Nelson, W. T., Bolia, R. S., McKinley, R. L., Chelette, T. L., Tripp, L. D., & Esken, R. (1998). Localization of virtual auditory cues in a high $+G_z$ environment. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*, 97-101 (Cleared for public release by ASC-98-0631, 1 April 1998).

LOCALIZATION OF VIRTUAL AUDITORY CUES IN A HIGH $+G_z$ ENVIRONMENT

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The ability to localize a virtual auditory source was evaluated under varying levels of sustained ($+G_z$) acceleration. Participants were required to judge the locations of virtual auditory cues located along the horizontal plane (elevation 0°) during exposure to 1.0, 1.6, 2.5, 4.0, 5.6, and 7.0 $+G_z$. The experiment was conducted at the Air Force Research Laboratory's Dynamic Environment Simulator - a man-rated, three-axis centrifuge. No significant increases in localization error were found between 1.0 and 5.6 $+G_z$; however, a significant increase did occur at the 7.0 $+G_z$ level. In addition, the percentage of reversals did not vary as a function of $+G_z$ level. Collectively, these results indicate that one's ability to localize virtual auditory cues is well maintained at various levels of sustained acceleration.

INTRODUCTION

While auditory localization technology was used as early as World War I to aid in the detection of enemy aircraft (see Wenzel, 1992 for a brief history), it was not until the 1980s - after the development of powerful digital signal processors and head-related transfer function (HRTF) filtering techniques - that virtual 3-dimensional auditory displays could be generated in real-time for headphone presentation. As might be expected, much of the initial research involving virtual auditory technology focused on the psychophysical validation of these devices (see Wightman & Kistler, 1989). The results of these studies indicated that, in general, virtual auditory technology was capable of generating veridical spatial cues. Such evidence supported the conjecture (Calhoun, Valencia, & Furness, 1987; Doll, 1986; Furness, 1986; Stinnett, 1989) that virtual 3-D auditory technology may be particularly useful for conveying spatial information in tactical airborne applications.

Indeed, investigations over the past decade have demonstrated the utility of virtual 3-D auditory displays for tasks that are relevant to air combat, including (1) enhancing visual target detection and identification (Bronkhorst, Veltman, & van Breda, 1996; D'Angelo, Bolia, McKinley, & Perrott, 1997; Nelson, Hettinger, Cunningham, Brickman, Haas, & McKinley, in press; Perrott, Cisneros, McKinley, & D'Angelo 1996); (2) increasing the effectiveness of collision avoidance displays (Begault, 1993; Begault & Pittman, 1996); (3) improving the monitoring of simultaneous communication signals (Ericson & McKinley, 1997; Koehnke, Besing, Abouchacra, & Tran, 1998; Nelson, Bolia, Ericson, & McKinley, 1998; Ricard & Meirs, 1994); and (4) alleviating problems associated with visual detection tasks in helmet mounted displays (Nelson et al., in press).

Given the impressive body of psychoacoustic and human factors research that has been gathered over the past decade, one might be tempted to conclude that there is sufficient scientific evidence supporting the incorporation of virtual 3-D audio technology into tactical cockpits. However, an important set of empirical studies - namely, research that addresses the effectiveness of 3-D audio displays when operators are exposed to high levels of sustained acceleration - remains to be done. To be sure, advances in aircraft performance and weapons technology require that pilots adopt tactics that result in prolonged exposure to extreme accelerative force. As reviewed by Johnson and his colleagues (1998), exposure to high levels of $+G_z$ has been shown to produce numerous physical and perceptual maladies, including, but not limited to, loss of consciousness, visual loss, cardiac arrhythmias, and vestibular malfunctions. In addition, exposure to high levels of linear acceleration has been shown to degrade auditory acuity (Barer & Grishanov, 1976; Grishanov, 1976) and may cause cochlear damage (Johnson, Allen, Schultz, Liening, & Bell, 1998).

Present Investigation

Given the evidence just described, it is reasonable to expect that exposure to high levels of sustained acceleration may negatively affect one's ability to localize virtual auditory cues. Toward that end, the purpose of this initial investigation was to assess the effects of high $+G_z$ exposure on the localization of a virtual sound source.

