by the optical expansion pattern produced by visual approaching objects. Interestingly, humans systematically underestimate the source location and generally also underestimate the TTC, expecting contact before the source arrives [Ref.[49]]. This tendency may provide enough time to initiate an appropriate behavior to avoid the object. This primary warning role of the auditory system is also at work in the estimation of auditory distance judgments by a listener in motion toward an auditory object [Ref.[50]].

1.2.3. Virtual Acoustics and Head-Related Transfer Functions (HRTFs)

A virtual auditory space (VAS) is created using loudspeakers or headphones and designed to replace or augment the natural listening environment. An anechoic individualized VAS can be generated by simulating the wave pattern at the eardrum of an external sound source in the free field [Ref.[51]]. For each sound source location in space relative to a listener’s head, a unique spectral and temporal pattern is imposed on the

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sound by the head, pinnae, and torso. These patterns are termed Head Related Transfer Functions (HRTFs) in the frequency domain (Head-Related Impulse Responses HRIRs, in the time domain) and can be captured and reproduced to create a purely virtual simulation. Alternatively, the simulation can overlay the listener's existing environment to create an augmented-reality display. In a static anechoic environment, filtering of a source signal with the HRTFs for a given direction delivers to the listener's eardrums the same acoustic pressure wave as the true source in the same environment. By including reverberation and motion cues due to ego-motion of the listener, one can synthesize more realistic environments [Ref.[52]]. Unfortunately, individual differences in anatomy, especially the shape of the pinnae, means one HRTF dataset does not fit all. Pinnae, head, and torso sizes can vary greatly from one person to the next. Thus, spectral characteristics can also vary greatly so that the HRTFs of one individual can yield significant perceptual distortions when used for another.

1.3. Tactile Displays

1.3.1. Vibrotactile Perception

A tactile stimulus can be characterized by frequency, intensity and duration. vibrotactile frequency is used to reliably encode information, such as increased urgency with increased frequency. Changes in vibration intensity or amplitude could also be used to convey information such as proximity or range of a vehicle to an obstacle. Temporal variation in a tactile stimulus (burst duration, pulse repetition rate, inter-pulse interval, and number of pulses) is another variable that may be used to encode information in a tactile display. Rhythms can also be created to encode information by grouping vibrotactile pulses of varying durations (e.g., signaling urgency of message, proximity of vehicle). Tactile rhythm and complexity of the waveform to create tactile patterns called *tactons*, analogous to visual icons or auditory earcons.

Spatial coordinates of tactile stimuli are topographically represented in the sensory cortex according to the location and density of innervation of the various body parts. In general, the ability to localize a point of vibrotactile stimulation on the body is best when it is presented near anatomical points of reference such as the wrist, elbow, spine, or navel. Like spatial resolution in the auditory system, van Erp [Ref.[58]] found that localization accuracy was highest for stimuli presented in the mid-sagittal plane of the body and that errors were higher for stimuli presented on the side of the torso, differences which have direct consequences when designing tactile displays.

1.3.2. Tactile Display Devices

Most tactile displays depend upon *taction* (the act of touching) derived from mechanical receptors in the skin. Tactile display devices can be categorized into three types of devices based on the mechanism with which they stimulate the skin: vibrotactile, electrotactile, and static actuators. Vibrotactile displays, the most commonly used, stimulate the skin using an actuator that converts electrical energy into a mechanical displacement of either the whole tactor or a contactor pad at frequencies ranging from 10 to 500 Hz.

1.3.3. Tactile Display Roles and Applications

To date, the primary applications of tactile information presentation can be grouped into two main categories: sensory substitution and spatial guidance. Tactile cues have been used to substitute/offload other modalities to aid those with visual or hearing impairments [Ref.[53]], help with overcoming difficulties related to data overload, present non-visual communication [Ref.[54]], and provide information that is confidential [Ref.[55]]. With respect to spatial guidance, tactile cues have been used to support interaction with objects, to help with orienting/guiding 2D localization [Ref.[56]], and to aid in navigating unfamiliar terrain [Ref.[57]].
A variety of tactile displays have been developed to aid spatial orientation and navigation in situations in which the human operator can become disoriented. Circumstances leading to disorientation may include an absence of stable reference frames, such as when flying through clouds or flying under high G-load conditions [Refs.[58,59]], working in microgravity environments, or navigating in unfamiliar terrain [Ref.[58]]. In such displays, vibrotactile actuators are used to present information about the intended direction of an operator or vehicle, the pitch and roll of an aircraft, and/or the location of way points in the environment. The Tactile Situational Awareness System (TSAS) was developed for fixed and rotary wing aircraft and other military platforms [see Rupert, Refs.[57,60]].

1.4. Trimodal Display Integration

The number, quality, and interaction between sensory modalities are key to the realism of the simulated environment and ultimately, to its usefulness. Modality combination should support thematic congruent manageable information loading, complementarity, consistency (spatial, temporal, and semantic congruency), viewpoints (shared reference frames and map orientation), and redundancy, i.e., the use of several modalities for processing identical information [Refs.[61,62,63]]. A natural basis for sensory substitution (one modality replacing another) or complementarity (one modality providing supplementary information to

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another) is the isomorphism of the perceptual representations created by two senses. Under a range of conditions, visual and auditory perception (the two most studied modalities for spatial perception) result in nearly isomorphic perceptual representations. The similar representations are likely the basis both for cross modal integration, where two senses cooperate in sensing spatial features of an object, and for the case with which subjects can perform cross-modal matching, i.e., hearing an object and then recognizing it visually. Spatial isomorphism between representations from two modalities ensures that the spatial dimensions extracted from one will match those of the other, without systematic bias. Consequently, spatial and temporal register between the sensory inputs is a pre-requisite for an integrated user experience. It will ultimately support the semantic information congruency and unity assumption (i.e., a dog's image and a barking sound) [Ref.[64]].

2. THE PRESENT RESEARCH

Under the auspices of the ADD DVE-M program, a trimodal display has been developed, integrating visual, spatial-auditory, and tactile display elements into the Integrated Cueing Environment (ICE) [Ref.[65]] to provide 360° SA around the aircraft. The first task was to provide spatial-auditory cues for obstacle detection and avoidance. The Augmented-Reality Spatial-Auditory Display (ARSAD) [Refs.[2,3,65]] was developed to present the locations of the two most-urgent obstacles and the nearest power line segment using augmented-reality spatial sonifications. Ultimately, the locations of obstacles in the environment will be provided by a multi-elevation 360° bumper RADAR system. For development, a simulator software Sensor Model is used to emulate RADAR behavior. The locations of power lines are assumed to be available in a terrain database.

To complement ARSAD, two visual displays were designed, a top-down terrain, RADAR, and obstacle display termed the Integrated Collision Avoidance Display (ICAD) and additional symbology added to ICE referred to as the ICE Collision Avoidance Symbology (ICE-CAS). Most recently, the Tactile Situation Awareness System (TSAS) was integrated to provide obstacle azimuth tactile cueing using a 12-tactor belt, as well as warn of altitude conditions using a shoulder harness and seat cushion. Together, these four displays provide an integrated and unified trimodal display to warn of potential collisions in the vicinity of the aircraft, inside and outside the field of view. Being augmented and multimodal, it provides increased immersion, SA, and spatial accuracy, as well as redundancy in case of system failure, unimodal perceptual masking, or channel unavailability.

The display has been integrated and experimentally evaluated in the NASA Ames SIL (System Integration Laboratory) simulator [Ref.[3]] and twice in the U.S. Army Aeromedical Research Laboratory's (USAARL's) immersive, 6-Degree of freedom (DOF), full-motion, and full-visual (Level D equivalent) NUH-60FS Black Hawk helicopter flight simulator (Refs.[2,65], and current work).

2.1. Obstacle Threat Assessment

The unifying concepts of the four displays are like RADAR Threat Assessment, the selection of the most urgent obstacles for display, and, partially, the treatment of power lines (TSAS does not have a *unique* power line display).

2.1.1. The Radar Sensor Model

To determine the location of obstacles in the environment, Four Echodyne MESA-DAA RADARs with a beam width of 4° and beam height of 12° will be installed on a UH-60 helicopter for inflight demonstration. This allows three elevations to be scanned 360° in azimuth, with a 4° azimuth increment, at a 1.6 Hz update rate. The RADARs will collectively sweep 360° in azimuth at multiple elevations. Three elevation profiles are being investigated, ascending, level, and descending flight, e.g., ascending covering -6° to 30° elevation, level -18° to +18°, and descending -30° to +6°. The pointing directions of the RADARs will be modified based on ownship pitch and roll to approximate gimballed behavior.

Given that the display elements are being prototyped and evaluated in helicopter simulators before migrating to the physical platform, the RADAR behavior is approximated by a Sensor Model. Since the ascending and descending algorithms have yet to be completed, the level flight elevation range was assumed with gimballed behavior. Professional simulators often provide the capability of doing hit testing using a virtual laser polygon hit test. This allows the virtual environment to be scanned in a fashion analogous to RADAR sweeps in the real world (albeit more like the tight beam of a laser, rather than the broad beam of RADAR). The azimuth increment is every 0.75° with an update rate of 2 Hz for a full scan.

The location and height of Power Line Towers will be available in a database. The visual, spatial-auditory, and tactile displays are being designed for these two obstacle inputs.

2.1.2. The Threat Space

A static-obstacle Threat Assessment [Ref.[65]] maps static obstacle threats in the vicinity of the helicopter to a normalized threat value that can be ordered and sorted to determine the obstacles of

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greatest urgency. It uses a threat scale from 0 to 1 where 0 corresponds to the periphery of a 3D *Threat Space* and 1 to the helicopter blade radius sphere. The shape of the Threat Space is fixed and spherical at low speeds (less than 7.3 knots) and extends in the direction of the velocity vector as speed increases.

The Threat Space is composed of two regions, an outer Caution region and an inner Warning region. The max extent of the Caution region is defined by a time-to-collision (TTC) value of 6.5 knots, the max extent of the Warning region by a TTC of 3.0 knots. At 7.3 knots, the Threat Space begins to ignore threats from the rear (Figure 5). All sensor hits are mapped into this space to determine their threat level. The threat values are then sorted to determine the most urgent (aka Urgent1) and second-most urgent (aka Urgent2) sensor-detected obstacles for presentation.

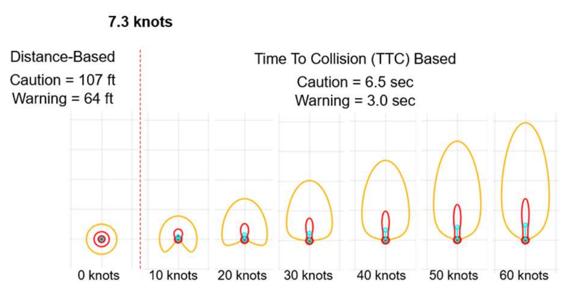

Figure 5. The speed-dependent evolution of static obstacle Threat Space for two cueing regions, Caution and Warning (corresponding to the static Threat Tune defaults). The Threat Space is Distance-Based below 7.3 knots, and Time-To-Collision Based above 7.3 knots. At 7.3 knots, the Threat Space begins to ignore threats from the rear. 2D slices through 3D threat volumes are shown on planes containing the velocity vector (cyan line).

