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Design and Development of a Portable Auditory Situation Awareness Training (PASAT) System

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Abstract

Auditory situation awareness (ASA) is essential for safety and survivability in military operations where many of the hazards are not immediately visible. Unfortunately, the Hearing Protection Devices (HPDs) required to operate in these environments can impede auditory localization performance. Promisingly, recent studies have exhibited the plasticity of the human auditory system by demonstrating that training can improve auditory localization ability while wearing HPDs, including military Tactical Communications and Protective Systems (TCAPS). As a result, the U.S. military identified the need for a portable system capable of imparting auditory localization acquisition skills at similar levels to those demonstrated in laboratory environments. The purpose of this investigation was to design and develop a Portable Auditory Situation Awareness Training (PASAT) system capable of reproducing acoustically accurate localization cues similar to a proven laboratory grade system. Extensive research of components and equipment helped ensure optimal performance and packaging of the PASAT system. Selection of these components included a formal decision algorithm developed for optimizing component selection decisions for human-equipment systems. The innovative PASAT system consists of an accordion-style, collapsible frame housing 32-loudspeaker capable of training 360-degrees of azimuth and 60-degrees of elevation operated by a user-controlled tablet computer. Two human factors experiments and a usability study demonstrated the effectiveness of the PASAT system to test and train localization and to detect differences in performance between hearing protection devices.

Keywords
Auditory Situation Awareness; Human-Systems Integration Design; Component Analysis; Decision Analysis,

1. Introduction
1.1. Literature Review
The primary objective of this study was to develop an innovative, portable auditory localization acclimation training system that incorporated an optimized training strategy to train and test service members' ability to localize with both the open ear and with a hearing protection device (HPD), including the U.S. military's Tactical Communication and Protective Systems (TCAPS). TCAPS are electronic powered hearing protection devices that impart signal processing on acoustic signals. A series of auditory localization studies at Virginia Tech led to the development of a test battery and full-scale laboratory training and testing system termed "DRILCOM," after the four major elements of auditory situation awareness: Detection, Recognition/Identification, Localization, and pass-through COMmunications [1]. The DRILCOM system along with localization portion of the test battery demonstrated the ability to measure and train localization acquisition skills. It also proved sensitive enough to detect localization ability differences between listening conditions, namely between the open ear and with an HPD/TCAPS and between types of HPDs/TCAPS [1]-[3]. The DRILCOM system highlighted the detrimental impacts that TCAPS devices impart on localization, a key component of auditory situation awareness. Focus group studies of military

service members and interviews with senior military researchers in the U.S., Canada and Great Britain confirmed the need to train localization under TCAPS conditions but underscored the challenges of developing localization tests and equipment that could consistently train localization in non-laboratory environments [4, 5]. With these results in mind, the Office of Naval Research issued a research grant to design and evaluate a portable system capable of providing the requisite auditory localization acquisition skills necessary to improve auditory situation awareness.

1.2. System Requirements

The Portable Auditory Situation Awareness Training (PASAT) system was intended to be assembled and operated by a trainee in a small room, test and train throughout 360-degrees of azimuthal auditory localization, and store in a portable shipping container. More specifically, the portable system was required to setup in a space no more than 7-feet wide by 7-feet long by 7-feet high. The entire system, complete with small directional loudspeakers, structure, user interface, and audio equipment had to breakdown and fit in a large storage case. An optimal number of loudspeakers were required to be attached in equidistance spacing around a portable structure. Furthermore, the loudspeakers needed to be height-adjustable to align with the trainee's ear height when seated in the middle of the array. Where possible, the system should use commercially off-the-shelf products; this was desired to alleviate a long design phase and control costs. The overriding goal of the PASAT system was to provide a user-friendly device that allowed trainees to improve auditory localization skills with the open (unoccluded) ear and while wearing a TCAPS device. Given the demonstrated success of the DRILCOM system, the PASAT system was required to incorporate the optimized DRILCOM training protocol [6] and provide a similar learning benefit over the same number of learning units.

