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Medical Standard Considerations for the Implementation of Spatial Audio in Aviation

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14. ABSTRACT

As the Army advances its force modernization priorities, the development of Future Vertical Lift (FVL) aircraft has become an area of concentrated effort. Tremendous focus placed on extending the reach of current rotary-wing aircraft and operating over new terrains will allow completion of novel mission sets. Given the ambitions of FVL aircraft operations (i.e., high-altitude desert plateau and the urban canyons of megacities), it is imperative the aviator is provided with state-of-the-art technologies and capabilities aimed at increasing an operator's situational awareness, enabling safe operations, optimizing crew performance, and reducing pilot fatigue. One potential solution is the implementation of spatial auditory display technologies (i.e., 3D audio displays). Spatial auditory displays support a natural, ecologically valid, egocentric representation of space where auditory objects behave realistically in terms of direction, distance, and motion. The present report details the state of science for spatial audio displays in aviation, considerations for medical standards and biomedical design criteria, an overview of current Department of Defense hearing standards, and highlights the various applications for which spatial audio could benefit the aviator.

15. SUBJECT TERMS

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Summary

The current report details recommendations for medical standards for users of spatial audio systems, i.e., three-dimensional (3D) audio displays. As the Army advances its force-modernization priorities, the development of Future Vertical Lift (FVL) aircraft has become an area of concentrated effort. Given the ambitions of FVL aircraft operations (i.e., high-altitude desert plateaus and the urban canyons of megacities), it is imperative that aviators are provided with state-of-the-art technologies and capabilities aimed at increasing awareness, enabling safe operations, optimizing performance, and reducing fatigue.

Based on a review of the literature and sparse preliminary testing in military aircraft, it does not appear that stereo-specific hearing standards are needed at this time. First, there is currently no implementation of spatial audio in Army aircraft. Second, research is needed to determine the impact asymmetric hearing loss has on the ability to accurately perceive spatial audio displays for delivering positional or locational information to aviators. Additionally, present day Aeromedical Policy Letter (APL) classifications of hearing status are sufficiently stringent to select aviators most likely to benefit from spatial audio systems in the aircraft. No additional changes to the APL for aviators who meet the current hearing requirements are currently recommended.

However, it should be noted that pure tone threshold testing does not specifically test for functional performance of spatial hearing abilities (i.e., sound localization and speech in understanding in noise). As such, additional medical standards need to be considered for those individuals who do not meet the APL standard. Following a similar format to the updated Department of the Army Pamphlet (DA PAM) 40-502, it is recommended that only aviators who exceed the APL standard should be assessed further for performance on spatial hearing tasks. Furthermore, it is recommended that the Military Operational Hearing Test (MOHT) is added to the APL for aviators who exceed the hearing standard.

Future research is needed to correlate the clinical adaptation of the Modified Rhyme Test (MRT) and Spatial Digit Test (SDT) within the MOHT with functional performance of aviators on spatial hearing tasks. It is also recommended that medical standards consider the application of spatial audio (e.g., to improve speech communication or to improve waypoint finding) for aviators. For example, asymmetric hearing loss may not preclude an aviator from benefiting from spatial audio when used for radio communications. However, asymmetric hearing loss may become a problem for aviators if they need to localize a spatial audio alert for target identification and/or waypoint guidance to locations outside of the aircraft.

Performance criteria for each spatial audio display application need to be determined for aviator-specific requirements. These criteria could then be used to develop medical standard requirements that users must meet to achieve those tolerance limits for a specific application of spatial audio. For example, if using spatial audio for target avoidance, criteria need to be developed detailing the degree of error limits that would be considered acceptable for detecting the location of spatial audio alerts. As mentioned above, it is currently unknown whether large degrees of asymmetric hearing loss might limit an aviator’s ability to accurately localize a spatial audio indicator for target identification or waypoint finding. Further studies are needed to determine the degree to which asymmetric hearing loss may affect a user’s perception and performance on certain applications of spatial audio in FVL.

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Introduction

The current report details recommendations for medical standards for users of spatial audio systems, i.e., three-dimensional (3D) audio displays. Present day Department of Defense (DoD) hearing standards are reviewed here and spatial audio applications presently available in military aviation are addressed. To date, the United States Air Force (USAF) and the Royal Danish Air Force have fitted their A-10 and F-16 aircraft, respectively, with spatial audio systems (Air ForceTechnology, 2018; Laird, 2018; Ray et al., 2022). Considerations discussed in the current report serve as a starting point for informing the modernization design of the Future Vertical Lift (FVL) cockpit for Army Aviation.

Pilots, aircrew members, and flight medics must perform numerous mentally intensive tasks that demand rapidly switching focus and communication throughout a mission, as well as an extraordinary amount of situational awareness. Such tasks involve the need to process excessive amounts of sensory information quickly in order to make crucial decisions, often with life-or-death consequences. To combat sensory and mental overload during flight, the aviation community has long considered the implementation of spatial audio displays into cockpit design, as this technology creates a natural, ecologically valid, egocentric representation of space where auditory signals behave realistically in terms of direction, distance, and motion. Potential aviation applications of spatial audio displays include threat location warnings, wingman location indications, spatially separated multi-channel speech communications, and audio target location indicators for collision avoidance or navigation guidance.

Briefly, spatial audio displays deliver audio signals in a similar manner to how individuals listen to sounds in everyday environments and can provide auditory cueing, usually in conjunction with visual cueing on the display. The addition of auditory signals to the communications display allows pilots to understand verbal instructions quicker, with less effort, and to make better decisions in critical situations. Spatial audio display systems have the capability of processing auditory signals and presenting them over headphones, giving the user the perception that a sound is emanating from an external source location. For instance, pilots would receive information such as aircraft orientation and radio communications in an ecologically intuitive manner, which inherently would increase situational awareness during high-stress points in a mission.

Previous research has shown an increased understanding of verbal messages over multiple communication channels (Brungart et al., 2002; Drullman & Bronkhorst, 2000; Ericson et al., 2004; McAnally et al., 2002) and quicker target acquisition (McKinley et al., 1994; McKinley & Ericson, 1995; Veltman et al., 2004). In addition, spatial audio displays aid in threat/collision avoidance (Begault, 1993; Begault & Pittman, 1996; Hartnett et al., 2020) and general navigation (Foyle et al., 1996; Milam et al., 2019). Despite the long-term interest in this technology, military aircraft are only recently being fitted with spatial audio displays (Haywas et al., 2021). The current report discusses the basics of spatial audio, current medical standards for aviators, aviator-specific spatial audio applications, review of design criteria and provides recommendations for medical standards for users of spatial audio displays.

Basics of Spatial Audio

Spatial hearing refers collectively to the ability to locate sound sources in space (i.e., sound localization) and discriminate between different sound sources (e.g., understanding speech in the presence of multiple talkers and noise). Acoustic cues to a sound source's location result from the sound interacting with the head and pinna as it travels from its source, which causes the signal to arrive slightly differently between the ears (for review, see [Middlebrooks & Green, 1991; Wightman & Kistler, 1989]). Spatial audio systems essentially process sounds digitally to mimic over headphones the acoustic cues used by the central auditory system to locate sound sources.

For example, a sound originating to the far left of an individual will arrive at the left ear earlier than the right ear (Figure 1, top left) and will be higher in intensity because the head creates an "acoustic shadow" at the ear further from the sound source (Figure 1, top right). The difference in the time of arrival and level of sounds between the ears are known as the interaural timing difference (ITD) and interaural level difference (ILD), respectively. These two interaural differences systematically change as the source location moves from the left to the right side of the individual. Thus, human perception of sound source locations in the environment, or spatial hearing, arises from the central processing of the interaural cues present in the sounds arriving at the two ears.

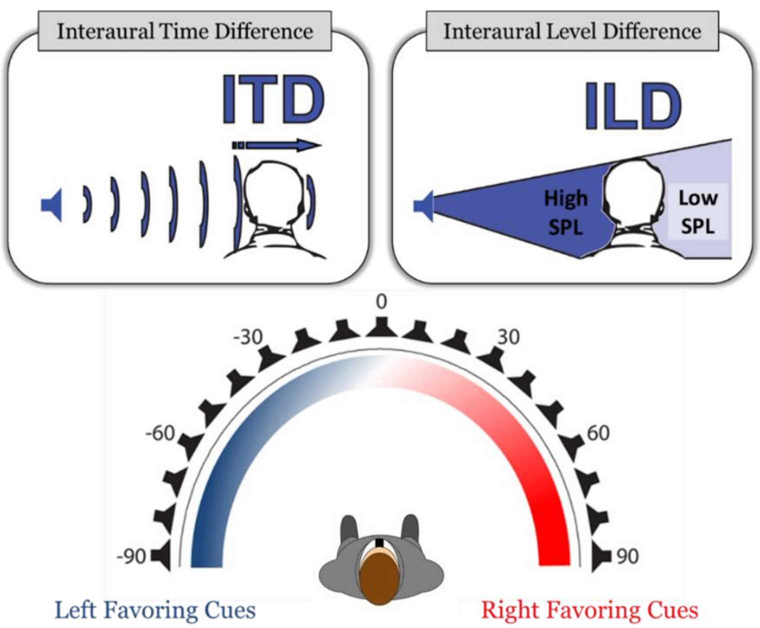

Figure 1. Acoustic cues to sound source location along the horizontal plane. (top) Sounds originating from a source to the side of a listener take additional time to travel to the further ear (top left) and arrive lower in sound pressure level (SPL) or intensity (top right), creating an interaural time difference (ITD) and interaural level difference (ILD), respectively. (bottom) The loudspeakers depicted on the image represent sound sources located on the horizontal plane, level with the ears, to the side and in front of the listener.

Not depicted in Figure 1 are the spectral shape (SS) cues, which are location-dependent changes to the sounds' frequency spectrum that result from interacting with the external pinna of the ears. Each ear "shapes" the sounds reaching the eardrum differently, and the brain uses this information to determine the elevation of the sound source, as well as whether it is in front of or behind the listener. Spectral shaping is also the main reason we perceive the spatialized sounds presented through headphones as coming from outside of the head. Basic stereo audio can only give the perception of sounds moving from left to right *inside* the head. Additional signal processing is required to give the perception of sounds coming from *outside* the head. Such additional processing, commonly known as and referred to in this report as spatial audio processing, results in the externalization of sounds delivered over headphones.

Spatial audio processing involves creating digital filters simulating head-related transfer functions (HRTFs) for different sound source locations and then passing audio signals through them. The HRTF is a transfer function describing how a sound from a specific point in space arrives at the ear. More specifically, the HRTF represents changes across the frequency spectrum of sounds caused by interactions with the head, pinna, and torso on the way to the ear canals. As sound waves move from a source location to a listener, the physical structures of the body transform the sounds, boosting some frequencies and attenuating others. How the sounds are transformed changes systematically as a function of spatial location of the sound source. By simulating these transformations for both the left and right ears, a pair of HRTFs can be used to synthesize and deliver a sound over headphones that is perceived as originating from a particular point in space. Basically, spatial audio processing causes sounds presented over headphones to be perceived at various places in a virtual acoustic space around the listener.

Applications for Spatial Auditory Displays in Aviation

As the amount of binaural research over the past several decades has increased and as spatial audio technologies have become more readily available, it is becoming clearer that separating radio communication and displaying aircraft positional information across virtual places in space perceived to be external to the pilot listening may be useful for improving situational awareness, enhancing performance, and reducing workload during several different flight tasks. Numerous studies over the years have demonstrated improvements in performance using spatial audio (Abouchacra et al., 2001; Bolia & Nelson, 2003; Bronkhorst et al., 1996; Brungart et al., 2007; Calhoun & Draper, 2015; Feltman et al., 2018; Feltman et al., 2020; Kim, 2016; Kim et al., 2018; MacDonald et al., 2002; McAnally et al., 2002; McAnally & Martin, 2007; McKinley et al., 1994; McKinley & Ericson, 1995; McLntire et al., 2010; Milam et al., 2019; Naqvi, 2008; Nelson et al., 1999; Niermann, 2015, 2018; Oving et al., 2004; Philbrick, 2012; Pinedo, 2006; Pinedo et al., 2005; Romigh et al., 2017; Simpson et al., 2005; Veltman & Oving, 1999; Veltman et al., 2004; Wenzel et al., 2000). Here we review spatial audio applications for aviation.