2.1.3. Ground and Down Rejection

Given the -18° sensor scan (and potential lower elevation scans), several ground hits can occur, especially during takeoff, landing, and taxiing. Since in these conditions, the pilot is typically more aware of the ground than other potential obstacles in the environment, a ground filter was introduced. The ground filter rejects sensor hits below 10 ft above the ground. This also helps to avoid oversaturation and to reduce the annoyance and distraction of the alerts. Similarly, if the pilot is flying Nap-of-the-Earth, the pilot is intentionally flying near objects beneath the helicopter, necessitating a down filter. The down filter rejects sensor hits 30 ft below the helicopter's landing gear. When used together, one seamlessly transitions into the other as shown in Figure 6.

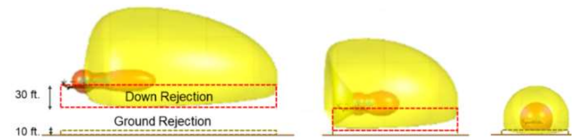

Figure 6. Down Rejection transitioning to Ground Rejection for a Down Rejection Offset of 30 ft and a Ground Rejection Height of 10 ft.

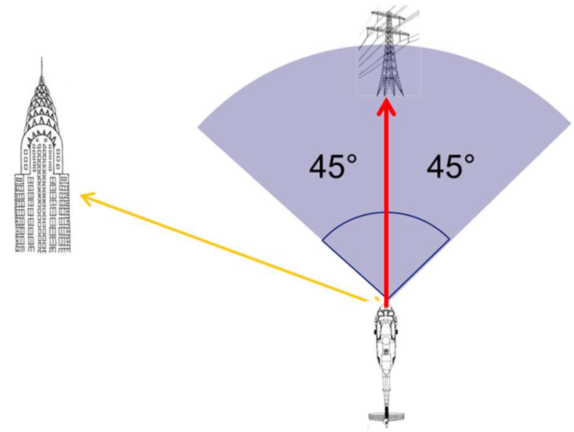

Figure 7. The sensor Angular Rejection window of $\pm 45°$ about Urgent1 to omit from the search for Urgent2.

2.1.4. Angular Rejection and the two Most Urgent Obstacles

A goal of the display design is to warn of two sensed obstacles simultaneously. Thus, all sensor hits are mapped via the Threat Assessment to threat values and sorted. The hit with the highest threat level is then assigned to be Urgent1. Given a sensor azimuthal angular scan pattern and resolutions on the order of a few degrees, it is best to avoid warning of two adjacent hits on the same obstacle. Also, Urgent1 will have already cued that general region of space as a threat. This yielded an *Angular Rejection* of 45°, a +/- azimuth angle about Urgent1 specifying a region to omit from the search for Urgent2 (Figure 7). In the previous design iteration [Refs.[2,3]], Angular Rejection was termed "tolerance" and set to 90°. For the present iteration, the evaluation is taking place in a dense urban environment where a higher resolution might prove useful.

2.2. The Obstacle Avoidance Trimodal Display

Once the two most-urgent obstacles (Urgent1, Urgent2) have been identified via the Threat Assessment above, they are presented to the pilot using the trimodal visual-auditory-tactile display. In addition to sensor detected obstacles, the display also includes one *database* obstacle type, power

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lines. In past experiment debrief sessions [Ref.[65]], pilots commented that power lines (or wires, in general) would be the primary instance in which the obstacle *type* would be important. Thus, due to their unique and significant threat, power line tower locations are stored in a database and presented with power-line specific visual symbology and sonifications. When detected by the sensor, a power line hit will also be treated as a general sensor-detected obstacle.

The modalities are presented in a layered approach (see section 2.2.6 for detail) where the visual information will precede or be presented simultaneously with the auditory information. Likewise, the auditory information will precede or be presented simultaneously with the tactile information. The visual symbology is presented on both Panel Mounted Displays (PMDs), the left MFD and right PFD. The PFD obstacle symbology is considered an addition to ICE [Ref.[66]] and termed the Collision Avoidance Symbology, or ICE-CAS for short. ICE-CAS can also be presented using a Head-Mounted Display (HMD). The MFD Integrated Collision Avoidance Display (ICAD) includes sensor hits and Threat Assessment symbology overlaid on a terrain map. The Obstacle and Power Line spatial sonifications are part of the Augmented-Reality Spatial-Auditory Display (ARSAD) tool suite. And the tactile information is presented using a Tactile Situational Awareness System (TSAS).

2.2.1. ICE-Collision Avoidance Symbology (Primary Flight Display)

The PFD contained actual ICE and modified Collision Avoidance Symbology (CAS) elements (Figure 8) and scene-linked conformal symbology superimposed over a FLIR image (FOV 60° x 45°). The ICE “Highway in the Sky” indicating the direction of flight was flattened and presented as a magenta chevrons overlaying the terrain. This modification was chosen in order to better test the trimodal obstacle avoidance cueing.

When in the field of view, the two most-urgent obstacles are rendered on the PFD using diamonds colored according to their Threat Assessment threat level, where a threat of 0.0 (Caution threshold) colored yellow linearly transitions to a threat of 1.0 (blades) colored red. They are presented as fixed-sized billboards so that their size increases as the obstacle nears providing a visual looming effect. Their dimensions are 30’ x 30’ so that their visual extent approximately matches the RADAR beam width of 4° at 200 ft.

A power line represents a special case of an obstacle in that it is a database object versus a RADAR sensed object (though it can be sensed as well).

Figure 8. The Primary Flight Display (PFD) Integrated Cueing Environment-Collision Avoidance Symbology (ICE-CAS) overlaid on the Forward Looking InfraRed (FLIR) image. In this Figure, the yellow diamond indicates the most urgent obstacle. The Diamond’s color indicates the threat level from 0 (yellow) to 1 (red). A conformal line is superimposed over powerline wires and towers with the color indicating clearance, orange below, blue cleared.

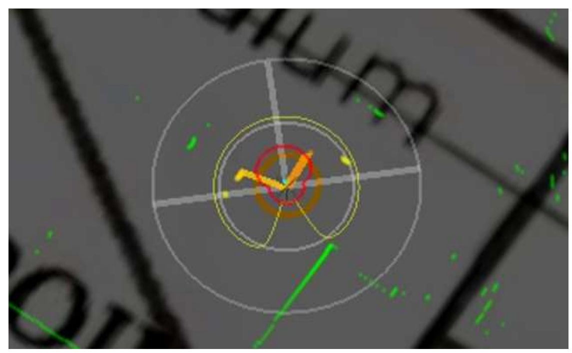

Figure 9. The ICAD 2.5D display composed of a Circular Rule (gray), Caution Contour (yellow), Warning Contour (red), Urgent1 and Urgent 2 obstacle vectors (color coded to threat value, yellow to red), velocity vector (cyan) (very short given speed), and RADAR hit color coding (inside and outside the Threat Space): yellow-red = Threat Space threat level, green = outside of Threat Space, brown = Ground or Down rejected, and gray = no hit.

The Power Line symbology consists of a conformal dashed line superimposed over powerlines and towers when within a kilometer (3281 ft) of ownship. The line color indicates the clearance state, orange below and blue cleared. The helicopter is considered clear of the power line once the landing gear exceeds 30 ft above the line.

2.2.2. Integrated Collision Avoidance CAD (ICAD) Multifunction Display

The Integrated Collision Avoidance Display is a Helicopter Terrain Awareness and Warning System (HTAWS) that includes sensor-detected obstacle information and power line symbology. It presents the terrain, power line, and RADAR information in an exocentric 2D top-down heading-up moving map and the Threat Assessment and obstacle information with a 2.5D axis (Figure 9). This configuration facilitates an intuitive mapping with the OTW, ICE-CAS/PFD, ARSAD, and TSAS egocentric reference frames (ERFs). The map viewpoint zooms in below 6 knots and below to provide additional detail for low-speed maneuvers. The 2D display includes a terrain map superimposed with a magenta ground track line, power line symbology, and RADAR hits color-coded to their threat level (see the color mappings in Figure 9). Two vectors are drawn from the ownship to the two most urgent obstacles which are also color coded to their threat level. The RADAR hits, obstacle vectors, and diamonds are all shown using the same yellow Caution threat 0.0 to red Warning threat 1.0 color scale. The heading-relative ICAD vector, ICE-CAS diamond (when within the FOV), ARSAD spatial sonification, and tactor stimulus (Urgent1 only) all point the same direction, reinforcing the rapid acquisition of obstacle incidence angle.

The 2D Presentation of a 3D Threat Space

With this iteration of the obstacle avoidance display, the sensor obstacle hits, and the corresponding Threat Assessment expanded to include regions off the horizontal plane. This resulted in the Threat Space volume shown in Figure 6 which always points in the direction of the velocity vector. Previously, the Caution and Warning regions were superimposed on the terrain map (and RADAR hits) to provide a *safety profile* of threat in the vicinity of ownship.

To preserve this concept, the new safety profile takes advantage of the radial symmetry of Threat Space to rotate and tilt a horizontal plane into alignment with the velocity vector along the plane's longitudinal axis.

A circular rule and the Threat Space Caution and Warning contours can then be drawn on this tilted plane to create a 2.5D safety profile display using perspective rendering [Ref.[67]]. The ownship-relative 2.5D circular rule includes 100-ft and 200-ft radii circles for distance judgements, a 200-ft longitudinal axis in the direction of the velocity vector, and a 400-ft lateral axis. The rotation of the lateral axis depicts the azimuth of Threat Space while the 2.5D perspective effects provide elevation. Note, the lateral axis always remains a fixed display distance on an Earth-parallel horizontal plane and provides the axis about which the 2.5D display pivots. Figure 10 depicts a series 2.5D displays where the azimuth of the velocity vector matches the heading and the elevation of the velocity vector is lowered from +80° to -80°. The contour lines correspond to a speed of 15 knots and the cyan line depicts the velocity vector.

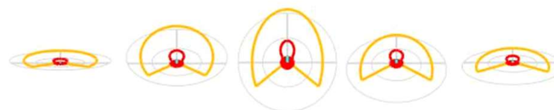

Figure 10. The 2.5D depiction of a 15-knot 3D Threat Space between +80° (left) and -80° (right) velocity vector elevation relative to the horizontal plane. The rotation about the lateral axis provides the 2.5D effect.