2. Method

The design of the prototype PASAT system was conducted through extensive research, application of human factors techniques, and a formal decision algorithm developed by David Meister for optimizing component selection decisions for human-equipment [7]. Component alternatives were tested for electronic and acoustical performance reproduce acoustically accurate localization cues similar to the proven laboratory grade system. While not the primary focus of this paper, upon completion of prototype, the PASAT system was tested via two comprehensive human factors experiments to compare the training results from the PASAT system to those from the full-scale, hemi-anechoic room DRILCOM system and in a large-scale lab-to-field experiment to evaluate how PASAT's training transferred to an outdoor "real-world" environment.

2.1. PASAT Structure

The shape, size, materials, and functionality of the PASAT system were selected using human factors principles to reduce user workload, increase safety, and ensure consistent proper use. The investigator conducted a thorough literature review and evaluated 18 unique localization apparatus designs used in published studies to discover design features that could be used to develop a portable system. The extensive literature search yielded no results for a portable auditory situation awareness device. The reviewed apparatus designs were predominantly rigid framed structures, operated in rooms with sound-absorptive materials, and were too large to meet portability requirements. The number of loudspeakers used varied from 8 to 36 resulting in respective azimuthal angular separation between loudspeakers, measured from the center point, from 45-degrees to 10-degrees. Without a defined standard, the investigator first determined the optimal number of loudspeakers for the PASAT system based on human auditory capabilities and impacts of directing visual field of view based on auditory localization. One of the primary purposes of auditory localization is to orient the listener to the direction of the sound and cue the visual modality effectively reducing the response time in target identification [8]. The wider the azimuthal separation angle at the listener the broader the visual field of view search as the distance increases from the listener.

System requirements limited the size to a 7-foot diameter in order maximize portability and flexibility. From an acoustical perspective, a radius one-meter distance from center head to the loudspeaker places the trainee right at the edge of where the near field transitions into the far field for low frequencies. The acoustical near field is the region closest to the sound source where the sound pressure and the velocity of the wave particles are not in phase, meaning no simple relationship exists between the sound pressure and sound intensity, thus, obfuscating localization cues [9, 10]. It is hard to define an exact equation for the size of the near field but is described in general terms by one wavelength or three times the largest dimension of the sound source, whichever is largest [9]. Equation (1) was used to calculate the length of the wavelength where λ is the wavelength in meters, c is the speed of sound in meters per second (343 m/s), and f is the frequency in Hz.

$$\lambda = \frac{c}{f} \tag{1}$$

2.2. PASAT Components

Loudspeakers are one of the most critical components of the PASAT system and as such required a deliberate analysis and selection process developed by David Meister. Meister's forced-choice decision analysis uses a series of pairwise comparisons of the evaluation criteria and alternatives to derive a weighted score for each alternative and identify the alternative that best meets the prioritized performance criteria [7]. The investigators first identified 10 performance measurement criterion essential for acoustical quality and portability to include: *frequency response*, *total harmonic distortion*, *ability to reproduce DRILCOM acoustical signal*, *sensitivity*, *recommended power rating*, *impedance*, *weight*, *physical dimensions*, *loudspeaker transducer (driver) type*, and *wire terminal (connection) type* [11]. The top three loudspeakers for the PASAT system were down-selected from over 20 feasible alternatives and purchased to conduct in-depth testing and evaluation. Acoustical testing for *frequency response*, *total harmonic distortion*, and *ability to reproduce DRILCOM acoustical signal* was performed on all three loudspeakers in the Virginia Tech Auditory Systems Laboratory. Data were also collected on the remaining performance criteria based on manufacturer specifications and the resulting data for all 10 performance measurement criteria were summarized into a questionnaire. Six Subject Matter Experts (SMEs) in the fields of acoustics, audiology, psychology, human factors, and military operations research were chosen to evaluate the acoustical performance metrics and loudspeaker alternatives for the PASAT system.