Current Implementation of Spatial Audio Displays in Military Aircraft

Despite the growing literature on the benefits of spatial audio, such displays are only now making their way into real-world environments and slowly finding their way into U.S. military applications. Currently, the U.S. Air Force (USAF) National Guard is the only Service within the DoD that the authors are aware of that has begun field-testing spatial audio displays for pilots.

As part of a major cockpit upgrade, several A10 aircraft have been fitted with spatial audio technologies enabling better radio communications and directional auditory warnings that draw the pilot's attention to a specific threat or area of interest (Air Force Technology, 2018; Ray et al., 2022). Additionally, the Royal Danish Air Force has upgraded their F-16 into a robust multi-mission aircraft with one of the upgrades being the use of a 3D audio system (Laird, 2018). As other Services move forward with modernizing their aircraft to include spatial audio systems, it is prudent that U.S. Army aviation considers such technologies in the design of aircraft for FVL. The aim of the present section is to discuss the various applications for which spatial audio displays may be useful to aviators during flight.

Spatial Audio Displays for Informational Cueing

As mentioned above, spatial audio is typically one component of multisensory cueing displays which take advantage of auditory, tactile, and visual information. Multi-sensory cueing uses inherent biological systems to distribute different pieces of information about the aircraft across different sensory modalities. For example, spatial audio processing allows sounds to be perceived realistically in terms of direction, distance, and motion within a headset in an intuitive and natural manner. Currently auditory components within the cockpit convey no spatial information and generally draw attention to a visual display for the pilot to action. Using spatial audio technology, information about the aircraft's geolocation relative to a waypoint or nearby threat can easily be provided to the pilot.

In aviation, spatial audio displays can provide spatially localized information about the orientation of the aircraft in reference to some specified target location. Simpson et al. (2005) used 3D audio displays as a navigation aid and attitude indicator. Three test pilots used a virtual navigation "beacon" (i.e., a train of broadband noise bursts) and the verbal cue "Set Course" designed to sound as if it were originating from the indicated heading. The results showed the 3D audio display alone did not approach the performance of using a verbal command. Using spatial audio cues as an attitude indicator improved performance (percent correct) when an audio horizon was used. Although the study used 3D audio display technologies, the task used was 2D, and altitude/elevation information was not encoded into the task. Likewise, Brungart et al., (2007) and Simpson et al. (2007) utilized a 3D audio display, but limited the spatial cues to the horizontal plane. These studies highlight the need for additional research on providing elevation information to pilots using spatial audio technologies.

Towers et al. (2014) used a spatial audio display to encode changes in aircraft heading and course deviation. Using a combination of a musical "carrier" note and a square wave, the authors signaled azimuth changes or deviations only. Their results indicated that audio sonifications, with or without head tracking, provided significantly better performance on mean course deviations and mean waypoint errors (Towers et al., 2014). Further, they suggested that in rotary-wing aircraft operations in combat arenas, 3D sonifications "may find use as a supplemental cue to assist the crew in navigating while conducting high-workload out-of-cockpit visual tasks associated with detecting and avoiding enemy threats" (Towers et al., 2014, pp. 1425-1426). In fact, any piloting task involving out-of-cockpit viewing, including tasks using unmanned aerial vehicles, could benefit from these sonifications.

Milam et al. (2019) investigated using spatial audio cueing to aid rotary-wing flight in a degraded visual environment (DVE) simulated in a sophisticated UH-60 Black Hawk simulator. In a side-step-to-hover task, the time-to-completion metric was significantly better with 3D sonifications than in the control condition (i.e., complete visibility outside the aircraft). Pilots also completed an approach to a moving station task where they needed to approach a landing point on a moving Navy ship in a straight line and then hover over it to complete the task. Subjects had no problem flying to the ship in the control condition with complete visibility (Milam et al., 2019). In DVE conditions with no visibility, subjects using 3D sonifications were able to perform the same as subjects in the control condition.

Essentially, subjects were able to use the spatial audio cues to help correct their flight trajectory if traveling in the wrong direction. The most compelling finding from Milam et al. (2019) was observed for the approach-to-moving-station flight task. Pilots were able to actively track a moving target location while using spatial audio and navigate to it in an extremely challenging flight environment in which they would not normally operate. Findings from these studies, implementing spatialized audio for aiding pilots' navigation along the horizontal plane, demonstrate these technologies to be beneficial.

Previous aviation research with spatial audio includes its effects on situational awareness (Feltman et al., 2018; Feltman et al., 2020; Milam et al., 2019; Parker et al., 2004; Szoboszlay et al., 2021), flight task performance (Oving et al., 2004; Parker et al., 2004; Veltman et al., 2004) and measured and/or perceived cognitive workloads (Feltman et al., 2020; Parker et al., 2004; Spagnol et al., 2018; Tannen et al., 2004; Veltman et al., 2004). Specifically, 3D audio cues have shown reduced response times to localizing objects, which is of significant value in helping pilots track the presence of other aircraft, enemies, targets, or obstacles (Brungart et al., 2007; Milam et al., 2019; Parker et al., 2004; Simpson et al., 2004). General navigation tasks with 3D audio improved maneuverability or flight trajectory corrections during DVE or other nonoptimal visual conditions (Bolia et al., 1999; Milam et al., 2019; Oving et al., 2004). Additional spatial audio cueing has also shown sustained task performance when pilots are given primary and secondary tasks (Parker et al., 2004). Despite the compelling nature of 3D audio integration into aviation, gaps in research remain. Additionally, spatial audio is only one sensory cueing system currently in consideration for FVL platforms and will likely be part of a multisensory cueing package.

As a result of spatial audio being only one component of a multisensory cueing package, studies involving spatial audio cueing are typically integrated with visual head- or panel-mounted displays, as this better personifies real-world flight and/or tactile cueing systems. Different cueing modalities for different tasks may prove beneficial in high visual workload conditions, but these multisensory combinations, including when and how to use them in flight are still being determined. Feltman et al. (2020) determined that using multi-sensory cueing was likely beneficial but noted the substantial amount of variability in individual preference to cueing. Multisensory cueing adds stimuli to the cockpit, and there is a critical need to ensure that this addition does not increase the cognitive workload of the pilot. Research is starting to demonstrate that the presence of spatial auditory cueing either has no effect or decreases perceived workload. This has been demonstrated perceptually and with biophysiological measures (Feltman et al., 2020; Simpson et al., 2004; Tannen et al., 2004; Veltman et al., 2004).

Spatial Audio Displays for Speech Communication

Presently, military personnel use a split monaural (diotic) presentation mode for radio communication, meaning that the same signal is routed to both ears (see Figure 2, left). There are multiple problems with diotic presentation of speech signals. First, simultaneous presentation of two or more signals to the two ears mask each other, which makes each signal more difficult to hear. Second, this presentation mode causes the perception that the signals are originating from the center of the head, which adds to the difficulty of hearing one signal over another. Spatial audio processing attempts to simulate over headphones the natural way in which sounds appear around us in the real world, by modifying sound as if it had travelled around the head and into the ears (Figure 2, right). This "outside" of the head perception generated by spatial audio simulates how we listen to conversations in everyday, real-world situations, which makes teasing out the speech signal the listener wants to attend to easier than if all the voices were coming from "inside" of the head.

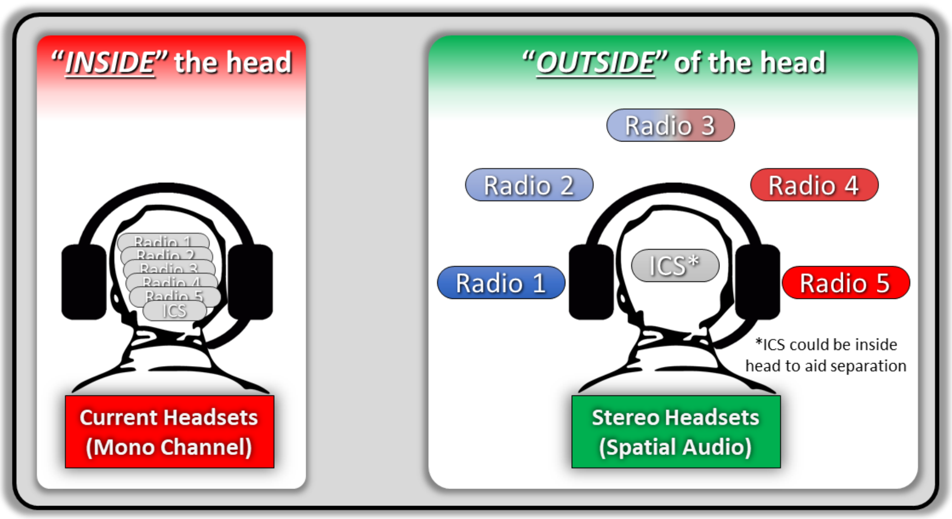

Figure 2. Radio communication configurations. (left) Current radio headset used in military aviation. (right) Spatial audio concept using stereo headsets to "spatialize" the communication channels.

Previous research demonstrates that listening to more than one channel of speech presented diotically results in poor speech understanding (Abouchacra et al., 2001; Brungart et al., 2002; Ericson & McKinley, 1997; Kim et al., 2018). Brungart et al. (2002) demonstrated that the presentation of multiple speech signals resulted in degraded performance on speech understanding. Brungart et al.'s (2002) findings showed speech recognition scores decreased for two or more signals presented simultaneously compared to a single speech signal. When two speech signals were presented simultaneously, performance dropped from > 90% to 62%, when three signals were presented simultaneously, performance dropped to 38% and when four talkers were presented simultaneously, performance fell below 25%. Given this significant drop in performance with the addition of speech signals, speech understanding would improve by either reducing the number of speech signals or changing the delivery configuration of those signals.

If a listener needs to monitor two channels, the first improvement could be to direct one channel to one ear and the second channel to the other ear in a stereo configuration, also referred to as dichotic. Presentation through a dichotic configuration would improve the understanding of two speech signals by about 10-20% over diotic presentation (Ericson & McKinley, 1997); however, this improvement declines when needing to monitor three or more channels. Achieving further improvements to speech understanding for multiple channels is possible using spatial audio presentation. Spatial audio allows for multiple channels of auditory input to appear as though they are in different places around the listener's head.

Several researchers have demonstrated the benefits of spatial audio on speech recognition (Abouchacra et al., 2001; Bolia & Nelson, 2003; Brungart & Simpson, 2003; Ericson & McKinley, 1997; MacDonald et al., 2002; Nelson et al., 1999), response times (Kim et al., 2018; MacDonald et al., 2002) and perceived workload (Kim et al., 2018). Ericson and McKinley (1997) demonstrated that spatial separation of audio in both quiet and noisy environments improved performance over multiple speech sources originating from a single location. In a series of studies wherein they used multiple speech streams and measured speech recognition of the target signal, speech recognition was better in the spatial audio condition.

Interestingly, simply providing stereo (dichotic) presentation over diotic (the same signals to both ears) presentation showed increases in speech recognition performance of approximately 10-20%, depending on the gender of the target signal talker and masker signal talker. Providing speech signals through a spatial audio paradigm resulted in further improvements in speech recognition over what was gained by dichotic listening. A maximum of 90 degrees of separation between the target talker and masker showed the greatest benefit for speech recognition, approximately 10-30%. Furthermore, the spatial separation of target talker and masker was of greater value in the presence of background noise than in quiet environments. This points to a likely benefit of using this technology in high-noise applications, such as aviation.

In a study examining the impacts of spatial audio on speech recognition with a systematic increase in the number of talkers simulating monitoring multiple channels of radio communication, Nelson et al. (1999) demonstrated that spatial audio presentations resulted in superior speech recognition over diotic presentation in conditions with up to six channels of audio. In a free-field environment, listeners had to detect their call sign and then indicate the message sent to that call sign for speech signals presented either through 1) one loudspeaker directly in front of the listener or 2) several loudspeakers surrounding the listener. Improvements to speech understanding measured for the spatial condition demonstrate the advantage of spatialized audio. Such a configuration represents similarities to a pilot's job of monitoring multiple streams of radio simultaneously.

Abouchacra et al. (2001) showed that spatial audio presentation of radio communication allowed for better speech recognition than listening in a split monaural (diotic) mode, even in high levels of background noise. Using the Vehicle Inter Communication System (VIS) helmet, Abouchacra et al. (2001) measured speech recognition in three modes: diotic (same signal to both ears), stereo (dichotic), and spatial. The testing included listening to between two and four talkers with one serving as the target signal and the others serving as maskers. Performance was best in the dichotic and spatial audio configurations over the diotic mode. Brungart and Simpson

(2003) demonstrated that spatial audio increased speech recognition across the board for configurations of up to seven competing talkers. Dichotic listening improved performance by 25% over diotic listening but spatial audio added an additional 5% of speech recognition. This finding justifies the additional expense needed to implement spatial audio in applications where speech understanding is critical to mission success.