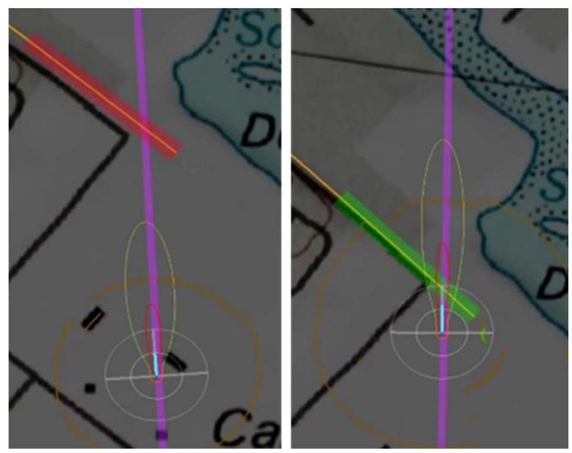

Figure 11. The Integrated Collision Avoidance Display (ICAD) nearest Power Line symbology is red when the ownship is below clearance (left) and green when the ownship has cleared the power line (right). The power line flashes slightly transparent/opaque at 1.5 Hz when not cleared to capture the pilot's attention.

Power Line

Being based on terrain database information, the ICAD Power Line segment symbology is attached to the moving map using linear orange segments between the towers. The nearest segment is highlighted with bands on either side that serve as an altitude-to-go clearance indicator. When the helicopter landing gear are below the clearance altitude of 30 ft above the wire, this band flashes red at 1.5 Hz. When clear, this region is green and fixed. Note, at this time, the clearance behavior is not matched auditorily other than by the perception of elevation cues.

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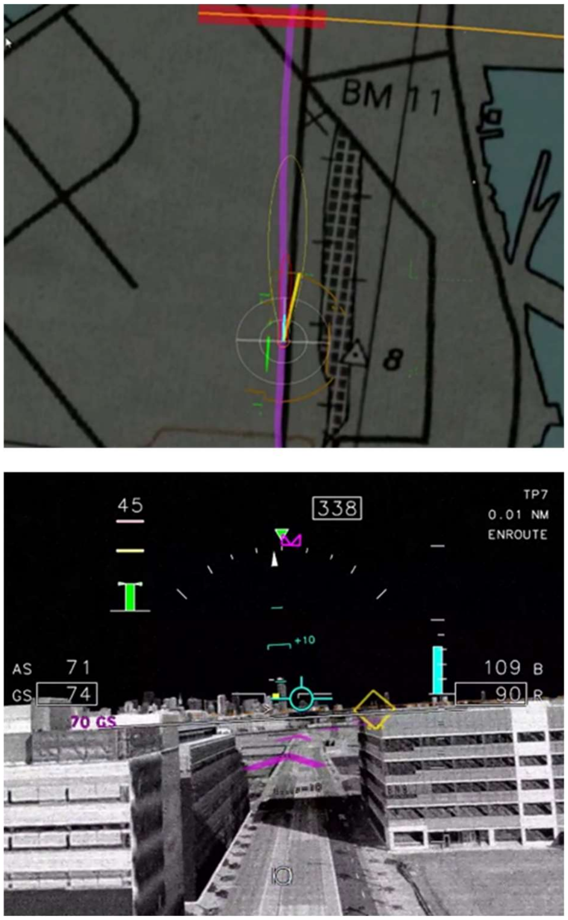

Figure 12. Top: the Integrated Collision Avoidance Display (ICAD) 2.5D and Bottom: Integrated Cueing Environment-Collision Avoidance System (ICE-CAS) 3D Panel Mounted Displays (PMD) demonstrating paired symbology for: (1) the most-urgent obstacle shown as an ICAD obstacle vector and ICE-CAS diamond, both colored according to threat level (Caution in this example), (2) the nearest power line segment shown by the ICAD clearance indicator (red indicating below clearance) and ICE-CAS conformal dashed line (orange indicating below clearance), (3) the ICAD 2.5D velocity vector (cyan line) and ICE Flight Path Marker (cyan circle).

However, 1.5 Hz was selected as the flash rate to match the rhythmic behaviour of the Power Line sonification to reinforce the multimodal depiction of the obstacle.

The ICAD and ICE-CAS displays are shown together in Figure 12. Note, the PFD display elements for the most urgent obstacle (diamond) and the ICE flight path marker (cyan circle) are essentially cross sections of the ICAD most urgent obstacle vector and velocity vector. E.g., for level flight, there is a heading and Earth-orthogonal viewport in the ICAD scene through which the pilot views the right image. In this way, a tight coupling exists between 2.5D and 3D display elements.

2.2.3. Augmented Reality Spatial Auditory Display (ARSAD)

The ARSAD sonifications are developed using the slab3d-based AvADE Aviation Auditory Display Engine [Refs.[2,68]].
slab3d (http://slab3d.sonisphere.com/) is an Open-Source real-time virtual acoustic environment rendering system developed and used by NASA Ames Advanced Controls and Displays (ACD), AFRL Battlespace Acoustics, and the Army Aviation Development Directorate - Ames. AvADE adds spatial sonification support and provides a server for simulator integration. The ARSAD sonifications are described in detail in [Refs.[2,3,65]].

Sonification Mappings

Obstacle Urgency to Earcons

Blattner et. al. [Ref.[69]] proposed an approach to construct earcons, and earcon families, based on the musical qualities of auditory information. For the obstacle sonification, the two most urgent obstacle hits are identified by two unique spatial earcons, termed “Urgent1” for the most-urgent obstacle and “Urgent2” for the second-most urgent obstacle, mapping urgency to timbre and pitch. The Urgent1 earcon sounds slightly higher in pitch and harsher in timbre relative to the Urgent2 earcon. The details of the sound design are discussed in [Ref.[2]].

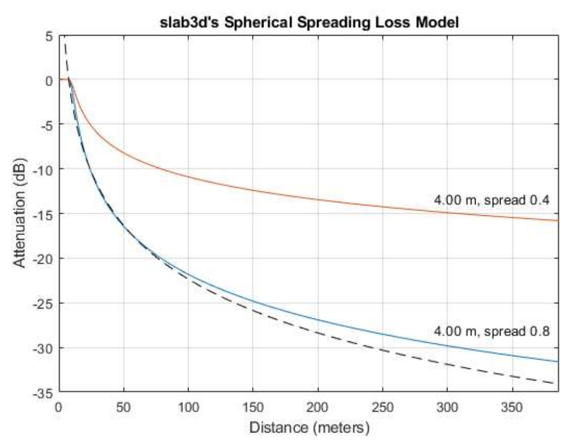

Figure 13. The Obstacle (top) and Power Line (bottom solid) Looming Effects implemented via slab3d's source-listener distance gain model with a 0-dB reference at the helicopter blade radius of 27 ft (8.2 m).

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Obstacle Location to Augmented-Reality Display Location

Given that obstacle locations are presented using an augmented-reality display, obstacle location is mapped to the acoustic model parameters azimuth, elevation, and range relative to the listener. Azimuth and elevation are implemented via HRTF indexing and interpolation, and range via a spherical-spreading loss gain model (see Figure 13).

Obstacle Azimuth to Pitch Scaling

To accentuate obstacle azimuth angle relative to ownship and to reduce front-back reversal (i.e. source localized to the incorrect front-back hemifield) a Sonifier "Pitch Scaling" algorithm was developed. Inspired by HRTF head and pinna shadowing (a darkening of the sound due to the head and pinna's obstruction of high frequencies for rear-incident sources), it reinforces HRTF shadowing when the pilot is looking forward. Eight azimuth pie slices are used to decrease earcon pitch 40 cents per slice, front-to-back (Figure 13). Since the pitch scaling is performed relative to ownship, the pitch remains unchanged with head-tracked head motion.

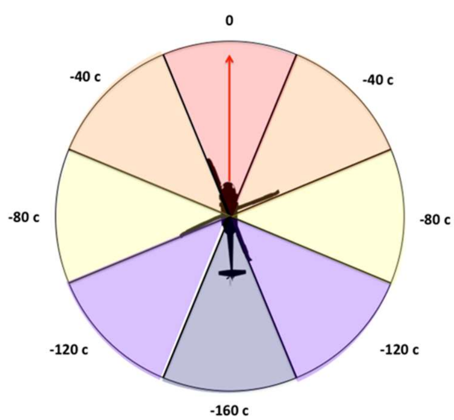

Figure 13. Obstacle-Ownship azimuth pie slices for sonifier earcon pitch scaling. It was designed to reduces the occurrence source localized to the incorrect front-back hemifield (front-back reversal).

Dynamic Obstacle Range to Looming Effect

Visual looming refers to the rate of change in the size of an approaching object's retinal image. A corresponding auditory "Looming Effect" occurs with an oncoming sound's increase in intensity over time. Therefore, it is advantageous for a visual object's sonification to share an overall stimulus energy profile with the visual object (when visible).

Obstacle Range to Pulse Period

Patterson [Ref.[70]] and Edworthy [Ref.[71]] stated that temporal aspects are critical in distinguishing between sounds and that pulse rate is probably the strongest influence on perceived urgency. Later work by Brewster [Ref.[72]] showed that rhythm and tempo variations (i.e., speeding up or slowing down pulse patterns) are an effective method for differentiating earcons. The pulse parameters used are based on the work of Hellier et al. [Ref.[73]], who used a 200 ms tone with inter pulse intervals ranging from 9 to 475 ms (i.e., pulse rates of 1.5 - 4.8Hz). Small pulse durations (< 80 ms for complex and < 30 ms for simple earcons) decrease perception and should be avoided [Ref.[74]]. Given pilots were already accustomed to the pulse-period collision indicators provided in some modern vehicles, pulse period was selected for sonifying distance.

Between the Caution and Warning maximum extents, the Obstacle sonification uses complex tone pulses 80 ms in duration with an inclusive fade in and out of 30 ms. The low-speed obstacle-ownship range mapping consists of a range-to-pulse period maximum distance of 80 ft for Caution and 37 ft for Warning with the pulse period linearly scaled 2000 ms (½ Hz) to 250 ms (4 Hz) between them. If the range is under the maximum Warning extent, the pulse period remains a constant 250 ms, while the pulse duration doubles to 160 ms. If the obstacle is outside of the Caution region, the sonification is muted. At speeds above the Fixed-Distance Threshold (7.3 knots), the maximum distance is based on time to collision and ownship speed with a Caution TTC of 6.5 secs and a Warning TTC of 3.0 secs. The maximum distances occur in the direction of the velocity vector. Given the new threat level-based Threat Assessment, in the future, pulse patterns dependent on threat will be explored.

2.2.4. Powerline Sonification

The Power Line sonification uses a recording of a power line [Ref.[75]] as a spatial auditory icon (a sound representing the object to which it is referring). The sonification's augmented-reality virtual emitter is swept up and down the power line at a rate of 100 ft/sec. The nearest power line segment in the terrain database is found with the closest point chosen as the central location from which to sweep 33 ft on either side. Although this yields a travel frequency of 0.76 Hz, an audible pulse is heard with the end-to-end sweep and direction change, yielding an audible pulse frequency of 1.5 Hz. For a perpendicular approach and a constant sweep extent, the perceived spatial extent increases as the pilot approaches the power line (Figures 15a and 15b), like how it appears visually.