METHOD

Participants

Seven men and one woman from the Air Force Research Laboratory's Acceleration Subject Panel, ages 23 to 30, served as paid participants. Audiometric testing indicated that four of the participants had normal hearing (Goodman, 1965), while four had a mild ($\leq$ 10 dB HL) unilateral loss at 6 KHz. All participants had normal localization acuity and had prior experience with sustained acceleration experiments.

Experimental Design

A 6 (G LEVEL) x 3 (BLOCK) within-subjects design was employed to assess the effects of sustained acceleration on participants' ability to localize virtual auditory cues. The six levels of the G LEVEL factor were 1.0, 1.6, 2.5, 4.0, 5.6, and 7.0 $+G_z$. Data collection sessions were organized into blocks of 24 localization trials - an entire block of trials was collected at each G level. Over the course of the experiment pariticpants completed three BLOCKs at each of the six G levels. Participants completed four blocks of trials per experimental session. The order of the blocks was determined using a Latin square design with the constraint that either a 1.0 $+G_z$ or a 1.6 $+G_z$ practice block occurred during each experimental session. Dependent variables included average localization error (degrees) and the percentage of trials which resulted in a reversal.

Apparatus and Procedure

Virtual Sound Source Localization. Spatialization of the signals was achieved using an Air Force Research Laboratory four-channel 3-D Auditory Display Generator (3-D ADG). The 3-D ADG, illustrated in Figure 1, uses the techniques of digital signal processing to encode naturally occurring spatial information in an audio signal and present the resulting "spatialized" image over stereo headphones (Sennheiser HD-560). This encoding is accomplished via digitally filtering a sound source by means of an FIR filter created from measurements of a human's head-related transfer functions (HRTFs), which represent the direction-dependent modification of a sound source by the person's head, torso, and pinnae (see Wightman and Kistler, 1997, for a review of HRTFs). For the purposes of this experiment, HRTFs were measured at 1° increments in the horizontal plane. The spatialized auditory cues - band-limited, pulsed pink noise - were presented binaurally via a set of active noise reduction headphones, and were generated so as to be perceived as emanating from varying positions in the horizontal plane (see Figure 2). Active noise reduction headsets were used to compensate for the relatively high levels of ambient noise in the cab of the centrifuge (noise levels were found to be approximately 92 dB(A) inside the cab and did not vary as a function of G level). Due to electro-magnetic interference in the cab of the DES centrifuge, head-position tracking was not used in this experiment.

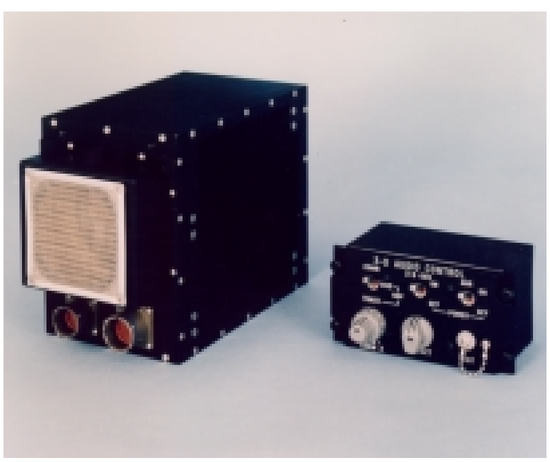

Figure 1. The Air Force Research Laboratory's 3-Dimensional Auditory Generator was used to generate virtual auditory cues that appeared to emanate from various locations along the horizontal plane.