Several studies have examined the importance of the location of the speech signals when applying spatial audio to speech communication. MacDonald et al. (2002) found better performance in both speech recognition and response times when the sounds were located along the lateral planes (on either side of the listener) as opposed to along the transverse plane (in the front or the back of the listener). This finding is important for the implementation of spatial audio and the decisions of where to position sounds within the perceived auditory space of the listeners.

Brungart and Simpson (2003) expanded on the MacDonald et al. (2002) finding and examined several different talker configurations. They found that listeners were better able to distinguish between two talkers when they were located along the frontal horizontal plane where auditory resolution is greatest than when the talkers were off to the sides of the listener. They were able to add additional talkers in a near-far configuration whereby two talkers presented to the same ear had differences in intensity such that one appeared to be farther away than the other. Spatial separation in the near-far configuration along with separation along the frontal plane allowed for improved speech understanding with increasing numbers of competing talkers. Spatial separation of talkers can be smaller in the frontal horizontal plane but needs to be larger for areas to the sides of the listener.

In addition to improving speech recognition, the use of spatial audio has been shown to reduce response times and workload. Kim et al. (2018) demonstrated that the use of spatial audio for radio communication resulted in significant reductions in response time and workload over a traditional audio communication system (split monaural). Furthermore, increasing the number of call signs presented did not affect response times, indicating that spatial audio provided a robust advantage in the operator's ability to monitor up to seven channels of communication. The participants rated workload using the National Aeronautics and Space Administration-Task Load Index (NASA-TLX) and indicated that the perceived workload was significantly less when using spatial audio than when using the traditional configuration (Kim et al., 2018). Workload ratings remained unchanged for the spatial audio condition even with the increase in channels of communication. Furthermore, participants reported a preference for spatial audio.

Limitations

None of these studies have examined the effects of hearing loss, specifically unilateral or asymmetric hearing loss. Unilateral hearing loss or asymmetric hearing loss may negatively impact spatial audio perception, as binaural hearing is the mechanism humans use to perceive sound source locations. There is also the issue of user acceptance. The type and duration of auditory stimuli used in the cockpit will need to be investigated to ensure user acceptance and that it is not an added source of annoyance or additional cognitive load. Lastly, it is important to note the reliance on generic HRTFs in current spatial audio applications as opposed to individually measured HRTFs, which will be discussed in the next section.

Medical Recommendation: Consider Application of the Spatial Audio

For radio communications, asymmetric hearing loss may not preclude an aviator from benefiting from spatial audio. However, asymmetric hearing loss may become a problem for aviators if they need to localize a spatial audio alert for target identification and waypoint guidance to locations outside of the aircraft. This means the tolerance limits for acceptable hearing loss may be different when listening to spatialized radio communications compared to locating an auditory signal accurately. For instance, it could be the case that the degree of resolution may not need to be as large if the goal is simply locating an audio signal accurately and may need to be even smaller when separating radio communications across virtual locations in space. Although performance on a sound localization task may be a limiting factor when using any spatial audio applications. If sound localization assessment criteria were researched and written into the APL medical hearing standards, aviators performing within these limits might not have difficulties using spatial audio displays, regardless of the application.

Medical Aspects of Spatial Hearing

Although decades of research in the literature support the benefits of spatial audio for speech communication and signal detection, the task of defining the medical standards required for Army aviators to use spatial auditory displays remains largely undiscussed. For example, questions regarding whether pilots with large asymmetric hearing losses (i.e., one ear has poor audibility) would benefit from a spatial audio display remain unanswered. Because spatial audio requires stereo headsets delivering independent channels of auditory information to each ear, a pilot with unilateral hearing loss may have trouble hearing radio communications on the side with the hearing loss and/or may have difficulty discriminating between locations in virtual acoustic space.

According to the military standard for visual 3D displays (MIL-STD-1472H), the user population will have normal stereoscopic vision, which suggests users of these technologies are not intended to be individuals with abnormal stereoscopic vision. Such language, if applied to users of spatial audio, would mean these technologies would not be intended for pilots with asymmetric hearing loss. However, pilots with asymmetric hearing loss at a small number of frequencies may still benefit from a spatial audio system, and it is suspected that such a display may even enhance their speech understanding of radio communications over a split monaural system. Individuals with asymmetric hearing loss typically only experience a difference in sensitivity at a few frequencies rather than across the full range of frequencies. Signals that occur at the frequencies for which a Service Member has an asymmetric hearing loss may be problematic, but auditory icons are not typically narrow in frequency range. Speech signals are broadband in nature and encompass a wide range of frequencies. Therefore, although a hearing loss at some frequencies puts the listener with an asymmetric hearing loss at a disadvantage, the ability to hear well at other frequencies allows for them to compensate and still perceive spatial audio.

There is still much research needed to provide developers of these technologies with medically-based design criteria to ensure effective display use by Army aviators. Future research should focus on evaluating new auditory display technologies (specifically spatial auditory displays and auditory icons) for use by pilots who have been granted a waiver for presenting with a hearing loss that exceeds Army APL standards for aviators. Research should be conducted specifically on the benefits of spatial audio with asymmetric hearing loss with different auditory icons and speech communication. Additionally, these and similar technologies could potentially be used to improve aviator headsets such that a pilot's individual hearing loss could be compensated for by increasing the gain of output levels across specific frequencies.

Spatial Audio in Listeners with Normal Hearing

Listeners with normal hearing have access to all interaural cues and frequency information within a specific sound if it is above their hearing thresholds. The listener receives all available information and integrates ILDs, ITDs, and spectral cues across frequencies and makes judgements on the location of the sound in space. The more information that is available to the listener, the better they can identify the location of the sound source. The localization of single tones is far less accurate than the localization of signals that contain a wide range of frequencies; the greater the bandwidth, the more frequencies are included in the signal and the more accurately a listener can identify its location (e.g., Stevens & Newman, 1936; Yost & Zhong, 2014). The ability to localize sound is innate in humans and develops as we grow through real-world experiences and expectations. Each human's pinnae are unique to them and the specific shaping that occurs with our pinnae as opposed to someone else's allows us to perform at our best.

Sound localization.

Sound localization performance measured using spatial audio has been shown to be nearly equivalent to performance in a free-field environment, indicating that if the sounds are spatialized using an HRTF, the perception of the location of the sounds is similar to what a listener would perceive in a typical real-world listening environment (Wightman & Kistler, 1989; Wightman & Kistler, 1992). The separation in auditory space of alarms, alerts, and streams of speech can allow a listener to perceive and process more information over time than if all sounds arrive to the listener in both ears without spatial separation.

Listeners with normal hearing are quite good at identifying the location of a sound source within the frontal horizontal plane. Additionally, individuals can distinguish between two sound sources that are physically separated in space. Indeed, it has been shown that localization accuracy is best along the frontal horizontal plane and decreases as sound sources are moved to the sides of the listener (Makous & Middlebrooks, 1990; Stevens & Newman, 1936). Importantly, localization accuracy is poorer along the vertical plane than in the horizontal plane. To measure sound localization accuracy, a listener is typically seated in the center of a sound-treated room with loudspeakers surrounding them. The listener is presented with a sound and then asked to indicate the location from which the sound originated. The sound localization performance is measured in terms of a user's average error from the correct target location. This method of measuring sound localization is referred to as free-field testing.

In the development of spatial audio, research groups investigated the localizability of sounds processed with a person's own HRTFs versus with generic ones (often measured from a manikin). Human listeners are most accurate at localizing sounds when processed with their own HRTFs than with the HRTFs of another listener (Middlebrooks, 1999; Wenzel et al., 1993); however, listeners can adapt to differences in HRTFs through experience or specific training

(Mendonça et al., 2012). The need for individualized HRTFs is most important when it is desired that the listener be able to identify the precise location of a sound. In other tasks, where listeners are asked to identify the presence or absence of an alarm, or to follow more than one stream of audio without regard to precise location, generic HRTFs are sufficient.

Importance of high and low frequencies on sound localization accuracy.

As mentioned previously, the interaural cues provide information to the listener for sounds arriving along the horizontal plane (i.e., azimuth). Monaural spectral cues, or the unique shaping of the stimulus as it arrives at the ear, provide information the listener uses to differentiate sounds arriving from the front versus the back of the listener, and along the vertical plane (i.e., elevation). Of the two binaural cues, the interaural timing cue is more salient than the interaural intensity cue and as stated previously, is most beneficial in the low frequencies (Middlebrooks & Green, 1991; Wightman & Kistler, 1989). It has been shown that ITD cues in the lower frequency range (below 1500 Hertz [Hz]) are the dominant cue for localization, whereas ILD cues are used for localization of high frequency sounds (above 2000 Hz). This is due to the size of the wavelength and its ability or inability to travel around the head. For low frequencies, the wavelength is long, so it can pass over or around the head without reflection. For high frequencies, the head blocks the sound, and it is received at the ears at two different intensities.

Spectral shape cues (i.e., changes in intensity across frequency) in the auditory signals caused by sound interacting with the pinna are not only the primary cue used for sound localization in the vertical plane, but they also are responsible for the perception of sounds as originating from outside of the head when listening under headphones. While basic stereo audio can give the perception of sounds moving from side to side inside the head, it takes additional signal processing to apply the correct spectral shape cues that give the perception of sounds delivered over headphones as if they were presented outside of the head. The spectral shape cues vary as functions of location in the vertical plane (i.e., front to back and above to under) and are present in the 6-10 kilohertz (kHz) frequency range (Middlebrooks, 1997). Currently, the APL and medical standards for hearing assessments in the clinic do not include testing at these higher frequencies.

Speech understanding in noise.

Spatial separation of target and masking auditory signals creates a release from masking that often improves speech intelligibility. Cherry (1953) was among the first to demonstrate the human auditory system's ability to focus on one voice originating from one spatial location and ignore others coming from other locations, which was dubbed the 'cocktail party problem' or 'cocktail party effect.' This research demonstrated the benefits of talkers being in different spatial locations on a listener's ability to hear and attend to audio messages of interest to the listener (Cherry, 1953; Cherry & Taylor, 1954). One key takeaway from these seminal studies is the importance of having two ears and spatial separation in the sound sources for aiding the segregation of voices from each other and directing one's attention to a particular talker. The benefits of spatial separation of sound sources can be simulated using spatial audio systems.

Spatial Audio in Listeners with Impaired Hearing

When an individual loses their hearing, they often have a difference in sensitivity across frequencies, whereby loss is experienced at some frequencies more than others. For many individuals, particularly those with hearing loss due to age (presbycusis) or noise exposure (noise-induced hearing loss), hearing sensitivity is lost more in the high frequencies than in the low frequencies. For military Service Members, the most common cause of hearing loss is due to noise exposure. This noise exposure can affect one or both ears. When an individual is exposed to high-level sounds on one side, the result is often noise-induced hearing loss and results in a difference in hearing sensitivity between the two ears at one or more frequencies, with the ear closest to the sound having the greater degree of hearing loss than the ear furthest from the sound.

Noise-induced hearing loss occurs in the noise-sensitive frequency range of 3000 and 6000 Hz (Seixas et al., 2012). Hearing sensitivity often remains good in the low frequencies and is only affected in the high frequencies. High frequency hearing loss can affect a listener's ability to identify the location of a high frequency sound source but will not affect the listener's ability to identify the location of a low frequency sound source. Furthermore, sounds that encompass a large band of frequencies or a combination of low and high frequencies will still be able to be localized based on the sensitivity remaining in the low frequencies.

For an individual with hearing loss, their ability to identify the location of a sound source depends on their hearing sensitivity as well as the frequency composition of the signal. Sounds that appear in nature typically contain multiple frequencies that allow listeners to integrate the information provided across frequencies. Although signals such as whistles or bird calls contain a small number of high frequencies, sounds such as speech and animal noises contain a larger number of frequencies both high and low, making them easier to localize (Yost & Zhong, 2014). For sounds that are composed of a single high frequency or a small number of high frequencies, hearing loss at those frequencies will result in difficulties perceiving the sound and a difference in hearing sensitivity at those frequencies may contribute to difficulties in knowing its location.

Sound localization and hearing loss.