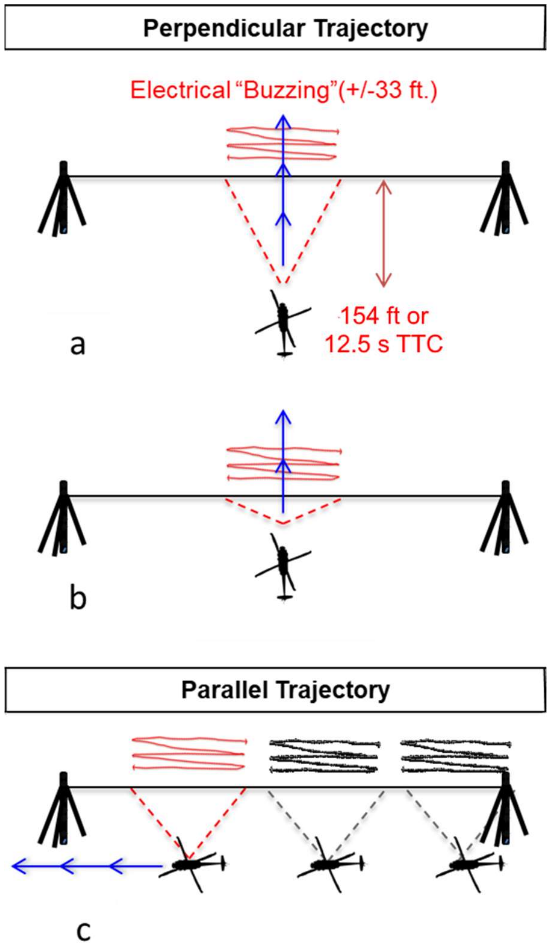

Figure 15. The Power Line sonification behavior for a perpendicular (a and b) and parallel (c) trajectory relative to the wires. The sonification enables at 154 ft below 7.3 knots and 12.5 s TTC above 7.3 knots.

For a parallel heading (Figure 15c), the sonification's relative center point remains fixed and produces a longitudinal (front-back) sweep.
Like the Obstacle sonification, the Power Line sonification is in a fixed-distance mode below the Threat Assessment Fixed-Distance Threshold (360 SA default 7.3 knots) and a Time-to-Collision mode above (TTC 12.5 seconds). This results in the sonification being enabled at 154 ft from the blades at low speeds and at 12.5 seconds from contact at higher speeds.
This yields a cylindrical Caution region with a varying radius centered on a line between the nearest two towers.
Whenever the helicopter is in this region, the sonification will be audible with the distance-dependent gain profile shown in Figure 14. Thus, the Power Line sonification maps obstacle location to augmented-reality location, and dynamic ownship-obstacle range to the auditory Looming Effect. Note, the Power Line does not have an explicit Warning region. However, as the power line nears, the gain slope relative to distance increases significantly, creating a very noticeable and pronounced Looming Effect.

2.2.5. Tactile Situational Awareness System (TSAS)

The Tactile Situational Awareness System (TSAS) manufactured by Engineering Acoustics, Inc. consists of a belt, shoulder strap, and seat pan tactors (Figure 16). The belt is equipped with 12 tactors equally distributed about the waist, 0° forward to 330° in 30° increments. When the most urgent obstacle enters the Warning region, a vibration emanates from the direction of the detected obstacle. The shoulder straps indicate that the altitude has exceeded the recommend height and matches the ICE monaural cue "radar tracking". The seat pan indicates excessive downward speed and matches the ICE monaural cues "vertical speed excessive" and "pull-up". For the 12-tactor belt, the azimuth of the most urgent obstacle is mapped to a tactor using 30° angular regions centered at the tactors (i.e., 12 pie slices). The tactile Warning pulse period matches the Obstacle sonification Warning pulse period of 250 ms. However, the pulse duration is slightly lower at 100 ms (versus auditory 160 ms) in order to preserve the impulsiveness of the tactor. The tactors were set to full amplitude gain.

Figure 16. The Tactile Situational Awareness System (TSAS). The belt provides obstacle cueing from 12 directions, 0° forward to 330° in 30° increments.

2.2.6. Integrated Trimodal and Layered Approach

The visual, spatial auditory, and tactile displays are structured such that Cautions and Warnings occur in a "layered approach" where the visual display

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provides cueing before or simultaneously with the spatial auditory display which, in turn, cues before or simultaneously with the tactile display (Figure 17).

The logic behind a layered approach is complementarity rather than redundancy, at least for the auditory and tactile components of the display. For example, the belt tactors represent the “ultimate” obstacle warning after the visual and auditory warnings failed to correct the pilot’s obstacle avoidance trajectory. This sequential rather than parallel presentation mode has been selected to reduce the potential workload resulting from the division of attention between the different sensory modalities. It also mimics the natural order in which the different modalities are usually perceived in ecological conditions, where tactile cueing is restricted to the peripersonal space (space immediately surrounding the body, ~70 cm in humans).

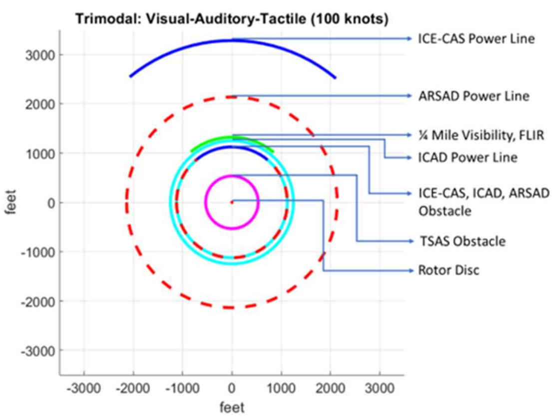

Figure 17. The 360° Situational Awareness trimodal Visual-Auditory-Tactile display layered approach shown in distance and bearing angle for an ownship speed of 100 knots (heading-up). In general, the cueing for a database Power Line or RADAR-detected Obstacle is ordered: Visual (V) before or at the same time as Auditory (A), Auditory before or at the same time as Tactile (T). ICE-CAS (V, PMD) elements are shown as solid blue arcs, ICAD (V, PFD) elements as solid cyan circles, ARSAD (A) elements as dashed red circles, and TSAS (T) as a solid magenta circle. The rotor disc is at the origin.

3. METHOD

3.1. The study

This test plan’s objective was specified by the sponsor and refined in the integrated product team (IPT) coordination meetings between the Aviation and Missile Research, Development, and Engineering Center (AMRDEC), the Army Research Laboratory, Human Research and Engineering Directorate (ARL-HRED), and the U.S. Army Aeromedical Research Laboratory (USAARL). The symbology and cueing assessed during this evaluation are part of an ongoing series of simulations and studies to provide pilots with increased capability to safely operate in urban environments in DVE conditions. The complete results of the study will be reported in a Technical Memorandum.

3.2. The Simulation Environment

All testing was conducted in the U.S. Army Aeromedical Research Laboratory (USAARL) with the 6-Degree of freedom (DOF), full-motion, and full-visual (Level D equivalent) NUH-60FS Black Hawk helicopter flight simulator. A high-resolution PLW Modelworks visual database of the San Francisco Bay Area was used for all the simulated flights. Ten routes (see Figure 18) were used for the Experimental conditions, two for training. They were selected to ensure similar mission profile (Taxi/Hover, Enroute, Approach and Landing) and difficulty level.

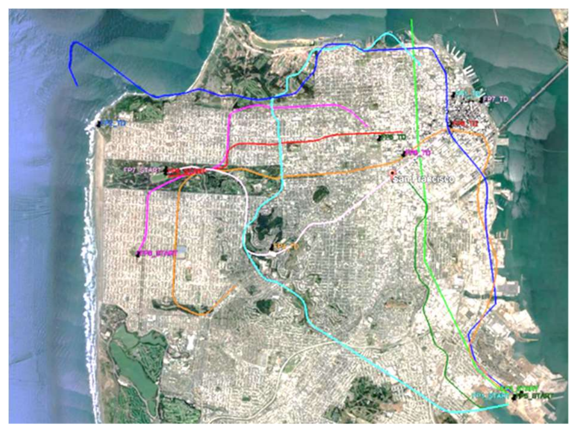

Figure 18. Mission Routes in the San Francisco Bay Area.

3.2.1. Spatial Auditory Display Presentation

The spatialized sonifications were presented via communications earplugs (CEPs) developed by (USAARL) at Ft Rucker, Alabama [Ref.[70]] worn in combination with the standard Helmet General Use–56/Personal (HGU-56/P) rotary wing aircrew helmet equipped with an Acension LaserBIRD2 head-tracker. Slab3d’s default HRIR database, jdm.slh, was used.

3.2.2. Tactile Instrumentation

Tactile cues were presented to the evaluation pilots via Tactile Situational Awareness System (TSAS) belt (for obstacle avoidance), shoulder harness, and seat cushion tactor instrumentation (for altitude cueing) and supporting software algorithms.

3.2.3. Visual Display

Two visual systems were evaluated: SA Photonics Head Mounted Display (HMD) and the UH-60M Panel Mounted Display (PMD). ICE visual symbology, SA visual symbology, and forward looking infra-red (FLIR) sensor imagery was always present on the PMD configuration and the HMD configuration.

PMD

FLIR scene imagery with overlaid visual symbology (ICE-CAS) was displayed on an emulated UH-60M instrument panel. The display screen visible area subtended 15.8 x 12.0 degrees. The screen had a resolution of 1024 x 768 pixels (with 997 x 756 viewable) and a maximum viewing angle of 85°.

HMD

The SA Photonics HMD was selected because it provides high resolution (1920 x 1200 pixels), wide field of view imagery (76° Horizontal, 33° Vertical FOV) via see-through binocular optics with almost no peripheral obscurations. The HMD was also selected based on the ease to integrate ICE-CAS visual symbology.

3.2.4. Cueing Sets

Integrated Cueing Environment (ICE) Visual symbology

The baseline visual symbology used during the evaluation is the ICE visual symbology (Figure 12). It was developed to present critical flight information to enable safe landing, hover, take-off, and enroute flight while in zero visibility conditions. The design philosophy for ICE is to provide the pilot with both the current aircraft state and the optimal aircraft state information. It is then up to the pilot to close the control loop and move toward the required (optimal) state as determined by the ICE guidance.

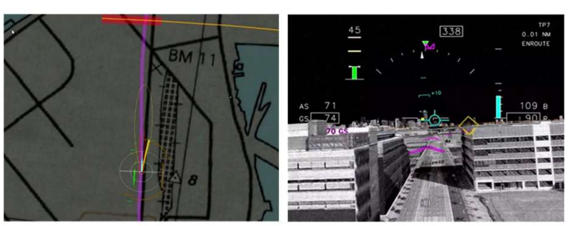

Figure 19: Left: ICAD cockpit moving map (PMD). Right: ICE-CAS symbology (orange diamond on this example) overlaid on the Primary Flight Display (PFD).