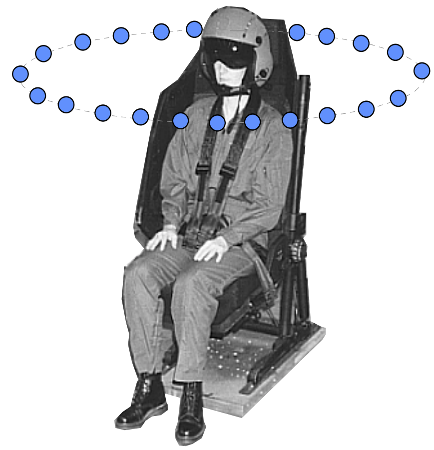

Figure 2. An illustration of a participant in the cab of the DES centrifuge. Virtual auditory cues were presented binaurally via active noise reduction headphones under varying levels of $+G_z$. Participants indicated the perceived location of the virtual auditory cues by marking its location on a computer generated display.

Acceleration Facility. The Dynamic Environment Simulator (DES), depicted in Figures 3, is a man-rated, three-axis centrifuge used to simulate the acceleration stresses encountered by pilots.

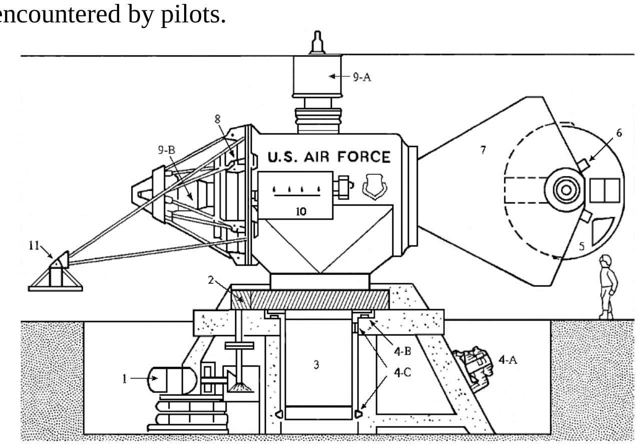

Figure 3. The Air Force Research Laboratory's Dynamic Environment Simulator centrifuge. (1) main arm drive motor; (2) drive pinion; (3) main rotating trunion and bull gear; (4a) hydraulic pumps; 4(b) thrust pad; (4c) upper and lower radial pads; (5) cab; (6) cab drive motor; (7) fork; (8) fork drive motor; (9a) main arm slip rings; (9b) fork slip rings; (10) motor driven counterweight; (11) aft-mounted platform.

The DES has a radius of 5.8 m to the center of the large spherical cab and can create a force of 20 G at the rotational velocity of 56 RPM. The control system uses a digital computer and provides for automatic, manual, or closed-loop modes of operation. Typical uses for the DES facility include the investigation of the effects of sustained G forces on pilot performance, the definition of physiological changes, the development of more effective anti-G equipment and tactics, the provision of specialized training, and the testing and evaluation of hardware

Procedure. Upon arrival at the DES facility, participants donned a g-suit and a flight helmet equipped with an active noise reduction headset connected to the AFRL 3-D ADG. Positive pressure breathing was not employed in this investigation. Next, participants were brought to a specified $+G_z$ level and completed 24 auditory localization trials. The spatial locations of the auditory targets were randomly selected with the constraint that an equal number of auditory targets appeared in each quadrant of the horizontal plane (e.g., 0°-90°, 90°-180°, 180°-270°, and 270°-360°). During each trial, participants listened to the virtual auditory cue and indicated its perceived location on a computer generated display. More specifically, participants used a right-hand knob to rotate a radius vector through an angle corresponding to the perceived azimuth of the sound source. Participants received feedback - the correct location of the virtual auditory cue - after each trial. In order to ensure familiarity with the localization task and the response procedure, participants completed a minimum of three blocks of localization trials outside of the DES centrifuge. Two additional blocks of practice trials were completed in the DES centrifuge prior to the collection of the experimental data.