The reduction in the audibility of sounds caused by hearing loss makes perceiving the sound source location more difficult. However, hearing loss only partly explains variation in localization performance of hearing-impaired subjects, suggesting that aspects of hearing impairment other than reduced sensitivity may be operating (Noble et al., 1994). Therefore, simply knowing the hearing profile of an individual, such as whether they have elevated audiometric thresholds, may not be a strong indicator of their perception of spatial audio displays or their performance with specific spatial audio applications.

There is an assumed relationship between sound localization abilities and understanding speech in spatially separated noise. This is not surprising, as the neural pathways and mechanisms responsible for sound localization abilities inherently support the teasing apart of auditory signals carrying speech information. Such anatomical links between the neural systems enabling sound localization abilities and the capacity to benefit from the spatial separation of speech signals suggest hearing impairments would affect both adversely. However, developing medical standards and pilot selection criteria based solely on hearing thresholds and performance on one spatial hearing task (i.e., sound localization, understanding target speech amongst competing voices) may not be enough to determine the potential benefit for listeners using spatial audio displays for other tasks. For instance, knowing how well an individual performs on a sound localization task does not provide enough information to know how they would perform on a speech understanding in noise task.

There are very few studies examining the use of spatial audio displays and the impact hearing loss has on performance (Abel & Lam, 2008; Ellis & Souza, 2020; Kumpik & King, 2019; Marrone et al., 2008). Abel and Lam (2008) occluded the right or left ear of normal-hearing listeners with an expandable-foam earplug and earmuff. Listeners indicated the source location for broadband noises presented from one of six loudspeakers separated by 30 degrees arranged across the frontal plane or left or right lateral plane. Results showed listeners with both ears unoccluded performed better than in either monaural condition. Further, azimuth performance using the frontal array was poor on the occluded side. When the lateral display was located on the right, performance (percent correct) was significantly better when listening with the right ear compared to listening with the left. Performance over the three replications did not improve. In addition, Ellis and Souza (2020) reported that localization of physical sound sources was independent of audiometric pure tone average (0.5, 1.0, and 2.0 kHz).

Kumpik and King (2019) published a review of the effects of unilateral hearing loss on spatial hearing. If the ITD and ILD cues are chiefly responsible for localization of sound along the horizontal plane, then unilateral hearing losses would severely limit localization performance. They report that listeners with unilateral hearing losses “reweight” sound localization cues, apparently de-emphasizing ITD and ILD cues and using spectral cues in the normal-hearing ear for azimuth localization. Thus, listeners with unilateral hearing losses learn, over time, to use the subtle differences in the spectral shape cues of sounds coming from the left and right to determine azimuth. Compared to the results of Abel and Lam (2008), it seems clear, therefore, that normal-hearing listeners are not the ideal listeners to evaluate sound localization in hearing-impaired listeners.

It is unknown how long "reweighting" of spectral cues takes in partial unilateral hearing losses for effective sound localization, or how the contribution of spectral cues interacts with ITD and ILD cues. It is also unclear whether manipulations to the signal processing and filtering employed by spatial audio techniques can compensate for the differences resulting from an asymmetric hearing loss. In short, medical standards for the use of spatial audio displays are not available and should remain so until extensive testing can address the affects that hearing loss have on using such display technologies.

Ray (2022) measured hearing thresholds as part of a study examining localization of tones and accuracy in the horizonal and vertical planes. Hearing thresholds in 14/25 participants were abnormal. Ten participants had mild unilateral hearing loss (25 to 40 decibel [dB] hearing loss [HL]) at one or two frequencies. Three displayed moderate unilateral or bilateral hearing loss (45 to 55 dB HL) at one frequency and mild hearing loss at multiple frequencies. One participant displayed moderately severe bilateral hearing loss (60-70 dB HL) at one frequency along with mild to moderate bilateral hearing loss at multiple frequencies (Ray et al., 2022). There was little correlation between the degree of hearing loss and localization performance.

The perceptual consequences of hearing loss on both a virtual localization task and an amplitude panning task (i.e., making an auditory signal sound like it is moving from one side of the head to the other over headphones) have been previously reported (Ellis & Souza, 2020). Briefly, listeners with hearing statuses from normal hearing through moderate sensorineural hearing losses performed a localization task in the free-field and virtually. Interestingly, listeners with normal hearing showed significantly larger errors for virtual sources generated with amplitude panning than for physical sound source locations; however, listeners with poorer hearing (i.e., higher average pure tone thresholds) showed no significant difference in errors between virtual sources generated with amplitude panning and physical sources. This means that individuals with higher than normal audiometric thresholds were able to perform similarly on the virtual location task as they were on actual sound source locations.

Note that studies examining the effects of asymmetric hearing loss on auditory localization have chosen to simulate asymmetry across a wide range of frequencies. This is quite different than what is experienced by most Service Members with hearing loss. Service Members often only experience asymmetric hearing loss at one or two frequencies. Research needs to be conducted to examine the effects of a narrow band of asymmetry on auditory localization and use of spatial audio.

Medical Recommendation: No Changes to the APL for Aviators Meeting Standards.

Based on a review of the literature and sparse preliminary testing in military aircraft, present day APL classification of hearing status is sufficiently stringent to select aviators most likely to benefit from spatial audio systems in the aircraft. However, it should be noted that pure tone threshold requirements do not assess the functional performance of spatial hearing ability. Additionally, research suggests the amount of asymmetric hearing currently allowed in the APL hearing standards would not preclude a pilot from using spatial audio. While hearing loss in the mid to high frequency ranges may impede a user from ‘externalizing’ spatial audio, i.e., hearing sounds over headphones as if they originated from sources outside of the head, the degree of hearing loss across frequencies and between ears that begins to degrade the ability to externalize spatial audio is unknown.

Future studies could present aviators with varying amounts of simulated hearing loss between the ears in normal hearing listeners and measure the degree to which the simulated hearing losses impact sound localization while listening to a spatial audio display. However, since aviators still maintain good hearing acuity even if asymmetry is present, no change to current APL standards to specifically address asymmetric hearing is recommended at this time.

Speech communication and hearing loss.

Speech communication requires adequate hearing acuity. Hearing loss results in the loss of audibility to speech information, which often leads to poor understanding. There is a frequency-dependent component to speech, in that vowels contain primarily low frequency information and consonants contain high frequency information. Syllables are typically a combination of a high frequency consonant along with a low frequency vowel. Consonants are the parts of the English language that carry the most important speech information as demonstrated through calculation of the Speech Intelligibility Index (SII), as published in the

American National Standards Institute (ANSI)/Acoustical Society of America (ASA) standard method for measuring the intelligibility of speech over communication systems (ANSI/ASA-S3.2-2009, 2009).

Humans lose hearing sensitivity as they age, hearing loss initially appears in the high frequencies and then slowly extends into the lower frequencies. Hearing loss in the high frequencies, whether due to age or noise-induced hearing loss, results in loss of understanding of speech due to loss of audibility of the consonants in speech (Amos & Humes, 2007). The presence of background noise further degrades speech understanding.

Along with a decrease in understanding, noise-induced hearing loss results in an increase in listening effort (McGarrigle et al., 2014; Ohlenforst et al., 2017; Winn et al., 2018). The increase in listening effort translates to a higher workload experienced by the aviator, which can contribute to higher rates of fatigue and lower performance. Spatial audio has the potential to reduce listening effort and therefore reduce workload. Although pilots experience hearing loss as they age, their years of experience make them valuable assets to the military. Because of the resources invested in their training and their years of experience, pilots with hearing loss continue flying for years with appropriate approvals (i.e., waivers for not meeting the hearing criteria), even after their first evidence of hearing loss.

Hearing loss negatively affects a pilot's ability to understand speech, which directly impacts their ability to communicate and perform their job. As such, studies investigating the limits of spatial audio utility by pilots with hearing loss, particularly hearing loss in one ear, would better inform biomedical bounds on performance for aircraft implementing spatial audio display technologies in the future. Studies examining the benefits of spatial audio for aviators with symmetric and asymmetric hearing loss would provide evidence for increased performance and decreased workload. Furthermore, studies examining different degrees of asymmetry would direct medical standards for limits on acceptable asymmetric hearing loss.

Summary: Medical Aspects of Spatial Hearing

Sound localization is accomplished using interaural difference cues of time and intensity between the two ears, as well as the 'shaping' of the frequency spectrum of signals by the ears. Applying a transfer function to a sound and providing it to a listener through stereo headphones can give the perception that sounds are arriving from different locations in space. For implementation of spatial audio for the purposes of separating multiple channels of speech information or to provide information on alarms, use of a generalized HRTF is sufficient.

While high frequency hearing loss is the most common configuration of hearing loss found in Service Members (Henry et al., 2021), the most salient cues for sound localization are interaural time differences, which are present in the low frequencies. Thus, the low frequency information is still available to users with high frequency hearing loss. In addition, the use of broadband signals allows for integration of binaural difference information across frequencies allowing for accurate localization. Therefore, listeners with normal or impaired hearing can benefit from spatial audio for localization of broadband signals.

Spatial audio may potentially be used in future applications for threat or obstacle avoidance, as a navigation instrument or aid during DVE operations, and other operations and applications where the accuracy of the perceived virtual acoustic signal location is important. Potential applications such as these could provide multimodal cues to reinforce or backup other sensory systems should they become unavailable or incongruent (e.g., during DVE or spatial disorientation). For these applications, abnormal hearing may negatively affect the perceived location of the virtual acoustic signal. However, the effects may not be significant.

Research is likely needed to determine the effect, and the degree of the effect, that degraded hearing, such as asymmetric hearing losses, may have on the perception of virtual acoustic signal locations. Based on our understanding of the hearing mechanisms and sound localization perception, it is believed that the effects of asymmetric hearing loss may be minimal for applications such as speech separation in virtual space (e.g., for multiple radio channels) but may negatively impact the accuracy of virtual target location applications (e.g., obstacle avoidance), particularly for narrow band signals when compared to normal hearing listeners. Thus, while hearing losses may affect the perception of spatial audio differently than normal listeners, the significance of the effects likely depends on the intended application. Lastly, it is yet to be determined the degree to which asymmetric hearing loss can impact performance with spatial audio.

Medical Recommendation: Addition of MOHT to the APL

Additional medical standards related to spatial hearing performance need to be considered for those individuals who do not meet the APL standard. In-flight assessments are identified in the APL but are not standardized or documented in a way that can be monitored or tracked. Following a similar format to the updated DA PAM 40-502, only aviators who exceed the APL standard should be assessed further for performance on spatial tasks and hearing performance. The addition of the MOHT to the APL for those exceeding the hearing standard could offer a solution. The DA PAM 40-501's Military Operational Hearing Test (MOHT), which has a spatialized hearing assessment, is standardized, and routinely documented in clinical encounters at the military treatment facility (MTF).

In-flight operations and flying the aircraft are considered hearing-critical tasks as aviators specifically require adequate speech recognition capabilities to effectively manage flight communications and performance (Beamer et al., 2014; Helfer et al., 2014). Further studies are needed to determine the degree to which asymmetric hearing loss affects the capacity to benefit from spatial audio during flight. One potential study might simulate hearing loss in normal hearing listeners, or find pilots with varying degrees of asymmetric hearing loss, and measure the degree to which the simulated/actual hearing losses affect speech understanding while listening to radio communication channels being presented via a spatial audio display.

Current Medical Standards for Hearing in Aviators

Some of the information provided below is also published in the USAARL technical report *"Army Aviator Audiometric Trends 2016-2023."*

Although military aviation has long considered spatial audio for use in the cockpit, one often overlooked consideration is the hearing sensitivity of aircrew members necessary to effectively use the spatial audio displays. Such a consideration points to a need for both a set of biomedical design criteria for spatial auditory displays in Army aviation as well as medical standards detailing aviator hearing requirements for its use. Presently, it is unclear whether hearing loss renders a spatial audio display useless, at what level of hearing loss or asymmetry this would occur, and what strategies might mitigate this effect.

For instance, perceiving spatial audio signals requires two ears, so questions such as, "At what point does hearing asymmetry impinge upon its utilization?" need to be answered. If so, perhaps additional computer programming of spatial audio displays could help mitigate or compensate for hearing loss an individual aviator may have. Research focused on understanding the limitations of individual hearing differences on the usefulness of spatial audio would provide the necessary evidence supporting the development of biomedical design criteria and medical standards for aviator hearing requirements following implementation of spatial audio in aircraft. The introduction of new technology, such as spatial audio, into the Army's FVL program warrants the question as to whether the current medical standards, as they relate to hearing and outlined in the APL, are stringent enough to ensure mission success and ensure aviators receive benefit from this new technology.