Situational Awareness (SA) Symbology

The Visual SA symbology set (Figure 19, but also 21, 22, 23) described in detail in section 2 included the Integrated Collision Avoidance Display (ICAD) and the ICE Collision Avoidance Display (ICE-CAS).

3.2.5. The Participants

Ten US ARMY pilots, age 27 to 51, with current up slips served as evaluation pilots for this study. Primary aircrafts included UH-60M (9 pilots), HH-60 (1 pilot) and AH-64 (1 pilot). Flight hours averaged 1,500 (min 540, max 2060).

3.2.6. The Task

Ten test flights (different routes) were flown with a single unassisted (minimal crew coordination) evaluation pilot at the controls with wind and turbulence turned off. The out-the-window views, including the chin bubbles, were intermittently obscured with blowing dust or dense fog. The FLIR scene imagery within the display was intermittently obscured with dense fog.

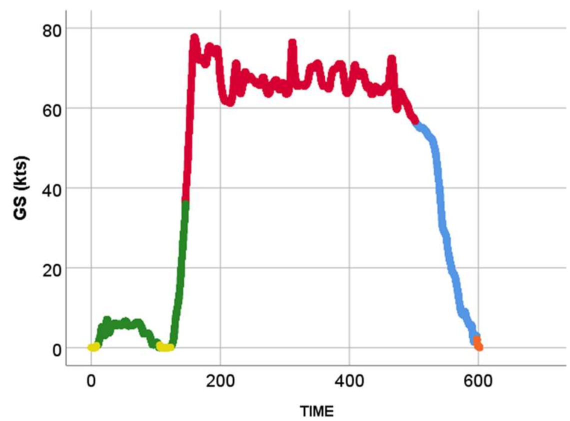

Figure 20. Flight Tasks for Route E, Pilot 6. From start to end: Taxi, Takeoff to Hover, Taxi, Takeoff to Hover, Enroute, Approach and Landing. Vertical axis: Ground Speed (GS, knots).

The pilots' task was to fly predetermined peri-urban and urban routes that encountered natural and man-made obstacles such as buildings, towers, and power lines. Each route lasted on average 10 minutes and consisted of the following maneuvers: Takeoff to Hover, Enroute, Approach-to-Hover, and Landing.

a. Takeoff to Hover starts with the aircraft parked on the ground. The pilot lifts off the ground while maintaining heading with minimal lateral drift.

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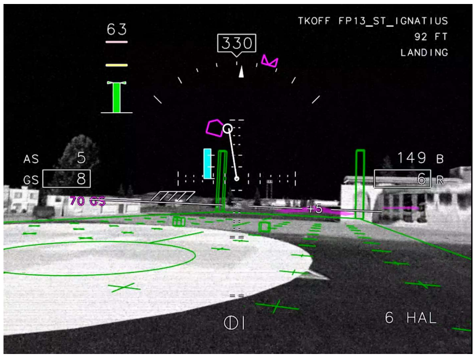

Figure 21: ICE-CAS Takeoff to Hover Page.

b. Taxi starts with the aircraft taxiing (hover or ground) at specified low speed. When the aircraft has cleared any obstacles, the pilot ascends to a specified altitude and accelerates to a specified airspeed (e.g., 70 knots).

c. Enroute is initiated with the aircraft traveling on an established flight path moving at a specified airspeed and altitude toward the approach point. Enroute includes aircraft transition in and out of DVE environments [i.e., transition from visual flight rules (VFR) flight into DVE and back to VFR].

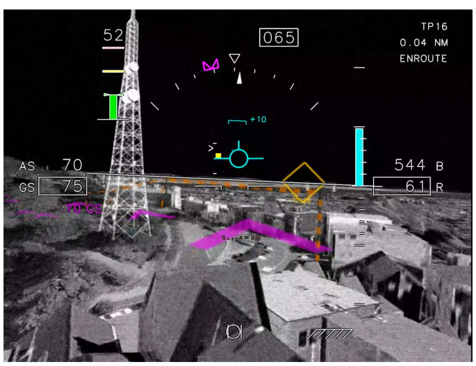

Figure 22: ICE-CAS Enroute Page.

d. Approach to Hover starts with the aircraft at a specified altitude and moving at a specified airspeed toward the landing point. Descent from altitude begins at a specified distance from the hover point. Approach to hover includes transition from VFR into brown-out, transition from VFR into DVE and back to VFR.

e. For Landing, the pilot lowers the aircraft to the ground and touches down with minimal drift.

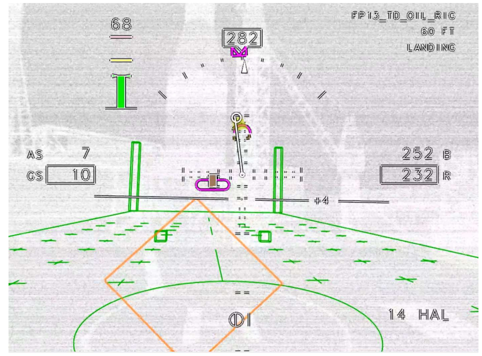

Figure 23: ICE-CAS Landing Page.

Training with the PMD or HMD displays, ICE visual symbology, SA Symbology, tactile cues, and spatial auditory and aural cues was provided before the experimental session and lasted on average 6 hours. All pilots flew five experimental conditions: a Baseline condition where no SA symbology was provides, a Visual only condition (ICAD + ICE-CAS), a Visual-Tactile condition (ICAD + ICE-CAS + TSAS), a Visual-Auditory condition (ICAD + ICE-CAS + ARSAD), and a Visual-Auditory-Tactile condition (ICAD + ICE-CAS +ARSAD + TSAS).

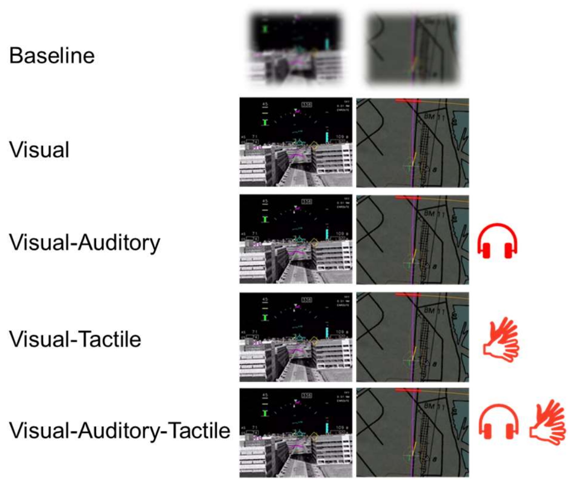

Figure 24: Test Matrix for Modalities. Each of the five conditions was flown with Head Mounted Display (HMD) and Panel Mounted Display (PMD).

Each experimental condition was flown with HMD and PMD. Randomization between mission vignette (route), display type and experimental condition was performed within and between pilots.

3.2.7. The Measures of Performance

The compatibility and effectiveness of each combination of cueing capabilities (Baseline,

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Visual, Visual Auditory, Visual Tactile and Visual-Auditory-Tactile) in a panel mounted (PMD) and head mounted (HMD) configuration were evaluated with quantitative measures of flight performance, pilot psychophysiological measures, Workload and Situation Awareness ratings and pilot's subjective reports. The study metrics were selected based on previous use in research, studies, and operational testing that showed them to be sensitive to performance measurement.
The selected quantitative measures of flight performance are:

- Commanded Heading, Speed and Altitude Deviation
- Exposure Time to Obstacle(s)
- Threat Level
- Controlled Flight Into Terrain (CFIT)
- TSAS activity

Psychophysiological metrics included Eye Tracking, electroencephalogram (EEG) and heart rate variability (HRV). The results of these data are not presented in this paper.
Subjective measures reported in this paper included the Bedford Workload Rating Scale, and the Situation Awareness Rating Scale. Results from Short Cueing Usability Questionnaire, and Post-test Cueing Usability Questionnaire will be briefly reported in the Discussion section.

4. RESULTS

Table 2 summarizes the method used for all the. For all cases comparisons were performed between Baseline, Unimodal Visual and Bimodal Visual-Auditory conditions. When TSAS was active, Visual-Tactile and Visual-Auditory-Tactile conditions were compared.

Table 2. Analyses Matrix. The Visual Tactile (VT) and Visual-Auditory-Tactile (VAT) conditions were compared when the Tactile Situation Awareness System (TSAS) was active (Warning and Rotor regions of the Threat Space).

		B	*V*	*VA*	*VT*	*VAT*
No Obstacle		X	X	X		
Obstacle	Caution	X	X	X		
	Warning	X	X	X	X	X
	Rotor	X	X	X	X	X

4.1. Flight parameters

The following analyses test for the effects of Obstacle (present or not within the Threat Space), Modality (Baseline, Visual, Visual-Auditory, and Visual-Tactile and Visual-Auditory-Tactile when the TSAS is active), Display Type (HMD vs. PFD) and Phase of the flight (Enroute and Approach) on the capacity to maintain the prescribed heading, speed and altitude. Enroute and Approach were selected because 1) they constituted the longest and most homogeneous phases of the flight and 2) the degrees of freedom in deviating from the prescribed parameters were the highest (heading, speed and altitude are more constraint in the Taxi/Hover and Landing phases).
The deviations from the Commanded flight parameters were calculated and the Root Mean Square Error (RMSE) computed. The deviation RMSE was compared between conditions using univariate ANOVAs. Means (μ) and Standard Deviations (SD) are reported. Post-hoc Bonferroni test were performed for multiple comparisons.

4.1.1. Commanded Heading Deviation

Deviations exceeding 90° (.8% of the data) and likely loss of heading, were excluded from the dataset.

Enroute

The presence of an obstacle within the Threat Space had no significant impact on the deviation from the Commanded Heading, as seen in Figure 25 (Obstacle: $\mu = 10.81°, SD = 7.74°$; No Obstacle: $\mu = 10.37°, SD = 4.67°$; $F_{1,181} = .55, p = .45$). There was no significant effect of Modality or Display.

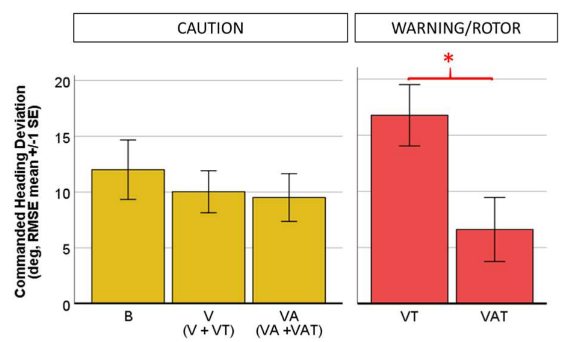

Figure 25: Enroute. Commanded Heading Deviation (deg, RMSE) as a function of Modality and Display when the TSAS was inactive (Caution region of the Threat Space, left) and when the TSAS was active (VT and VAT conditions, Warning and Rotor regions of the Threat Space, right).