The first step in the Meister analysis required each SME compare every pair of performance measurement criteria and select the criterion that they believed was most important for the system. The total criterion value, sum of winning pairwise comparisons, for each performance measure was then divided by 45, representing the total number of comparisons, to find a *criterion weighting coefficient.* Next, the SME conducted a pairwise comparison of each alternative for every design criterion based on objective data presented and the SME's professional experience. This resulted in a total of three pairwise comparisons for of the 10 criteria. The selected alternative from each pairwise comparison was assigned a value of 1 and a value of 0 was assigned to the alternative that was outperformed [7]. The total alternative choice tally, sum of winning pairwise comparisons, for each criterion was then divided by 3, representing the total number of comparisons, to find an *alternative choice coefficient.* The final step in the Meister plan analysis was to multiply the criterion weighting coefficient by the alternative choice coefficient for each criterion and calculate the sum of the products resulting in an *alternative score for each alternative*. The alternative scores from each SME were then compared using non-parametric statistical analysis to determine optimal loudspeaker for the PASAT system.

The remainder of the audio equipment and user interface were evaluated, selected, and designed using human factors principles. Task analysis was performed to identify all user requirements during setup, operation, and disassembly [8]. Where possible, design features were implemented to limit user workload to reduce human error. User interface device alternatives were evaluated to ensure the user would maintain proper head position and provide direct position control. The DRILCOM software menu display locations, arrangements, and symbols were modified to reduce clutter, standardize instructions, and increase legibility. The design features and user interface improvements were evaluated by participant ratings in two human factors experiments and during usability study involving experts in audiology and engineering.

3. Results and Discussion

3.1. PASAT Structure

The PASAT system was designed to be assembled and operated by a military service member in a small room to test and train throughout 360-degrees of azimuthal auditory localization. The structure consists of a 6.5-foot diameter, 12-sided accordion-style, expandable and collapsible steel tubing frame, similar to a pop-up canopy tent. The expandable accordion-style frame was selected to reduce the workload associated with setting up the loudspeaker apparatus and allow for one user to assemble and operate the system. In addition, the expanding frame maintains equidistant spacing of the loudspeakers in relation to the seated user in the middle of the frame reducing the possibility of localization errors due to improper assembly. The frame uses 12 upright poles to support a 32-loudspeaker array, 24 azimuthal loudspeakers with 15 degrees separation and two vertical loudspeaker mounts supporting 5 elevation loudspeakers each with 15 vertical degrees separation between the 5 loudspeakers (see **Figure 1**). Loudspeaker heights are adjustable to 43.5, 45.5, or 47.5 inches above the floor in order to align loudspeakers with the seated ear height of participants based on anthropometric data of military trainees. The complete PASAT system collapses to store inside a large, portable trunk and small audio equipment bag.

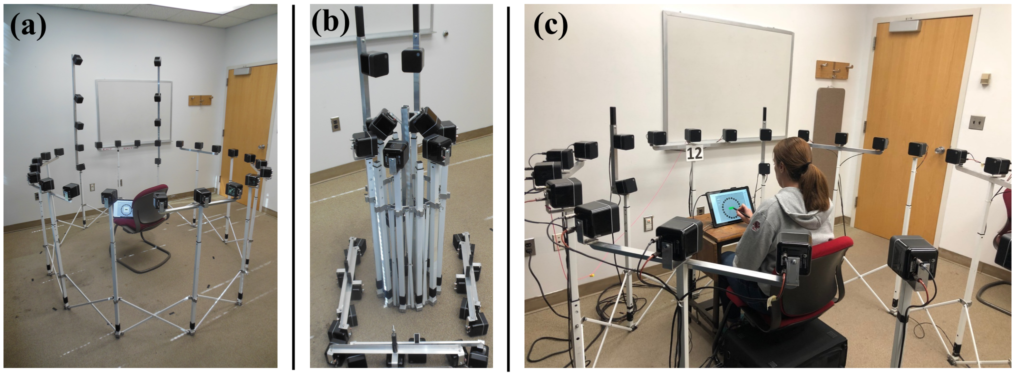

Figure 1: Photo of PASAT system expanded (**a**), collapsed (**b**), and as used by trainee for horizontal localization **(c)**.