Hearing Fitness-For-Duty Standards

Hearing fitness-for-duty standards delineated in Department of the Army Pamphlet (DA-PAM) 40-502, Army Regulation (AR) 40-501, and APL are based on pure tone audiometric thresholds. The Army has recently updated its medical readiness standards in terms of hearing acuity and auditory fitness-for-duty (AR 40-502, DA PAM 40-501, DA PAM 40-502). Hearing loss assessments and profiling conditions were changed dramatically under the revision. Consideration for performance on the new assessments, (i.e., the MOHT) and profiling conditions should be investigated for implementation in an updated APL or inclusion criteria for any exception to policy or waiver. The APL hearing standard, by way of audiometric thresholds or waiver criteria, has not been updated for decades. Currently, for aviators who do not meet the pure tone standards, waivers are granted based on meeting the criterion value of 84% binaural word recognition in quiet. Currently, no research exists that directly supports the predictive value of pure tone thresholds or word recognition in quiet on aviator-related performance. A thorough explanation of current Army and APL hearing standards follows.

Military medical standards for hearing.

Medical accession and entrance standards are outlined by the DoD as well as by each individual Service. The DoD Instruction (DoDI) 6130.30-V1 *Medical Standards for Military Service: Appointment, Enlistment, or Induction* (Department of the Army, 2022) outlines by threshold (HL) and frequency (Hz) what would disqualify an individual for initial entrance into the DoD. It also specifies that asymmetry of 30 dB or more in the mid-frequency range is cause for disqualification. These criteria are shown in Figure 3. Failure to meet any single condition renders an individual unable to gain entrance for military service. In addition to the DoDI, each individual service component (Army, Navy, and Air Force) has their own additional set of requirements. As shown in Figure 3, the requirements are based solely on hearing sensitivity.

Current hearing threshold level in either ear that exceeds: • 25 dB averaged at 500, 1000, and 2000 Hz • 30 dB at 500, 1000, or 2000 cycles per second • 35 dB at 3000 Hz • 45 dB at 4000 Hz • No standard for 6000 Hz
Unexplained asymmetric hearing loss as defined by a difference of 30 or more dB between the left and right ears at any one or more frequencies between 500, 1000, 2000 Hz

Figure 3. Service Member hearing thresholds as indicated by DoDI 6130.03-V1 (Department of the Army, 2022).

There are two standards used by the Army to evaluate a Service Member or candidate's fitness for duty. The initial entrance standards for the Army are governed by AR 40-501 *Medical Standards of Fitness*. Continued service and individual medical readiness are governed by AR 40-502 *Medical Readiness* and DA PAM 40-502 *Medical Readiness Procedures*. These regulations also outline various medical requirements for duties or jobs beyond initial entry to include Special Forces, Survival, Evasion, Resistance, and Escape (SERE) training, divers, Ranger Regiment, and aviation. Army aviation has its own APLs that guide medical entrance and retention standards for Army aviators, specifically. The APL hearing criteria are more stringent than regular Army medical standards outlined in any previous regulation. When an individual does not meet an established requirement, an exception to policy or waiver is required for them to enter or continue service.

As opposed to entrance into the Army, continued service is governed by DA PAM 40-502, *Medical Readiness Procedures* (Department of the Army, 2019a). All Army Service Members are enrolled into a Hearing Conservation program due to the innate noise exposure that accompanies military service. One requirement is that all Service Members receive an annual audiologic evaluation to assess for hearing loss or any shifts in their hearing status. All Service Members are assigned a hearing profile as part of their annual exam which is an indication of their current hearing status. Hearing profiles are designated serially from H1 to H4. An H1 profile suggests the best hearing, indicating a high level of medical fitness. An individual with an H1 profile is fully qualified to serve based on their hearing ability. Their hearing status is expected not to have an impact on their performance. As the profile number designator increases, so does the anticipated degree of impact on performance and limitations (e.g., H2, H3, and H4). These higher number designators are assigned after a diagnostic audiologic assessment.

In 2019, AR 40-502 was updated, replacing AR 40-501 *Standards of Medical Fitness*, and clarified the retention standard for hearing assessment with a diagnostic audiologic evaluation and for the first time, functional performance on the MOHT. Used in conjunction with AR 40-502, the updated DA PAM 40-502 outlines hearing profiles based on audiometric thresholds and MOHT performance. Values for H1 and H2 profiles are outlined in Table 1.

Table 1. DA PAM 40-502 Audiometric thresholds (dB HL) for Hearing Profiles H1 and H2

Profile		**500 Hz**	**1000 Hz**	**2000 Hz**	**3000 Hz**	**4000 Hz**	**6000 Hz**
H1	**Better Ear**	≤ 25	≤ 25	≤ 25	≤ 25	≤ 25	≤ 60
	Worse Ear	≤ 30	≤ 30	≤ 30	≤ 35	≤ 45	-
H2	**Better Ear**	≤ 25	≤ 30	≤ 25	≤ 40	≤ 60	≤ 70
	Worse Ear	≤ 40	≤ 40	≤ 60	-	-	-

This update of hearing profiles for Army Service Members was implemented after years of research conducted at Walter Reed National Military Medical Center (Brungart et al., 2023). The previous profiling system was based primarily off of a Service Member’s pure tone thresholds with assessment into their functional performance solely through word recognition performance in quiet. The MOHT was designed to evaluate the functional auditory performance of individuals with elevated auditory thresholds. Operational effectiveness is correlated with auditory thresholds; however, individual performance on mission critical auditory tasks can vary significantly. Therefore, if a Service Member’s audiometric thresholds exceed the H2 profile’s pure tone threshold criteria, the MOHT is administered, and functional performance dictates profile designation. The MOHT is comprised of three components: 1) diagnostic audiologic evaluation, including pure tone auditory thresholds and monaural word recognition in quiet scores for each ear; 2) an assessment of speech-in-noise performance, by administering the clinical adapted 80-word Modified Rhyme Test (MRT_{80}); and 3) an evaluation of spatial awareness, which is obtained by administering the SDT for any individual with significant hearing deficits in at least one ear.

Profile Determinations and MOHT Administration

All Service Members are required to complete an annual hearing readiness audiologic evaluation through the Defense Occupational and Environmental Health Readiness System (DOEHRS) as part of their enrollment into the Army hearing program and ongoing monitoring. The audiologic evaluation conducted through DOEHRS is an automated test conducted in a group setting. If a Service Member’s annual audiogram (results of the audiologic evaluation) presents with thresholds that exceed the DA PAM 40-502 standards, they are referred to an audiologist for a comprehensive diagnostic audiologic assessment. A comprehensive diagnostic audiologic evaluation is conducted on one Service Member at a time and is not automated. If the audiometric thresholds from this exam exceed H1 values, but not H3 values, they are assigned a hearing profile of H2, and no further assessment is required. If a Service Member’s audiometric thresholds exceed H2 levels, they are not guaranteed an H3 profile until the MOHT is administered, after which the results are used to make the profile determination. Table 2 outlines the MOHT scoring criteria and appropriate profile designations.

Monaural word recognition in quiet from the diagnostic audiologic evaluation is the first criterion to consider, with 78% correct designated as the minimum performance acceptable. If the monaural word recognition score is equal to or better than 78% in both ears, the MRT_{80} is administered. The criterion for a passing score is based on the Service Member's pure tone threshold in the better ear at 2000 Hz. Greater hearing loss requires the Service Member to perform better on the MRT_{80} in order to retain an H2 profile designation. If the Service Member meets the passing score after the first list, testing is complete; however, if the Service Member does not meet the criterion for a passing score, a second list is administered, and the final score is calculated out of a 160-word set (two MRT_{80}) as opposed to a single 80-word set. The MOHT is standardized across all Army MTFs via a tablet-based system. The tablet is interfaced with the clinical audiometer for calibrated administration. The Service Member completes the MRT_{80} under headphones, if applicable.

Spatial awareness is evaluated through the SDT, also conducted through the tablet and completed under headphones. The spatial awareness criteria are designed to ensure that those Service Members who have audiometric thresholds that are at an H3 profile level are not reassigned to an H2 profile unless they have some ability to identify and localize sounds. For individuals who score a monaural word recognition ≥ 78% but present with significant low to mid-frequency hearing loss in the worse ear (i.e., thresholds > 40 dB HL at 5000 Hz, > 40 dB HL at 1000 Hz, or > 60 dB HL at 2000 Hz) further assessment is required. The Service Member must complete the SDT and correctly identify the digit in the target ear for 8 out of 10 trials to obtain a passing score. If the Service Member's performance meets all the criteria under the following sections: 1) monaural word recognition score, 2) MRT_{80}, 3) SDT or low frequency thresholds, they can be reassigned from an H3 to a H2 profile.

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Table 2. MOHT Profile Determinations

	H2 Profile	**H3 Profile**	**H4 Profile**
Monaural Word Recognition Score (WRS)	≥ 78% in both ears	≥ 78% in better ear	< 78% in better ear
MRT_{80} or MRT_{160}	Better ear ≤ 20 dB at 2000 Hz; MRT ≥ 55/80 or 104/160 Better ear > 20 dB at 2000 Hz; MRT ≥ 59/80 or 112/160	≥ 80/160	< 80/160
SDT or Low Frequency Thresholds	SDT ≥ 8/10 (**or**) Worse ear ≤ 40 dB at 500 Hz; and ≤ 40 dB at 1000 Hz; and ≤ 60 dB at 2000 Hz	Not applicable (N/A)	N/A

Army aeromedical standards for hearing.

Aeromedical concerns for hearing loss include difficulty with in-flight communications, radio transmissions, and rapid and accurate assessment of warning tones in the cockpit. All these auditory tasks can impact flight safety and mission success. Inclusion into Army aviation requires even stricter adherence to auditory thresholds and referral criteria. Aviators are required to complete annual audiologic evaluations adhering to the DoD hearing readiness referral criteria (i.e., significant threshold shifts averaging 10 dB, etc.). Additionally, aviators must adhere to the APL referral criteria, such as a 20 dB shift in either ear at a single frequency (1000 through 4000 Hz), which requires a full audiologic evaluation. The APL outlines serial Class (C) categories 1 through 4 (C1-C4). All aviator applicants are Class 1, with exceptions granted to pilots transferring from another Service or rated international pilots. Class 2 represents all rated aviators or front seaters. Class 3 and 4 are trained aviation personnel with a requirement for flight status and include flight surgeons, aircrew, air traffic controllers, and unmanned aerial systems (UAS) operators. Table 3 outlines the hearing thresholds for C1 and C2/3/4 categories.

Table 3. APL Hearing Standards for Army Aviation and Air Traffic Control

	500 Hz	**1000 Hz**	**2000 Hz**	**3000 Hz**	**4000 Hz**	**6000 Hz**
Class 1	≤ 25	≤ 25	≤ 25	≤ 35	≤ 45	≤ 45
Class 2/3/4	≤ 25	≤ 25	≤ 25	≤ 35	≤ 55	≤ 65

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If the Class category is met with hearing thresholds alone, no further assessment is required. If an aviator does not meet the APL standard, an exception to policy (ETP) or waiver is considered. An ETP is for applicants wishing to enter aviation and a waiver is for those individuals already in service and wishing to continue. For simplicity, the term waiver will be used in the remaining document. According to the APL, hearing loss designated with an H2 profile may or may not be a disqualifying condition. Most Service Members with an H2 profile can apply for a waiver if their hearing status does not impact flight performance, which is decided by the flight surgeon. Waivers are not recommended for any Service Members with an H3 hearing profile. Any waivers are taken on a case-by-case basis.

The current audiologic workup required for a waiver includes pure tone air and bone conduction testing, tympanometry, acoustic reflex testing, speech recognition threshold (SRT) testing, and word recognition scores (WRS) in quiet in both monaural and binaural conditions. There is a requirement to score greater than or equal to 84% on binaural WRS. If an aviator scores less than 84%, the APL notes a requirement for an in-cockpit/flight evaluation. This evaluation is determined by the aeromedical provider and is not standardized. The in-cockpit/flight evaluation is an attempt to ensure that hearing loss does not have a functional impact on the aviator‘s operational performance. However, in-flight/cockpit evaluations are fiscally and time intensive when compared to clinical evaluations.

Regulatory guidance on asymmetric and unilateral hearing loss.