When an obstacle was present, but the TSAS was inactive (Caution region of the Threat Space, see figure 25 left), there was no significant effect of

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Modality on the magnitude of the deviation from the Commanded Heading (Modality: $F_{2,57} = 1.67, p = .19$).

When the TSAS was active, i.e. the stimulations were triggered (see Figure 25, right), the deviation from the commanded heading was significantly lower in the VAT than in the VT condition (VAT: $\mu = 6.61°, SD = 2.86°$; VT: $\mu = 15.49°, SD = 12.43°$; $F_{1,27} = 6.98, p = .01$). This represents a 58% decrease in deviation in the trimodal VAT condition. These results demonstrate the role of the auditory display in providing greater anticipation for the avoidance trajectory.

Approach

Tests of Between Subjects effects showed that the presence of an obstacle within the Threat Space didn't modify significantly the deviation from the Commanded Heading (Obstacle: $\mu = 3.38°, SD = 2.70°$; No Obstacle: $\mu = 4.03°, SD = 4.18°$; $F_{1,175} = 1.24, p = .26$). There was no significant effect of Modality. Conversely, Commanded Heading deviations were larger in the HMD than in the PMD condition (HMD: $\mu = 4.73°, SD = 4.63°$; PMD: $\mu = 2.76°, SD = 1.60°$; $F_{1,175} = 12.58, p = .001$). There was no effect of interaction with Modality or Display.

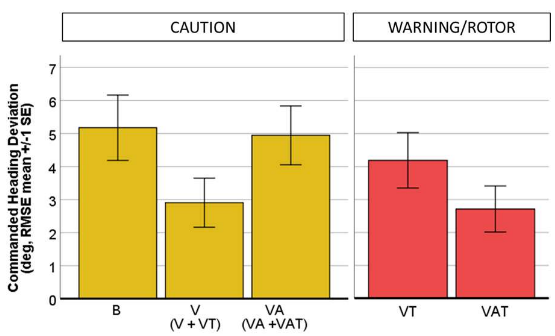

Figure 26: Approach. Commanded Heading Deviation (deg, RMSE) as a function of Modality and Phase when the TSAS was not active (Caution region of the Threat Space, left) and when the TSAS was active (VT and VAT conditions, Warning and Rotor regions of the Threat Space, right).

When an obstacle was present, but the TSAS was inactive (Caution region of the Threat Space, Figure 26 left), there was no significant effect of Modality on the magnitude of the deviation from the Commanded Heading (Modality: $F_{2,49} = 2.33, p = .10$).

When the TSAS was active, i.e. at least one obstacle was present within the Warning or Rotor region of the Threat Space (see Figure 26, right), the deviation from the commanded heading was lower in the VAT than in the VT condition, a difference that didn't reach significance (VAT: $\mu = 2.71°, SD = 1.91°$; VT: $\mu = 4.18°, SD = 3.21°$; $F_{1,20} = 1.82, p = .19$).

4.1.2. Commanded Speed Deviation

Enroute

Speed deviations exceeding 70 knots (26.6% of the data) were excluded from the Dataset.

Tests of Between Subjects effects showed no significant effect of Obstacle, Modality or Display (marginally significant) on Commanded Speed deviation. There was no significant effect of TSAS.

Approach

Commanded Speed deviation was significantly lower when an obstacle was in the Threat Space (Obstacle: $\mu = 30.90, SD = 8.98$; No Obstacle: $\mu = 19.36, SD = 13.08$; $F_{1,176} = 48.06, p < .0001$). Commanded Speed deviation was marginally higher in the HMD than in the PMD condition (HMD: $\mu = 26.88, SD = 12.59$; PMD: $\mu = 23.82, SD = 12.36$; $F_{1,176} = 3.65, p = .05$). There was no significant effect of TSAS.

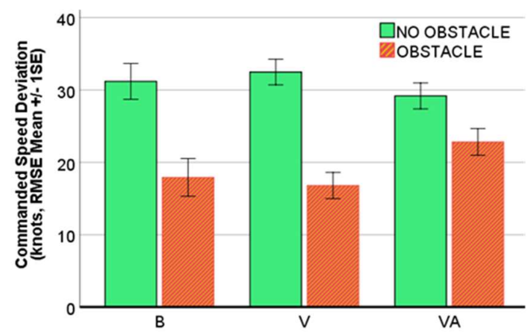

Figure 27: Approach. Commanded Heading Deviation (deg, RMSE) as a function of Modality, and Threat category (No Obstacle, Obstacle).

4.1.3. Commanded Altitude Deviation

Enroute

Tests of Between Subjects effects showed that the presence of an obstacle within the Threat Space didn't modify significantly the deviation from the Commanded Altitude (Obstacle: $\mu = 74.90\text{ft.}, SD = 48.29$; No Obstacle: $\mu = 81.30\text{ft.}, SD = 26.82$; $F_{1,183} = .56, p = .45$). The deviation was higher using the PMD than the HMD (HMD: $\mu = 71.21\text{ft.}, SD = 36.02$; PMD: $\mu = 85.02\text{ ft.}, SD = 40.64$; $F_{1,181} = 10.11, p = .002$). There was no

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significant effect of Modality. The effect of TSAS was not significant.

Approach

Tests of Between Subjects effects showed that the deviation from the Commanded Altitude was significantly lower when an obstacle was present within the Threat Space (Obstacle: $\mu = 87.86\text{ft.}, SD = 68.88$; No Obstacle: $\mu = 125.10\text{ft.}, SD = 46.82$; $F_{1,176} = 16.67, p < .0001$). There was no significant effect of Modality or Display. The effect of TSAS was not significant.

4.2. Obstacle Avoidance

The following analyses test for the effects of Obstacle (present or not within the Threat Space), Modality (Baseline, Visual, Visual-Auditory, Visual-Tactile and Visual-Auditory-Tactile), Display Type (HMD vs. PFD) and Phase of the flight (Taxi, Hover, Enroute, Approach and Landing) on:

- Exposure Time, T_{Exp},which is the total period (number of frames) during which one obstacle (Urgent1) or two obstacles (Urgent1&2) were present within the Threat Space
- The relative frequency of Urgent1 and Urgent1&2
- The Threat level for Urgent1 and Urgent1&2
- TSAS activity (for the Warning and Rotor regions of the Threat Space)
- Control Flight Into Terrain (CFIT) events

Multivariate outliers were identified by computing the Mahalanobis distance and excluded from the dataset (9.6%). The proportions of Threat and No Threat (Urgent1 + Urgent1&2) were computed. Because of the very high frame rate at which the data were collected (60Hz), statistical analyses are not presented given the extreme Chi-Square test sensitivity to high numbers.

4.2.1. Modality

Obstacle vs. No Obstacle

Overall, the percentage of obstacles depicted within the Threat Space represented 10.6 % of the Total Time on Task (TOT). It can be seen from Table 4 that the frequency of obstacles within the Threat Space (T_{Exp}) was, as expected, higher in the Baseline condition than when an Obstacle Avoidance Display was used. The difference between baseline and unimodal represented 12% of the Total Time of Exposure. When the Auditory Display was used in combination to the Visual Display (VA), Exposure Time was reduced by 13.5% as compared to the unimodal Visual Condition (V).

Table 4. Overall Time of Exposure (T_{Exp}), Time of Exposure for Urgent1 (most urgent obstacle only) and for Urgent1&2 (two most urgent obstacles).

	T_{Exp} TOT	T_{Exp} $Urgent1$	T_{Exp} $Urgent1\&2$
B	12.6%	9.6%	2.7%
V	11.1%	9.2%	1.9%
VA	9.6%	8.2%	1.3%
Total	11.0%	9.0%	1.9%

This result supports the hypothesis that the presence of the spatial auditory cueing element allows the pilots to react faster in presence of an obstacle.

Urgent1 vs. Urgent1&2

In 82.7% of the cases, only one obstacle was present within the Threat Space. The frequency of cases where two obstacles were present was the highest in the Baseline condition (see Table 4). The lowest frequency was observed in the Visual-Auditory condition, suggesting that the Auditory component of the Display allows a faster reaction to a second Threat.

4.2.2. Phase

Figure 28 depicts the relative frequency of obstacles (Urgent1&2) vs. no obstacles within the Threat Space for the five Display Modalities as a function of the Phase of the Flight.

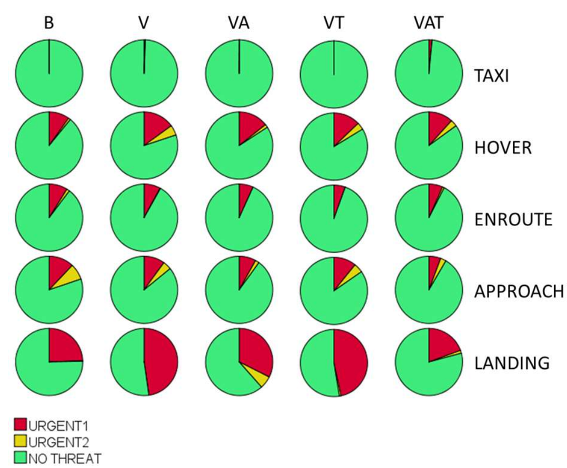

Figure 28. Relative frequency of no threat, Urgent1 and Urgent1&2 as a function of the Display Modality and the Phase of the flight.

Table 5. Proportions of Time of Exposure (T_{Exp}) as a function of the Phase of the Flight for the B, V (V + VT) and VA (VA + VAT) Display Modalities.

	T_{Exp} B	T_{Exp} V	T_{Exp} VA
Taxi	0%	.7%	0.2%
Hover	10.9%	19.9%	15.8%
Enroute	10.3%	8.1%	6.8%
Approach	19.8%	14.1%	10%
Landing	24.7%	47.7%	38.5%

The different phases of the flight were characterized by a very different likelihood to be exposed to obstacles (see Figure 28, and Table 5).

In the very brief Taxi phase, 100% of the cases where an obstacle was within the threat space were attributable to one participant (P3).

In the Hover Phase, Exposure Time represented 15.6% of the Total Time on Task. No clear pattern emerges from the comparison between Modalities.

For Enroute, T_{Exp} was relatively low (7.6% of TOT), and higher in the Baseline than when an obstacle avoidance display was used. Exposure Time was reduced by 21% when using the unimodal Visual Display, an advantage that increased in the VA condition (33%).

The Approach phase is probably the most significant in terms of Display usage for obstacle avoidance. The data highlight again an advantage of unimodal Visual over Baseline (28% gain, i.e. reduced T_{Exp}), and a further advantage of Bimodal (VA) over Unimodal Visual (29% gain). When the TSAS was active, there was a drastic advantage of the trimodal VAT Display (10.9% T_{Exp}) over the bimodal VT (23.1% T_{Exp}) display, with a 47% gain.