The azimuthal angular separation between loudspeakers was one of a few design parameters that was not constrained by system requirements. The decision to use 24 azimuthal loudspeakers resulting in a 15° azimuthal angular separation was; 1) based on human auditory capabilities, 2) to allow for evaluation and validation of the PALAT system against the proven full-scale DRILCOM system, 3) to allow for future testing at increased azimuthal angular accuracy, and 4) because of the impacts of directing visual field of view based on auditory localization. Localization accuracy studies demonstrated the need for an azimuthal angular separation less than 20° to accurately train and assess localization in front of the trainee. These studies also verified that an azimuthal angular separation less than 20° may not be worth the tradeoff of increased accuracy in the rear plane for extra weight and complexity of the portable system [12]. Additionally, 15° azimuthal angular separation significantly reduced the visual field of search distance at the effective range of military relevant signals to include 300 meters for small arms rifles and up to 3,000 meters for motor fire.

Analysis of the acoustical near field at a 1-meter distance resulting in the potential near field effects for low frequencies around 343 Hz and below. The PASAT loudspeakers chosen were tested to verify the frequency response of the dissonant tonal complex compared to the DRILCOM system. The PASAT loudspeakers emitted sound pressure levels of the 295 Hz frequency tone within 3 dBA of the same sound pressure levels of the 737 Hz tone [11]. These two tones would thus provide the necessary interaural timing difference cues for localization. A human factors experiment demonstrated no significant differences in localization performance between the PASAT and DRILCOM systems indicating negligible near-field effects for the 104 Hz and 295 Hz frequencies [11].

To increase safety, a spring-loaded, entry/exit swivel mount was designed to allow participants to easily enter and exit the apparatus without having to crawl under the loudspeaker mount as required in the DRILCOM system reducing the chance of injury. The entry/exit swivel mount holds three loudspeakers and allows the participant to rotate the loudspeaker mount in either direction opening up the full 21-inch entry/exit window into the system (see **Figure 2**). The spring-loaded mount ensures the loudspeakers return to the proper alignment without the user having to measure or align the loudspeakers reducing human error.

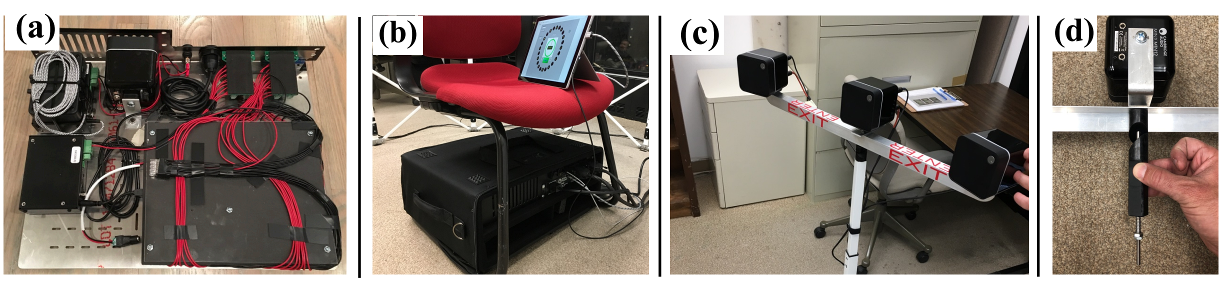

Figure 2: PASAT system audio equipment case (**a**,**b**), tablet user interface (**b**), and swivel entry/exit mount (**c**,**d**).

3.2. PASAT Components

The Meister loudspeaker analysis resulted in a unanimous selection by all SMEs of the Cambridge Audio Minx Min 12 loudspeaker. A Friedman test was applied to compare SME alternative scores. The Friedman non-parametric test for loudspeaker alternative rankings resulted in a significant difference between mean rankings, Bose® FreeSpace® 3 Satellite Speakers (M=0.30, SD=0.07), Cambridge Audio Minx Min 12 (M=0.55, SD=0.07), and Boston Acoustics® SoundWare XS (M=0.15, SD=0.4) across both systems ($\chi^2[2]=10.33$, p=0.006). Post hoc pairwise comparisons were conducted using Wilcoxon signed-rank tests to compare each alternative. Pairwise comparisons used a Bonferroni adjusted α level of 0.017. The Wilcoxon test results showed a significant difference in mean rankings of alternative score between Bose® FreeSpace® 3 Satellite Speakers versus Cambridge Audio Minx Min 12 (Z=-1.17, p=0.043), and the Boston Acoustics® SoundWare XS versus Cambridge Audio Minx Min 12 (Z=1.83, p=0.001). No significant difference was found between Boston Acoustics® SoundWare XS versus Bose® FreeSpace® 3 Satellite Speakers (Z=0.67, p=0.248). **Figure 3** displays the mean rankings of alternative scores for each loudspeaker with 95% confidence intervals about the means.