Previous sections referred to the importance of binaural hearing for the detection and localization of sound sources. It is crucial for a Service Member to have the ability to process information from both ears, particularly as we introduce new technology such as spatial audio, which requires binaural signal processing. The DoDI defines unexplained asymmetric hearing loss as a difference of 30 dB or more between the left and right ears at one or more frequencies of 500, 1000, and 2000 Hz as an exclusion criterion, but that only applies to initial entrance into service. If any asymmetry is acquired during time in service, there is less guidance as to how to proceed forward.

The monitoring aspect of DOEHRS will flag asymmetric hearing loss defined as a right-left ear difference of 25 dB at two consecutive frequencies. It does not preclude service, but it does warrant a follow up for a comprehensive audiologic evaluation. The old profiling authority allowed for a Service Member to be unilaterally deaf in one ear and maintain an H2 profile. This is no longer the case with the updated DA PAM 40-502. The updated DA PAM tolerates some asymmetry in hearing sensitivity between the two ears if there is documentation of adequate processing from both ears through the results of the SDT. Specifically, DA PAM 40-502 triggers a spatial assessment in the form of the SDT in the presence of low frequency hearing loss (500, 1000, 2000 Hz). Neither the DA PAM nor the APL directly address asymmetric hearing in terms of a cut off, but does so indirectly with the pure tone threshold standards.

Medical Recommendation: Standardizing in-flight evaluations.

Currently, for aviators who exceed the APL standard, in-cockpit/flight evaluations of speech understanding and localization in an operational setting are not standardized or tracked. Recommend standardizing in-flight evaluations and/or providing an alternative clinical assessment with operationally relevant content. Additionally, it is unknown the degree of hearing loss or asymmetry that reduces flight performance and to what degree. Future research should measure performance of aviators with various hearing profiles on spatial hearing assessments, specifically measuring sound localization performance and free-field speech in noise understanding. Performance on spatial hearing assessments could then be correlated to their flight performance, cognitive workload, and ability to accurately utilize spatial audio displays.

Findings from such research would be two-fold. First, the impact of audiometric profiling on spatial hearing assessments and the degree of performance decrement between hearing loss groups could be determined. Second, aviator performance limits of using spatial audio displays could be determined. Additionally, the tolerance limits of acceptable hearing loss would be better defined. Both findings would be used to inform updates to medical standards that ensure aviators of all hearing statuses have the capacity to benefit from spatial audio displays.

Additional Considerations for Spatial Audio Displays

As mentioned previously, sounds emanating from the left arrive at the left ear earlier in time than the right ear, and are higher in intensity in the left ear than the right. These two primary cues, the ITDs and ILDs, enable listeners to locate sound sources in azimuth (i.e., the horizontal plane). Spectral differences between sounds entering the ear from different directions provide the ability to localize sound sources in elevation (i.e., the vertical plane). Not only do these cues provide information about the spatial location of sound sources, but they also provide additional information that helps the brain tease apart competing speech signals. As much as medical standards currently require a certain hearing profile to grant flight status to a pilot, similar binaural hearing health factors need consideration and an evidence-based determination about whether biological constraints exist that would limit the effectiveness or benefits provided by spatial audio displays.

Although asymmetric hearing losses can impact spatial perception, as stated previously, it is not known whether this impact is permanent or whether a user's performance changes over time (natural adaptation) or if localization cues can be learned over time through training. Previously, a review of the learning effects for sound localization noted that the ability to learn localization cues over time varies across individuals (Wright et al., 2006). Some studies have demonstrated listeners' ability to improve localization performance over time (Butler, 1987), even with minimal training (Musicant & Butler, 1980). Butler (1987) examined the localization abilities of listeners wearing a foam plug in one ear by measuring localization performance across 95 trials per day for 5 days. The result was significant improvement in localization accuracy across those five days.

Musicant and Butler (1980), on the other hand, measured localization performance with just one trial per day for 60 days. Even with minimal experience with the auditory signal, listeners were able to learn to use the different cues to improve localization accuracy over time.

However, others have demonstrated very little learning over shorter periods of time (Slattery & Middlebrooks, 1994). Slattery and Middlebrooks (1994) examined localization performance over time in participants who wore an earplug in one ear for 24 hours and saw no improvement. The same was found in the study by Ellis and Souza (2008).

Medical Recommendation: Spatial Hearing Training

Research has shown individuals may be able to overcome localization deficiencies of hearing loss through training. Undoubtedly, learning to use changes in acoustic cues for sound localization varies significantly across individuals. Furthermore, it is unknown how long it takes in partial unilateral hearing losses for a “reweighting” of spectral cues for effective sound localization, or how the contribution of spectral cues interacts with ITD and ILD cues.

According to the DOEHRS data, the most common amount of asymmetry was 10 dB, which is not thought to impact localization. However, there are greater amounts of asymmetry present, which may result in localization difficulties. Several studies have shown that with training an individual can ‘reweight’ or relearn appropriate localization. It is important to note that for this to be successful, the asymmetry in the hearing loss needs to be identified and then appropriate training implemented. There is currently a means for identifying the hearing loss, but no standardized protocol for sound localization training in the Army.

Lastly, it is unclear whether manipulations to the signal processing and filtering employed by spatial audio techniques can compensate for the differences resulting from an asymmetric hearing loss. In essence, audio processing could be used to turn the spatial audio display into something akin to a hearing aid, in which the gain or volume of a particular frequency rage could be increased to compensate for a hearing loss within that frequency range. However, it is not clear what effect such processing would have on the ability of the system to present spatialized audio signals. Applying varying gain increases across frequencies to compensate for an aviator hearing loss profile would certainly alter the acoustic cues needed to externalize and localize signals presented by a spatial audio display.

Potential Impact for FVL

As requirements for design criteria are developed for the new cockpit of the FVL aircraft, it is important to keep in mind how aviators will be using spatial audio. As mentioned above, the implementation of the technology would require stereo headsets, and the audio delivery system would need to filter the audio signals appropriately, also known as virtual acoustic space. Considerations include what type of signals would be spatialized and how those spatializations would be implemented in the system.

Technologies implementing spatial audio require delivering independent audio signals to each of the ears, which is not possible in current Army aircraft. Furthermore, the health of both ears becomes a critical consideration for the effectiveness of aviators to benefit from spatial audio. For example, aviators with asymmetric hearing loss (i.e., hearing loss is greater in one ear) may not be able to take advantage of spatial audio benefits. There remains a huge need for research investigating questions such as, what degree of asymmetry between the two ears begins making spatial audio ineffective at providing benefits to the listener?

It is worth noting that the current aviator headset configuration of split monaural presentation of speech communication signals to pilots may indeed be beneficial to those with hearing loss, especially if the hearing loss is only present in one ear. Such a configuration can be beneficial due to the presentation of the same speech signal in both ears, such that if hearing loss is present in one ear, the pilot can perceive the speech signal in the better hearing ear. In contrast, spatial audio presents signals to the two ears differentially to provide the perception that a signal is arriving from a particular location in space outside of the head.

One could argue that providing speech signals through spatial audio rather than through the current split monaural configuration has the potential to be problematic to the pilot with hearing loss in one ear (unilateral hearing). However, given the use of broadband signals such as speech, and the tolerance for asymmetry in only one to two frequency bands, any asymmetry in hearing sensitivity within the current fitness for duty guidelines would not impact functional performance. It is important to keep in mind that the positive of being able to segregate multiple speech channels with spatial audio for those with normal hearing is of utmost importance.

Design Considerations

As mentioned above, spatial audio refers to giving a listener the sense of three-dimensional space beyond conventional stereo audio. Sounds are filtered using signal-processing techniques to provide the appropriate acoustic cues (i.e., ITDs, ILDs, and spectral shape [SS] cues) over a pair of *stereo headphones* (see note in Table 4 below). Such headsets deliver a separate channel of audio to each ear, independent of the other ear. This is important because each of the two ears needs the incoming auditory signals to arrive at slightly different times, levels, and with different spectral contours of the frequency content for the signals to be perceived at locations "outside" of the head. The changes in spectral shape are so subtle across sound source location that even the slightest deviation during spatial audio processing can cause the sound to be perceived as coming from a different location than intended. This extreme sensitivity to the acoustic cues gives rise to several design issues regarding the utility of such technology across the military. Although there are no instances of spatial audio being implemented currently in the U.S. Army, specifications for spatial audio displays are available. The present section aims to discuss these issues.

Technical Design Criteria: Spatial Audio Requires Stereo Headsets

Spatial audio is generated by filtering sounds using signal-processing techniques to provide the appropriate acoustic cues over a pair of stereo headphones. Such signal processing creates a "virtual acoustic space" around listeners where sounds delivered over the headset are perceived as coming from different locations in space, whether this is above, below, or anywhere within the full 360 degrees around them. It is important to note the changes in ITDs used for localizing sounds across the horizontal plane are 'on the order of' microseconds (μs). Studies examining the localization accuracy for spatial audio demonstrate that accuracy is greatest for HRTFs that match the individual. However, for the implementation of spatial audio for separation of signals in space without a requirement to identify their precise locations, generalized HRTFs are sufficient (Middlebrooks & Green, 1991; Wenzel et al., 1993).

Currently, MIL-STD-1472H details that the technical design criteria for 3D audio displays should be used only if they enhance human performance (MIL-STD-1472H, 2020). Tasks where 3D audio displays have been shown to enhance performance over two-dimensional displays are tasks that require knowledge of three dimensions, including object tracking tasks, spatial judgment tasks, interactive pointing tasks, and visual search tasks. According to MIL-STD-1472H, outlined in Table 4, when two or more items of communication equipment with audible signals (telephone, radio, and intercom) are in the same area, each shall have a distinct signal. If distinct signals are not possible, 3D audio technology shall be used.

Table 4. MIL-STD-1474H Design Criteria

MIL-STD-1472H		
5.3.9.7 3D Audio Displays		
5.3.9.7.1	Use	3D audio displays or multiple voice communications may be used in an environment with numerous and important spatial cues or where a user is likely to be highly tasked visually (e.g., fighter cockpits) to enhance situation awareness, segregate multiple channels, or rapidly redirect the user's vision.
5.3.9.7.2	Presentation format	For most applications, 3D audio displays shall present data as discrete sound sources located at a constant distance at various azimuths and elevations.
5.3.9.7.3	Angular separation	Angular separation between discrete sounds shall be not less than 15 degrees in the horizontal plane and not less than 30 degrees in the vertical plane unless indicating location of real objects or events.
5.3.9.7.4	Binaural versus monaural	3D audio cues shall be presented binaurally.
5.3.9.7.5	Frequency response	The audio system shall be compatible with stereo audio for one-third octave bands from 100 Hz to 16 kHz.
5.3.6.10	Binaural earphone latency difference	Except for 3D sound localization applications, critical voice communication systems shall not introduce a discernible binaural asynchronous delay (greater than 1 millisecond). Binaural earphones used for critical voice communication systems shall not have a latency difference between the earphones greater than 20 µs.

Head tracking.

One consideration assumed to be critical to the success of spatial audio is the implementation of real-time head tracking. If done correctly, head tracked spatial audio presented over headphones results in virtual sounds occupying fixed locations in virtual space that correspond to objects or events at actual locations in the real world, regardless of one's head movements. However, head trackers are typically the most costly and difficult to integrate component of a spatial audio display. One alternative is to render the spatial audio cues solely with respect to the heading of the aircraft, regardless of head position (e.g., aircraft-referenced cueing). This approach is simpler to implement because the onboard aircraft sensors already determine which information is made available to the display system, so no additional sensors are necessary. Presently, there are no specifications in MIL-STD-1472H regarding any requirement for spatial audio displays to have accompanying head tracking capabilities. Here we discuss studies in the literature concerning the use of head tracking for spatial audio displays and whether the potential benefits of including such capabilities are worth the increase in cost.

Previous studies have reported pilots exhibited better performance with aircraft-referenced compared to head-referenced cueing (Brungart et al., 2007; Simpson et al., 2007). Moreover, there is evidence that this approach can be effective in certain flight scenarios when visual information is degraded, where it has been suggested that pilots may revert to an orientation of the aircraft in relation to the environment when using visual instruments (Liggett & Gallimore, 2002) and auditory cues (Simpson et al., 2008). The idea behind the better performance observed with aircraft-referenced cues was that there might be an alignment mismatch between the pilot’s frame of reference and the position of the aircraft (Simpson et al., 2007). It is important to note that other studies have reported no differences in performance between head- and aircraft-referenced 3D spatial audio cueing (Milam et al., 2019; Towers et al., 2014). However, the pilots were typically facing forward for the flight tasks in this study and thus, may not have needed to move their head. Furthermore, as Towers et al. (2014) noted, pilots are typically seated facing forward, improving high-workload out-of-cockpit visual tasks.