Data for the Landing phase were not available in 6% of the cases (3% for P9) due to Control Flight Into Terrain (CFIT). No data were available in the B condition for Pilots P1 and P9. Note the very high frequency of T_{Exp} for this very short phase (35% on average). This result was expected given the fact that Landings were performed in very cluttered urban regions. Within the remaining data, no consistent result emerges.

4.2.3. Display

The frequency of obstacles within the Threat Space almost identical in the HMD and the PMD conditions (Threat: HMD: 10.6%; PMD: 10.7%).

4.3. Threat Level

A categorization of the Threat Space was performed to assess the Time on Task spent within a Caution region (Situation Awareness), a Warning region (evasive maneuver needed) and a Rotor Disc region, where the obstacle is within a 27ft blade radius sphere (likely a Controlled Flight Into Terrain, but not necessarily). Regarding the Threat Level parameter, the Warning region threshold is defined by:

(1) $threatWarning = 1 - ttcThreshWarningsS / ttcThreshCautionS$

The Warning Threat Level Threshold was set at: 1 - 3.0/6.5 = 0.5385 (0: obstacle outside of Caution and Warning Threat Space; >0 to <0.5385: obstacle in Caution region ; 0.5386 to <1.0: obstacle in Warning region, 1.0: obstacle within 27 ft blade radius sphere).

Overall, obstacles were within the Caution region of the Threat Space 90.1%% of the time, in the Warning region 6.2% and in the Rotor Disc region in 3.7% of the cases. It can be seen from Table 6 that the highest frequency of T_{Exp} in the Warning and Rotor disc regions of the Threat Space was observed in the Baseline condition. Conversely, the VA condition was associated to both the highest frequency of T_{Exp} in the Caution Region and the lowest frequency of T_{Exp} in the Warning and Rotor Disc regions of the Threat Space. These results suggest that the Auditory cueing element(s) prevents further penetration of the Threat Space as compared to the unimodal Visual Display.

Table 6. Percentage of Exposure Time as a function of the level of Threat (Caution, Warning or Rotor region of the Threat Space, discretization performed based on Threat level values).

	Caution	Warning	Rotor Disc
B	87.7%	7.0%	5.3%
V (V+VT)	92.5%	5.2%	2.3%
VA (VA+VAT)	94.4%	4.1%	1.4%

4.4. Tactile Situation Awareness System (TSAS) Activity

When an obstacle was present within the Warning or Rotor Region of the Threat Space, the frequency of TSAS activity represented at least half of the total T_{Exp}. The frequency of TSAS activity was 26% lower in the Visual-Auditory-Tactile condition than in the Visual-Tactile condition (see Table 7). This advantage was relatively constant whether one obstacle or two were present within these regions (Urgent1: 27.5%; Urgent1&2: 24.1%).

Table 7. Frequency of TSAS activity for the Visual-Tactile (VT) and Visual-Auditory-Tactile (VAT) conditions when an obstacle was within the Warning or Rotor region of the Threat Space.

	VT	VAT
$\boldsymbol{Total}$	70.5%	51.6%
$\boldsymbol{Urgent1}$	68.9%	49.9%
$\boldsymbol{Urgent1\&2}$	78.7%	59.7%

Figure 29 depicts the relative frequency of TSAS activity as a function of the Phase of the flight. For Hover and Landing, TSAS was never active. The frequency of TSAS activity was higher in the Approach Phase (72%) of the flight and relatively similar in the Hover and Enroute phases (Hover: 50.3%; Enroute: 52.6%). The frequency of TSAS activity was lower in the VAT condition for all the phases of the flight (respectively 21.2%, 32.2% and 15.5% for Hover, Enroute and Approach).

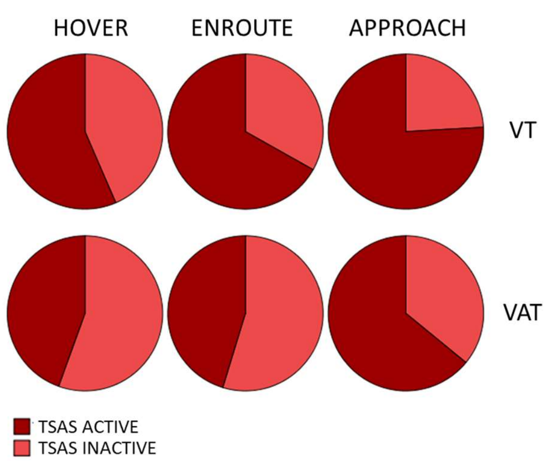

Figure 29. Frequency of Tactile Triggering as a function of the Phase of the Flight for the VAT and VT modalities.

4.4.1. Controlled Flight Into Terrain (CFIT)

Controlled Flight Into Terrain (CFIT) events (N=33) were largely pilot-dependent, and two pilots accounted for 48% of the events (Pilot 9: N = 11, Pilot 8: N = 5).

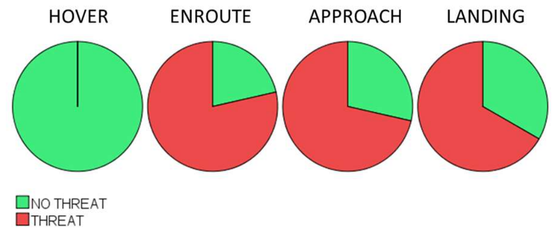

Figure 30. Control Flight Into Terrain (CFIT) frequency for the different Phases of the Flight, in presence or absence of Threat.

They occurred essentially during the Enroute (39.4%) and Approach (36.4%) phases of the flight (see Figure 30).
The CFIT events were more frequent in the Baseline condition (36.4%) and with HMD (60.6%) than PMD, as seen in Figure 31. Collision with an obstacle represented 69.7% of the cases. The TSAS was active in 18.8 % of the cases.

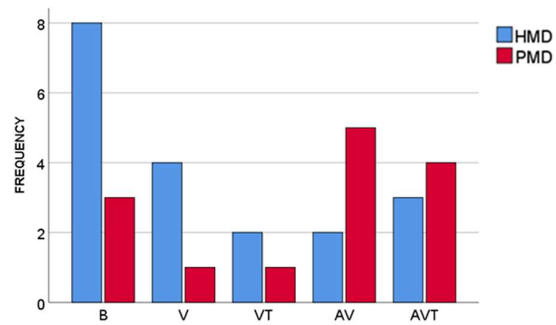

Figure 31: Frequency of CFIT events as a function of the Display Type, HMD vs. PMD.

4.5. Workload and Situation Awareness

4.5.1. Workload

Ratings

Perceived Workload was assessed using the Bedford Rating scale [Ref.[72]]. The Bedford Scale (see Appendix 1) is a uni-dimensional rating scale designed to identify operator's spare mental capacity while completing a task. The single dimension is assessed using a hierarchical decision tree that guides the operator through a ten-point rating scale, each point of which is accompanied by a descriptor of the associated level of workload. The Bedford Workload Scale is a modification of the Cooper-Harper (CH) rating scale, where the discriminator (task performance) is replaced by spare capacity. It ranks whether it was possible to complete the task, if workload was tolerable for the task, and if workload was satisfactory without reduction (Ref.[73]).

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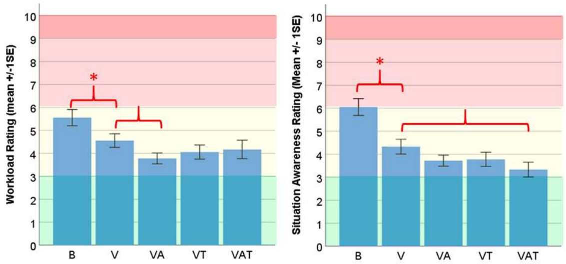

Figure 32. Left: Bedford Workload rating (0 indicates low Workload, 10 indicates very high Workload, see Appendix A for details). Right: Situation Awareness rating (0 indicates high SA, 10 indicates low SA). (* indicates statistical significance at *p*<.05).

The Bedford scale was originally developed for pilots. As with all subjective scales, there may be an influence from the tester, as the instructions and the subjects training with the scale are not exactly specified.
Wilcoxon Signed Rank Tests were performed to evaluate the statistical differences between conditions. Data were missing for Pilot 11.
It can be seen from Figure 32 that for all conditions, the level of workload was satisfactory with reduction. It was higher in the Baseline condition than in the unimodal Visual condition (B,V: $Z = 2.30, p = .02$). The workload rating was marginally lower in the VA than in the V condition (V,VA: $Z = 1.86, p = .06$). All the other differences were not significant.

Comments

Overall, the pilots were very favorable to the visual and auditory displays and considered that they contributed to reduce workload and improve safety: "…*without any audio and visual I could not make out a majority of the wires or obstacles*" (Pilot 4, Baseline). The role of the Auditory display was emphasized: "…*without audio it took longer to see things as no other hints were given until the tactile kicked in last minute*", "…*wires much harder to anticipate without audio*", "…*almost smacked wires due to no audio*", "…*Workload increases slightly with only visual cues*" (Pilot 1, V condition), "…*workload was doubled with reduced audio input*" (Pilot 10, V condition).

Sensory overload and distraction from the flying task were also reported for a minority of pilots: "…*the lack of audio and tactile seems to allow better focus on the approach*…" (Pilot 4, V condition), "…*a lot of attention was given in the scenario to identify what the different cues were telling me*" (Pilot 7, VAT condition).

Finally, familiarity with the system favored display acceptance: "…*familiarity with the system is starting to reduce workload*" (Pilot 1, VA condition),"…*As I become more familiar with the system, workload is beginning to depend on the route difficulty and not necessarily the obstacle avoidance technology*" (Pilot 1, VT condition), "…*Workload is becoming reduced as familiarity with system increases*" (Pilot 1, VAT condition), "…*I feel like the workload would be less with more training time and experience*" (Pilot 3, VT condition).

4.5.2. Situation Awareness

Ratings

The Situation Awareness (SA) rating scale was the analog of the Bedford rating scale. SA was significantly higher in the Visual condition than in the Baseline (B,V: $Z = 2.66, p = .008$). The difference between V and VAT was marginally significant (V,VAT: $Z = 1.80, p = .07$). All the other differences were not significant.