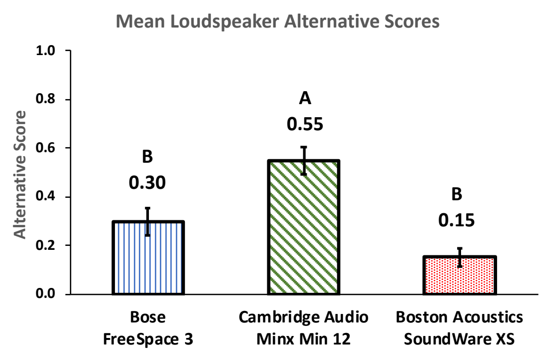

Figure 3: Mean alternative scores for each loudspeaker alternative. Means above 95% confidence interval error bars. Different letters indicate significant differences at p<0.05 with Bonferroni adjustment.

Several innovations were included in the design of the PASAT system to reduce the workload, increase safety, and provide efficiencies for the user. To reduce the setup workload on the user, the PASAT system audio equipment was packaged inside an audio equipment bag limiting the number of tasks required to operate the system (see **Figure 2**). The user is required to plug in a USB cable and 3.5 mm audio cable from the tablet to the front panel of the equipment bag. All 32 loudspeaker cables were designed to fit into two bundles of wires with DB-25 connectors that plug into the front of the audio case. A switch on the front plate operates the pink noise signal and another switch powers the equipment. **Figure 2b** displays the audio equipment bag positioned under the participant seat.

To reduce workload and increase usability, the PALAT system user interface was changed from a desktop and mouse as used in the DRILCOM system to a tablet computer. The PALAT system allows users to initiate auditory signals, record responses and receive feedback via a Microsoft® Surface Pro tablet (see **Figure 2**). The Surface Pro was selected based on compatibility with the LabVIEW™ software program used for localization testing, portable features, and stylus pen or touch screen interface that provide direct position control allowing the user to physically touch the control buttons and response locations [8].

Results of two follow-on human factors experiments supported the ability of the PASAT system employed in a non-laboratory environment to impart similar training benefits in accuracy, front-back reversal errors, and response times as the laboratory-grade DRILCOM system using an identical training protocol [11]. No statistical difference existed between the PASAT and DRILCOM systems on localization accuracy and front-back reversal errors at all stages of training [11]. In addition, results supported that training on the PASAT system was sensitive to auditory localization performance differences with the open ear and with an in-the-ear and over-the-ear TCAPS [11]. Lastly, participant ratings of the two systems showed no preference toward either system for ability to train localization tasks. However, participant ratings indicated a significant preference for the PASAT system user interface which was specifically designed to improve usability features to meet requirements of a user operable system [11]. A usability study conducted by Subject Matter Experts in audiology and human factors rated the PASAT system as easy to set-up and operate and assessed the user interface as providing a positive impact on the ability to use the system.

4. Conclusion

The Portable Auditory Situation Awareness Training (PASAT) system was developed to fill the operational gap in auditory situation awareness training by providing the military with a highly portable, objective, measurement- and feedback-intensive, and user-operable system that instills and improves auditory localization skills in service members over a regimented series of learning units. There are currently no studies that quantify a minimum or desired localization performance standard needed to successfully complete military operations. As such, it is difficult to determine if the PASAT system and training protocol developed for the system are capable of providing the requisite localization training needed in the U.S. military [6]. However, the implications of an affordable, user-operable auditory localization training system for use by military service members, or any industry workers who operate in hazardous noise environments, could potentially lead to improved auditory situation awareness, increased adoption of hearing protection, and reduced cases of noise-induced hearing loss. In addition, the low-cost PASAT system's ability to distinguish performance differences between HPDs enables compliance testing and vetting of hearing protectors for various industries.

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