Helicopter pilots may navigate from a vehicle reference perspective (i.e., based on where they think the aircraft is positioned/oriented relative to the outside world) and may not consider themselves as separate from that. In terms of increasing speech recognition, head tracking is not necessary. It only becomes a consideration when information about the orientation of the aircraft relative to a particular location (e.g., waypoint finding, obstacle avoidance) or relative to objects near the aircraft (e.g., target detection, threat identification, etc.) are necessary to complete the mission. As such, the findings from the multitude of studies discussed here, coupled with the apparent lack of difference between the two configurations, points to the conclusion that aircraft-referenced presentation of spatial audio cues may be sufficient for providing benefits to pilots. Since spatial audio displays that do not utilize head tracking capabilities are technologically easier and less expensive to implement, this configuration has the potential to become the standard technology employed by Army aviation. Aircraft that already implement head tracking capabilities will not be a detriment to the implementation of spatial audio.

Acoustic characteristics of auditory stimuli in the cockpit.

According to MIL-STD-1474H, communication requirements shall be based on the one-third octave band center frequency range of 160 to 5000 Hz. Most of the energy required for near-perfect speech intelligibility is in the range of 200 to 6300 Hz. Consonants contain energy mainly at frequencies above 1500 Hz, whereas vowels contain lower frequency energy. Unfortunately, the consonants, which convey most of the information in English language speech, contain very little energy overall. Although frequency range is important for preserving speech information within the audio signal, it is also an important consideration regarding spatial audio. Localizing sound sources along the vertical plane (i.e., both above and below) and disambiguating front-back confusion (i.e., correctly perceiving sound sources presented in front of a listener from sounds presented from behind them) is frequency-dependent and sensitive to source spectrum.

Much research over the past few decades has demonstrated spectral shape cues to be the primary cues for vertical localization. For example, narrow bandwidth stimuli or stimuli containing little energy at high frequencies is notoriously difficult to localize in the vertical plane. While there is some debate on the cutoff frequency for which spectral shape cues are most important, it seems that frequencies above 4 kHz are important (for review, see Middlebrooks & Green, 1991). Moreover, vertical localization can be disrupted by plugging the ear, changing shapes of the pinna, or any signal processing manipulation to the sound, which alters the ear's directional transfer function (Middlebrooks, 1999; Middlebrooks & Green, 1991). Such findings in the literature stress the importance of preserving the higher frequency ranges (> 4 kHz) for providing spatial audio that allows a pilot to discern 'front' from 'back,' as well as 'up' from 'down' sound source locations. Although not necessarily important for speech understanding using spatial audio, providing high fidelity spectral shape cues enables pilot cueing in the vertical plane. The lack of high frequency information in the headphones used for spatial audio systems in aircraft will largely negate the ability to implement vertical spatialization of signals.

Technical Design Recommendation: Frequency Content of Spatial Audio Signals

Signals containing a larger number of frequencies, both high and low, are easier to localize. This is especially true for Service Members who may present with hearing loss. Speech communication is broadband, and several studies have demonstrated the benefit of radio communications being spatialized for improved speech intelligibility. Spatial audio meant to provide locational information about objects outside of the aircraft should be comprised of broadband, low frequency signals (i.e., < 1.5 kHz). Both individuals with normal hearing and high frequency hearing loss would benefit from the salient localization cues contained in these low frequency sonifications.

Overall Recommendations

Standards for spatial audio are critical to ensure that individuals can effectively use and benefit from this technology. These standards should address both the medical and design considerations.

- **Medical Recommendation: Medical standards need to consider the application of the spatial audio (i.e., improved speech communication vs. waypoint finding)**. For radio communications, asymmetric hearing loss may not preclude an aviator from benefiting from spatial audio. However, asymmetric hearing loss may become a problem for aviators if they need to localize a spatial audio alert for target identification and waypoint guidance to locations outside of the aircraft. Understanding the spatial audio application in FVL will guide future medical standards.

- **Medical Recommendation: No changes to the APL for aviators who meet the current hearing requirements are recommended at this time**, based on a review of the literature and sparse preliminary testing in military aircraft. Present day APL classification of hearing status is sufficiently stringent to select aviators most likely to benefit from spatial audio systems in the aircraft. However, it should be noted that pure tone threshold requirements do not assess the functional performance of spatial hearing ability.

- **Medical Recommendation: Additional medical standards need to be considered for individuals who do not meet the APL standard.** Following a similar format to the updated DA PAM 40-502, only aviators who exceed the APL standard should be assessed further for performance on spatial tasks and hearing performance. The addition of the MOHT to the APL for those exceeding the hearing standard could offer a solution. In-flight assessments are identified in the APL but are not standardized and do not appear to be completed or documented in a way that can be monitored or reviewed, whereas the MOHT is routinely documented in clinical encounters at the MTF.

- **Medical Recommendation: Individuals may be able to overcome localization deficiencies of asymmetric hearing loss through training.** According to the DOEHRS data, the most common amount of asymmetry was 10 dB, which is not thought to impact localization. However, there are greater amounts of asymmetry present, which may present with localization difficulties. Several studies have shown that with training an individual can 'reweight' or relearn appropriate localization. It is important to note that for this to be successful, the asymmetry in the hearing loss needs to be identified and then appropriate training implemented. There is currently a means for identifying the hearing loss, but no standardized protocol for sound localization training in the Army.

- **Technical Design Recommendation: Consideration should be given to the type and frequency composition of signals used in the cockpit.** Signals containing a larger number of frequencies, both high and low, are easier to localize. This is especially true for Service Members who may present with hearing loss. Speech communication is broadband, and several studies have demonstrated the benefit of radio communications being spatialized for improved speech intelligibility.

- **Technical Design Recommendation: Spatial audio <u>requires</u> stereo headsets.** Sounds are filtered using signal processing techniques to provide the appropriate acoustic cues (i.e., ITDs, IIDs, and SS cues) over a pair of stereo headphones, which delivers a separate channel of audio to each ear, independent of the other ear. The implementation of spatial audio requires stereo headsets in which the two channels deliver independent auditory signals to each ear. The current aviator headset configuration is split monaural.

References

Abel, S. M., & Lam, K. (2008). Impact of unilateral hearing loss on sound localization. *Applied Acoustics, 69*(9), 804–811.

Abouchacra, K. S., Breitenbach, J., Mermagen, T., & Letowski, T. (2001). Binaural helmet: Improving speech recognition in noise with spatialized sound. *Human Factors, 43*(4), 584–594.

AirforceTechnology. (2018). Terma to install 3D-Audio system on-board USAF's F-16 jets. *Airforce Technology*. https://www.airforce-technology.com/news/terma-install-3d-audio-system-board-usafs-f-16-jets/?cf-view

Amos, N. E., & Humes, L. E. (2007). Contribution of high frequencies to speech recognition in quiet and noise in listeners with varying degrees of high-frequency sensorineural hearing loss. *Journal of Speech Language and Hearing Research, 50*, 819–834.

Beamer, S., Deaver, K., Hall, S., & Helfer, T. (2014). *Active duty-US Army noise induced hearing injury surveillance calendar years 2009-2013.* Retrieved from: https://apps.dtic.mil/sti/pdfs/AD1013106.pdf

Begault, D. R. (1993). Head-up auditory displays for traffic collision avoidance system advisories: A preliminary investigation. *Human Factors, 35*(4), 707–717.

Begault, D. R., & Pittman, M. T. (1996). Three-dimensional audio versus head-down traffic alert and collision avoidance system displays. *The International Journal of Aviation Psychology*, *6*(1), 79–93.

Bolia, R. S., D'Angelo, W. R., & McKinley, R. L. (1999). Aurally aided visual search in three-dimensional space. *Human Factors, 41*(4), 664–669.

Bolia, R. S., & Nelson, W. T. (2003). Spatial audio displays for target acquisition and speech communications. In L. J. Hetinger & M. W. Haas (Eds.), *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp. 187-197). Lawrence Erlbaum Associates.

Bronkhorst, A. W., Veltman, J. A., & Van Breda, L. (1996). Application of a three-dimensional auditory display in a flight task. *Human Factors*, *38*(1), 23–33.

Brungart, D., & Simpson, B. (2003). Optimizing the spatial configuration of a seven-talker display. In *Proceedings of ICAD 2003, 1*, 188–193.

Brungart, D. S., Ericson, M., & Simpson, B. D. (2002). Design considerations for improving the effectiveness of multitalker speech displays. In *Proceedings of ICAD 2002, 1,* 424–430.

Brungart, D. S., Sheffield, B. M., Galloza, H., Schurman, J. R., Russell, S., Barrett, M. E., Witherell, K., Makashay, M. J., & Heil, T. (2023). Developing an evidence-based military auditory fitness-for-duty standard based on the 80-word Modified Rhyme Test. *Ear and Hearing, 44*(1), 209–222.

Brungart, D. S., Simpson, B. D., Dallman, R. C., Romigh, G., Yasky, R., & Raquet, J. (2007, June 26 - 29). A comparison of head-tracked and vehicle-tracked virtual audio cues in an aircraft navigation task. In: *Proceedings of the 13th International Conference on Auditory Display,* Montréal, Canada.

Butler, R. A. (1987). An analysis of the monaural displacement of sound in space. *Perception & Psychophysics, 41*(1), 1–7.

Calhoun, G., & Draper, M. (2015). Display and control concepts for multi-UAV applications. In K. P. Valanavanis & G. J. Vachtsevanos (Eds.), *Handbook of unmanned aerial vehicles* (pp. 2443-2473). Springer.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *The Journal of the Acoustical Society of America, 25*(5), 975–979.

Cherry, E. C., & Taylor, W. K. (1954). Some further experiments upon the recognition of speech, with one and with two Ears. *The Journal of the Acoustical Society of America, 26*(4), 554–559.

Drullman, R., & Bronkhorst, A. W. (2000). Multichannel speech intelligibility and talker recognition using monaural, binaural, and three-dimensional auditory presentation. *The Journal of the Acoustical Society of America, 107*(4), 2224–2235.

Ellis, G. M., & Souza, P. E. (2020). The effect of hearing loss on localization of amplitude-panned and physical sources. *Journal of the American Academy of Audiology, 31*(09), 690–698.

Ericson, M. A., Brungart, D. S., & Simpson, B. D. (2004). Factors that influence intelligibility in multitalker speech displays. *International Journal of Aviation Psychology, 14*(3), 313–334.

Ericson, M. A., & McKinley, R. L. (1997). The intelligibility of multiple talkers separated spatially in noise. In R. H. Gilkey & T. R. Anderson (Eds.), *Binaural and Spatial Hearing in Real and Virtual Environments* (pp. 701-724). Erlbaum.

Feltman, K. A., Curry, I., Bernhardt, K., Hayes, A., Kirby, S., Davis, B., Sapp, J., Durbin, D., & Hartnett, G. (2018). *Integrated cueing environment: Simulation event four* (USAARL-TECH-FR--2028-16). U.S. Army Aeromedical Research Laboratory.

Feltman, K. A., St Onge, P., Aura, C., & Stewart, J. (2020). *Pilot cueing for 360° obstacle awareness during DVE missions* (USAARL-TECH-FR--2020-026). U.S. Army Aeromedical Research Laboratory.

Foyle, D. C., Andre, A. D., McCann, R. S., Wenzel, E. M., Begault, D. R., & Battiste, V. (1996). Taxiway navigation and situation awareness (T-NASA) system: Problem, design philosophy, and description of an integrated display suite for low-visibility airport surface operations. *SAE Transactions*, 1411–1418. https://doi.org/10.4271/965551

Hartnett, G., Hicks, J., Durbin, D., Godfroy-Cooper, M., Miller, J., Feltman, K. A., McAtee, A., St Onge, P., Aura, C., & Stewart, J. (2020). *Pilot cueing for 360 obstacle awareness during DVE missions* (USAARL-TECH-FR--2020-026). U.S. Army Aeromedical Research Laboratory.

Haywas, L. R., Merriman, B. J., & Martinez, R. A. (2021). *A-10 three-dimensional audio system force development evaluation plan* (AATC 19-023). Air National Guard Air Force Reserve Command Test Center.