Comments

Overall, pilots commented that the Visual, Auditory and Tactile displays increase SA. For tactile cueing, one pilot reported that he "...found tactile most usefull during Hover/Taxi than forward flight" (Pilot 1, VT condition).
The role of audio cues was considered very important for SA: "...*underflew wires, could not see smaller obstacles without cueing*" (Pilot 1, Baseline),"...*the loss of audio reduces SA*" (Pilot 1, V condition), "...*without audio it took longer to see things as no other hints were given until the tactile kicked in last minute*" (Pilot 4, VT condition), "…*wires much harder to anticipate without audio*" (Pilot 8, V condition), "...*almost smaked wires due to no audio*" (Pilot 10, V condition), "...*better SA on wires with audio*" (Pilot 10, VAT condition).
Among concerns were the facts that "…*some obstacles are recognized too late or when they are quick changes in terrain and can cause an unnecessary alert when flying on the route*" (Pilot 8, VA condition), "…*on short final, they are too many cues giving you command …sometimes the red line and also audio cues at the same time became too much*" (Pilot 9, VAT condition), "…*wire noise was distracting once passed*" (Pilot 1, VAT condition), "…*it's a tone overload having structures on both sides- audio cluttered*" (Pilot 6, VA condition).

5. SUMMARY AND CONCLUSION

This research is part of the ADD degraded visual environment mitigation (DVE-M) program which objective is the deliverable of an ecological, integrated (Visual, Auditory, Tactile) cueing solution to extend the current operational envelope

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for all visual environments while enhancing flight safety.
This paper reports the results of a high-fidelity simulation designed to evaluate the effectiveness of a trimodal display suite for obstacle avoidance. The displays were designed with in thought their integration with the existing ICE primary flight symbology set and the forthcoming top-down Mission Adaptive Autonomy (MAA) multi-function display map.
Each unimodal component was used in a layered approach for the presentation of obstacles within the Threat Space. Each layer provided an intuitive degree of urgency: Visual = Caution, Visual + Auditory = Warning, Visual + Auditory + Tactile = Imminent Collision.

A Multimodal Advantage

The analysis of the selected measures of performance, which included flight parameters, Exposure Time to obstacles and Threat level demonstrated quantitatively the usability of multimodal displays for obstacle avoidance. Modality combination provided both redundancy, when the threats were within the field of regard, and complementarity, when the threats were not visually accessible [Ref.[74]]. Because multisensory integration is supported by the heteromodal (associative) nature of the brain, its supports naturally response facilitation, in terms of speed, precision and accuracy [Ref.[75]]. The cross-modal matching, i.e., hearing an object, recognizing and localizing it in the visual and tactile domains was supported by the spatial isomorphism between representations.
The results also validate the concept of "layered" approach for the presentation of obstacles within the Threat Space, which objective was urgency-based sensory redundancy to keep the workload minimal.
The analysis of deviations from Commanded Heading exposed the benefits provided by the Spatial Auditory Display. In particular, Commanded Heading deviations were smaller in the visual-Auditory-Tactile condition than in the Visual-Tactile condition when the Tactile Situation Awareness System was activated.
A bimodal advantage was also reported in terms of Exposure Time, both for Total Time on Task, Exposure Time to one obstacle and Exposure Time to two obstacles. When an obstacle was within the Warning or Rotor region of the Threat Space, the frequency of Tactile activity was reduced by 25% on average when using the trimodal Visual-Auditory-Tactile Display as compared to the Visual-Tactile display. This trimodal gain that was relatively constant whether one obstacle or two were present within these regions of the Threat Space.
All together these results support the hypothesis that the spatial auditory cueing element(s) helped the pilots detecting a threatening obstacle and anticipating a collision avoidance trajectory.

Comparing Objective and Subjective Measures of Performance

Workload

The level of workload, as measured by the Bedford Rating Scale, was overall "satisfactory with reduction". It was lower in the Visual condition than in the Baseline and lower in the Visual-Auditory condition than in the Visual condition. A few concerns related to the potential overload created by the multiple cues. However, pilots mentioned that familiarity with the displays would further contribute to a reduction of the Workload. A few concerns related to the potential overload

Situation Awareness

Perceived SA was also facilitated by the usage of the displays, a facilitation which paralleled the number of modalities in use. The role of the spatial sonifications in providing greater anticipation was strongly highlighted.

Pilot's General Comments

Pilots commented that the ICE-CAS diamonds attached virtually to the location of the obstacle(s) and overlapping the PFD image were considered effective and helpful. Pilots reported that "…diamonds provided enhanced SA", that the threat level (0 to 1) next to the diamond was useful, and that they "…liked the size scale as you get closer" (to the obstacle).
For the Spatial Auditory cueing, pilots were generally pleased with the different elements (sonifications) and the spatial rendering (direction, distance). However, they were concerned about the overload and the cluttering it can provide with communications and aural alerts. For these reasons, a volume control, a mute switch, and/or an acknowledgement feature were recommended to mute the sonifications once the obstacle has been detected or when the frequency of hits is too high like when flying between buildings. The challenge with acknowledgement is the logic for re-enable, i.e., when and how the system should re-enable.
For the Tactile cueing, pilot's opinion diverged regarding the phase of the flight during which the tactile cueing would be more useful. Consensus was reached, however, for the concept of layered approach, one pilot reported that he would "…use tactile cueing the least". Another that he was

"happy with how tactile layering was approached with the three layers". Parameters adjustments for intensity levels were suggested.
The results of the objective measures of performance confirm the previously reported subjective data showing that multimodal displays were in general very intuitive, facilitated the detection of obstacles, and provided a greater sense of immersion [Refs.[3,65]]. The subjective measures collected for this experiment confirm the pilots' preferred modality of cueing was the bimodal Visual-Auditory Display followed by the trimodal Visual-Auditory-Tactile Display. They highlighted the obstacle detection facilitation in the Visual-Auditory-Tactile condition.

Sensitivity of the Measures

The results for the Flight Parameters data showed limitations due to the macroscopic level of analysis. The level of statistical significance was often low or not reached, a consequence of a very high variability that may be attributable to the very long time-window (the entire duration of the Phase) used for the analyses.
For the analysis of Exposure Time, a strictly descriptive approach was chosen due to the high sensitivity of Chi-square tests to the high frame rate. A reduction of the frame rate would simply bring the statistical significance level from highly significant to not significant. The difficulty to find an adequate level of analysis suggests that more granularity is necessary, and additional analyses need to be performed at the time where an obstacle enters the Threat Space. The effects should be evaluated within 5 to 10 seconds before and after an obstacle enters the threat space. This level of analysis, although very time consuming, would allow to assess detection and avoidance strategies to the obstacle(s).
The last limitation of the current analysis relates to the fact that 1) no categorization was performed as a function of the nature of the obstacle and in particular a distinction between Powerlines and other obstacles, and 2) it was not possible at that time to determine if two successive radar hits were attributable to the same or a different obstacle. The analyses of the video recordings will be key in this assessment.

Head and Eye Movements

The forthcoming analysis of head motion and eye tracking data will likely reveal strategies at the local level of the events, such as determining the locus of fixations, and the frequency, rate and magnitude of the saccades. It will also likely expose reaction time to the events, and how avoidance strategies were chosen based on the available nature of the information provided by the different displays.

To Conclude

This experiment was the last large-scale full simulation scheduled prior to the last phase of the ICE DVE-M program (scheduled for 2020), which will culminate with the integration of the multimodal Integrated Cueing Environment display suite in real flight conditions. To this end, the experimental UH-60 helicopter will be equipped with four RADARs that will capture the obstacles in the three dimensions of space (azimuth, elevation, range), allowing for an exhaustive depiction of the threats/ wingmen in the helicopter operational environment. A series of part-task experiments are planned prior to integration of the Multimodal Display suite on the physical platform.
An experiment will address the perceptual thresholds for the spatial resolution of the TSAS, assuming non-homogeneous space representation around the waist.
A second experiment will evaluate a potential ICE-CAS obstacle "corridor" cue (see Figure 33) to address the near-field size and hit uncertainty issues of the current obstacle diamonds. This alternative symbology will use the spatial resolution of the MESA-DAA RADAR beam (4° azimuth wide and 12° elevation tall) to indicate the location of the obstacles. In this configuration, the representation of the obstacles is conformal to the sensor beam geometry (sensor-conformal). Additional information is provided by a "corridor", where the internal rectangle dimension remains conformal to the RADAR beam dimension and an outer rectangle (for corridor) with gradient fill according to Caution yellow to orange and Warning pure red, to introduce a harder transition for Warning.

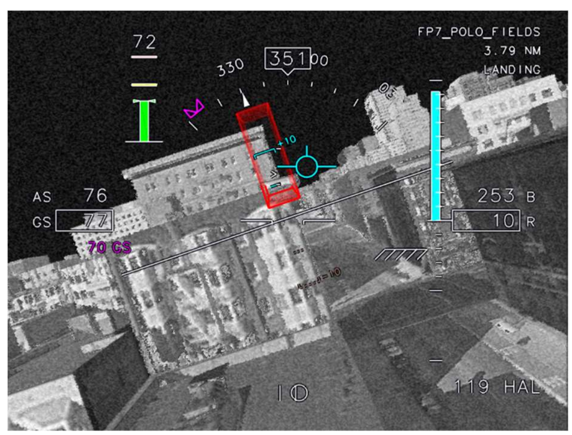

Figure 33. Sensor-Conformal Obstacle Symbology concept: the representation of the obstacles is conformal to the sensor beam geometry.

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Finally, a third experiment will evaluate the benefits of a predictive Threat Space model based on the current trajectory as compared to the current Threat Space model. The results of these experiments will conclude the lab testing and the ultimate modifications incorporated for the final in-flight evaluation. To this end, the experimental UH-60 helicopter will be equipped with four RADARS that will capture the obstacles in the three dimensions of space (left/right, up/down, forward, backward), allowing for an exhaustive depiction of the threats/ wingmen in the helicopter operational environment. Ultimately, the RADAR data should be merged with Enhanced Vision System data, such as Light Detection and Ranging (LIDAR)/ LAser Detection And Ranging (LADAR), to maximize obstacle detection and avoidance behavior, while keeping the workload at its minimum level.

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Appendix A

Bedford Scale

The Bedford rating scale is a three-rank ordinal structure used to assess pilot workload defined as: "… the integrated mental and physical effort required to satisfy the perceived demands of a specified flight task" [Ref.[72]]. The concept of spare capacity is used to help define levels of workload.

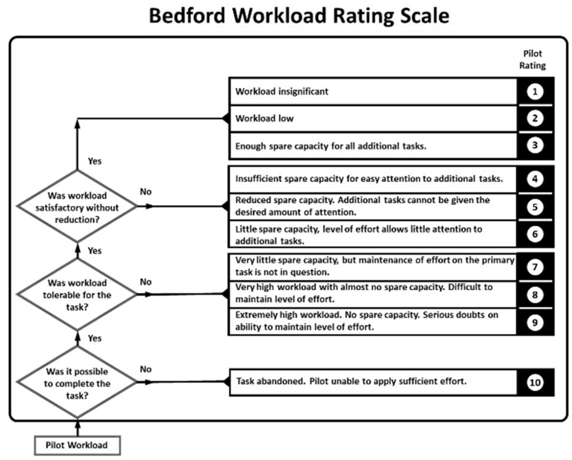

Figure 34. Bedford Rating Scale.

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