Helfer, T., Beamer, S., Deaver, K., & Hall, S. (2014). *Active duty-U.S. Army noise induced hearing injury surveillance calendar years 2008-2012.* Retrieved from: https://apps.dtic.mil/sti/pdfs/AD1013099.pdf.

Henry, J. A., Griest, S., Reavis, K. M., Grush, L., Theodoroff, S. M., Young, S., Thielman, E. J., & Carlson, K. F. (2021). Noise Outcomes in Servicemembers Epidemiology (NOISE) study: Design, methods, and baseline results. *Ear and Hearing, 42*(4), 870–885.

Kim, S. (2016). *Unmanned aerial vehicle (UAV) operators' workload reduction: The effect of 3D audio on operators' workload and performance during multi-aircraft control* (Publication Number AFIT-ENV-MS-16-M-163). Air Force Institute of Technology.

Kim, S., Miller, M. E., Rusnock, C. F., & Elshaw, J. J. (2018). Spatialized audio improves call sign recognition during multi-aircraft control. *Applied Ergonomics*, *70*, 51–58.

Kumpik, D. P., & King, A. J. (2019). A review of the effects of unilateral hearing loss on spatial hearing. *Hearing Research, 372*, 17–28.

Laird, R. (2018). *The Danish F-16 transition: From a garrison to an expeditionary Air Force*. DEFENSE.info. Retrieved from: https://defense.info/air-power-dynamics/2018/11/the-danish-f-16-transition-from-a-garrison-to-an-expeditionary-air-force/

Liggett, K. K., & Gallimore, J. J. (2002). An analysis of control reversal errors during unusual attitude recoveries using helmet-mounted display symbology. *Aviation, Space, and Environmental Medicine, 73*(2), 102–111.

MacDonald, J. A., Balakrishnan, J. D., Orosz, M. D., & Karplus, W. J. (2002). Intelligibility of speech in a virtual 3-D environment. *Human Factors, 44*(2), 272–286. https://doi.org/10.1518/0018720024497934

Makous, J. C., & Middlebrooks, J. C. (1990). Two-dimensional sound localization by human listeners. *The Journal of the Acoustical Society of America, 87*(5), 2188–2200.

Marrone, N., Mason, C. R., & Kidd, G. J. (2008). The effects of hearing loss and age on the benefit of spatial separation between multiple talkers in reverberant rooms. *The Journal of the Acoustical Society of America*, *124*(5), 3064–3075.

McAnally, K. I., Bolia, R. S., Martin, R. L., Eberle, G., & Brungart, D. S. (2002). Segregation of multiple talkers in the vertical plane: Implications for the design of a multiple talker display. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 46*(4), 588–591. https://doi.org/10.1177/154193120204600404

McAnally, K. I., & Martin, R. L. (2007). Spatial audio displays improve the detection of target messages in a continuous monitoring task. *Human Factors*, *49*(4), 688–695.

McGarrigle, R., Munro, K. J., Dawes, P., Stewart, A. J., Moore, D. R., Barry, J. G., & Amitay, S. (2014). Listening effort and fatigue: What exactly are we measuring? A British Society of Audiology Cognition in Hearing Special Interest Group 'white paper.' *International Journal of Audiology*.

McKinley, R. L., Erickson, M. A., & D'Angelo, W. R. (1994). 3-Dimensional auditory displays: Development, applications, and performance. *Aviation, Space, and Environmental Medicine, 65*(5, Sect 2, Suppl), A31–A38.

McKinley, R. L., & Ericson, M. A. (1995). Flight demonstration of a 3-D auditory display. In R. H. Gilkey & T. R. Anderson (Eds.), *Binaural and Spatial Hearing in Real and Virtual Environments* (pp. 683–699). Lawrence Erlbaum Associates.

McLntire, J. P., Havig, P. R., Watamaniuk, S. N., & Gilkey, R. H. (2010). Visual search performance with 3-D auditory cues: Effects of motion, target location, and practice. *Human Factors*, *52*(1), 41–53.

Mendonça, C., Campos, G., Dias, P., Vieira, J., Ferreira, J. P., & Santos, J. A. (2012). On the improvement of localization accuracy with non-individualized HRTF-based sounds. *Journal of the Audio Engineering Society, 60*(10), 821–830.

Middlebrooks, J. C. (1997). Spectral shape cues for sound localization. *Binaural and Spatial Hearing in Real and Virtual Environments*, Chapter 4, 77-97.

Middlebrooks, J. C. (1999). Virtual localization improved by scaling nonindividualized external-ear transfer functions in frequency. *The Journal of the Acoustical Society of America, 106*(3), 1493–1510.

Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology, 42*(1), 135–159.

Milam, L., Akins, E., Williams, H., Simpson, B., & Jones, H. G. (2019). Spatial audio cueing aids pilot navigation during simulated helicopter flight in degraded visual environments. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.* https://journals.sagepub.com/doi/abs/10.1177/1071181319631498

Musicant, A. D., & Butler, R. A. (1980). Monaural localization: An analysis of practice effects. *Perception & Psychophysics, 28*(3), 236–240.

Naqvi, M. H. (2008). *A flight test study to assess the utility of an aircraft referenced 3D audio display to improve pilot performance under high workload conditions* [Master's thesis, University of Tennessee].

Nelson, W. T., Bolia, R. S., Ericson, M. A., & McKinley, R. L. (1999). Spatial audio displays for speech communications: A comparison of free field and virtual acoustic environments. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. https://journals.sagepub.com/doi/abs/10.1177/154193129904302207

Niermann, C. A. (2015). Can spatial audio support pilots? 3D-audio for future pilot-assistance systems. *2015 IEEE/AIAA 34th Digital Avionics Systems Conference*. https://doi.org/10.1109/DASC.2015.7311401.

Niermann, C. A. (2018). 3D audio support for helicopter pilots during confined area landings. *31st Congress of the International Council of the Aeronautical Sciences*, Belo Horizonte, Brazil.

Noble, W., Byrne, D., & Lepage, B. (1994). Effects on sound localization of configuration and type of hearing impairment. *The Journal of the Acoustical Society of America, 95*(2), 992–1005.

Ohlenforst, B., Zekveld, A. A., Jansma, E. P., Wang, Y., Naylor, G., Lorens, A., Lunner, T., & Kramer, S. E. (2017). Effects of hearing impairment and hearing aid amplification on listening effort: A systematic review. *Ear and Hearing, 38*(3), 267.

Oving, A. B., Veltman, J. A., & Bronkhorst, A. (2004). Effectiveness of 3-D audio for warnings in the cockpit. International *Journal of Aviation Psychology*, *14*, 257–276.

Parker, S. P. A., Smith, S. E., Stephan, K. L., Martin, R. L., & McAnally, K. I. (2004). Effects of supplementing head-down displays with 3D audio during visual target acquisition. *The International Journal of Aviation Psychology*, *14*(3), 277–295.

Philbrick, R. M. & Colton, M. B. (2012). Effects of haptic and 3D audio feedback on operator performance and workload for quadrotor UAVs in indoor environments. J*ournal of Robotics and Mechatronics*, *26*(5), 580–591.

Pinedo, C. (2006). *Effects of a combined 3-D auditory/visual cueing system and non-distributed flight reference on visual target detection using a helmet-mounted display* [Doctoral dissertation, Massachusetts Institute of Technology].

Pinedo, C., Young, L., & Esken, R. (2005). *Effects of a combined 3-D auditory/visual cueing system on visual target detection using a helmet-mounted display* (AFRL-HE-WP-TR-2006-0128). Air Force Research Laboratory. https://apps.dtic.mil/sti/pdfs/ADA456521.pdf

Ray, J., Maw, E., & Muqolli, E. (2022). *F-16 3D audio localization final report.* Georgia Tech Research Institute.

Romigh, G. D., Villa, J., & Ayers, J. (2017). Evaluating spatial-auditory symbology for improved performance in low-fidelity spatial audio displays. *19th International Symposium on Aviation Psychology*, Dayton, OH.

Seixas, N. S., Neitzel, R., Stover, B., Sheppard, L., Feeney, P., Mills, D., & Kujawa, S. (2012). 10-Year prospective study of noise exposure and hearing damage among construction workers. *Occupational and Environmental Medicine, 69*(9), 643–650.

Simpson, B. D., Brungart, D. S., Dallman, R. C., Joffrion, J., Presnar, M. D., & Gilkey, R. H. (2005). Spatial audio as a navigation aid and attitude indicator. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.* https://journals.sagepub.com/doi/abs/10.1177/154193120504901722

Simpson, B. D., Brungart, D. S., Dallman, R. C., Yasky, R. J., & Romigh, G. D. (2008). Flying by ear: Blind flight with a music-based artificial horizon. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 52*(1), 6–10.

Simpson, B. D., Brungart, D. S., Dallman, R. C., Yasky, R. J., Romigh, G. D., & Raquet, J. F. (2007). In-flight navigation using head-coupled and aircraft-coupled spatial audio cues. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.* https://journals.sagepub.com/doi/abs/10.1177/154193120705101914

Simpson, B. D., Brungart, D. S., Gilkey, R. H., Cowgill, J. L., Dallman, R. C., Green, R. F., Youngblood, K. L., & Moore, T. J. (2004). 3D audio cueing for target identification in a simulated flight task. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.*

Slattery III, W. H., & Middlebrooks, J. C. (1994). Monaural sound localization: Acute versus chronic unilateral impairment. *Hearing Research, 75*(1-2), 38–46.

Spagnol, S., Wersényi, G., Bujacz, M., Bălan, O., Herrera Martínez, M., Moldoveanu, A., & Unnthorsson, R. (2018). Current use and future perspectives of spatial audio technologies in electronic travel Aids. *Wireless Communications and Mobile Computing,* 1–17.

Stevens, S. S., & Newman, E. B. (1936). The localization of actual sources of sound. *The American Journal of Psychology, 48*(2), 297–306.

Szoboszlay, Z., Miller, J., Godfroy-Cooper, M., Davis, B., Feltman, K., Hartnett, R. G., Durbin, D., Hicks, J., Plitsch, M., & Ott, C. (2021). *The design of pilot cueing for the degraded visual environment mitigation (DVE-M) system for rotorcraft* [Oral presentation]. Vertical Flight Society's 77th Annual Forum & Technology Display.

Tannen, R. S., Nelson, W. T., Bolia, R. S., Warm, J. S., & Dember, W. N. (2004). Evaluating adaptive multisensory displays for target localization in a flight task. *The International Journal of Aviation Psychology, 14*(3), 297–312.

Towers, J., Burgess-Limerick, R., & Riek, S. (2014). Concurrent 3-D sonifications enable the head-up monitoring of two interrelated aircraft navigation instruments. *Human Factors, 56*(8), 1414–1427.

Veltman, J., & Oving, A. (1999). *3-D sound in the cockpit to enhance situation awareness* (Report No. TM-99-A061). Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO) Human Factors.

Veltman, J. A., Oving, A. B., & Bronkhorst, A. W. (2004). 3-D Audio in the fighter cockpit improves task performance. *The International Journal of Aviation Psychology, 14*(3), 239–256.

Wenzel, E. M., Arruda, M., Kistler, D. J., & Wightman, F. L. (1993). Localization using non-individualized head-related transfer functions. *The Journal of the Acoustical Society of America, 94*(1), 111–123.

Wenzel, E. M., Miller, J. D., & Abel, J. S. (2000). Sound lab: A real-time, software-based system for the study of spatial hearing. *Audio Engineering Society Convention, 108*. Audio Engineering Society.

Wightman, F. L., & Kistler, D. J. (1989). Headphone simulation of free field listening. II: Psychophysical validation. *The Journal of the Acoustical Society of America, 85*(2), 868–878.

Wightman, F. L., & Kistler, D. J. (1992). The dominant role of low frequency interaural time differences in sound localization. *The Journal of the Acoustical Society of America, 91*(3), 1648–1661.

Winn, M. B., Wendt, D., Koelewijn, T., & Kuchinsky, S. E. (2018). Best practices and advice for using pupillometry to measure listening effort: An introduction for those who want to get started. *Trends in Hearing, 22*, 1–32.

Wright, B. A., Zhang, Y., & Stewart, C. C. (2006). Two types of learning revealed by evaluation of the best and worst daily performance during auditory-discrimination training. *The Journal of the Acoustical Society of America, 119*(5), 3331–3331.

Yost, W. A., & Zhong, X. (2014). Sound source localization identification accuracy: Bandwidth dependencies. *The Journal of the Acoustical Society of America, 136*(5), 2737–2746.

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