RESULTS

Localization Error

Average localization errors (degrees), corrected for reversal errors (i.e., occasions in which a sound source presented in the front hemifield is perceived to emanate from the rear hemifield and vice versa; see Wightman & Kistler, 1989), were calculated for each block of trials and submitted to a 6 (G LEVEL) x 3 (BLOCK) repeated measures analysis of variance. The analysis revealed a significant main effect for G LEVEL, $F(5,35) = 8.53$, $p<.05$; however, all other sources of variance lacked significance. The G LEVEL main effect is illustrated in Figure 4, which shows that increases in G LEVEL were accompanied by modest increases in localization errors - approximately 1.5°/$+G_z$. The G LEVEL main effect was further investigated with pairwise comparisons (*t*-tests with adjusted α-levels), which indicated that while localization error at 7.0 $+_{Gz}$ was significantly greater ($p<.01$) than at 1.0, 1.6, 2.5, and 4.0 $+G_z$, localization errors at each of the other $+G_z$ levels were not significantly different from each other.

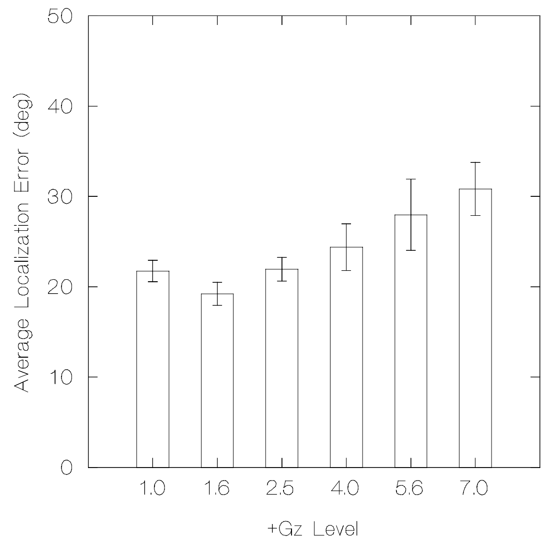

Figure 4. Average localization error (deg) across all $+G_z$ levels. It can be seen in the figure that increases in $+G_z$ level are accompanied by modest increases in localization error.

Reversal Error

The percentage of trials that resulted in a reversal error was calculated for each experimental condition and subjected to a similar 6 (G LEVEL) x 3 (BLOCK) repeated measures analysis of variance, which indicated a significant main effect for BLOCK, $F(2,14) = 8.97$, $p<.05$. The percentage of trials that resulted in reversal errors for blocks I, II, and III were 23.18, 26.49, and 29.25, respectively. More importantly, all effects involving the G LEVEL factor lacked statistical significance. This latter result is illustrated in Figure 5, which shows that the percentage of reversal errors did not vary with increases in $+G_z$ level.

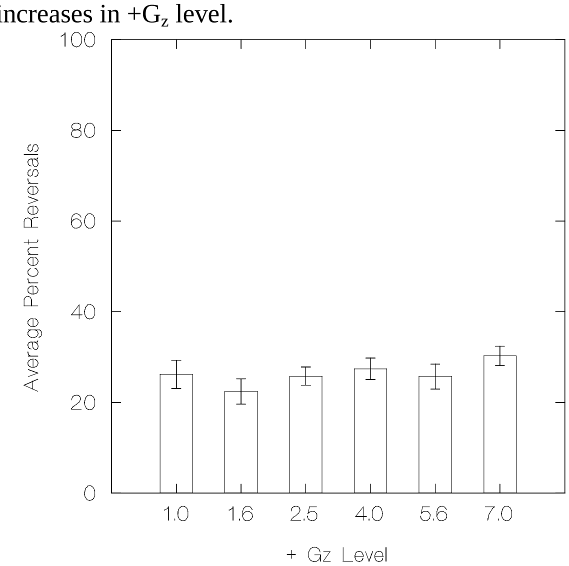

Figure 5. Average percent reversals are plotted under each level of $+G_z$. It can be seen in the figure that reversal "confusions" did not vary as a function of $+G_z$ level.

CONCLUSIONS

The results reported herein indicate that one's ability to localize virtual auditory cues in the horizontal plane is well-maintained under exposure to high $+G_z$ forces. Both metrics of performance efficiency - average localization error (see Figure 4) and percentage of reversal confusions (see Figure 5) - indicated that, in general, increases in $+G_z$ level were ***not*** accompanied by appreciable reductions in the listener's ability to localize virtual auditory cues in the horizontal plane. In fact, statistically significant increases in average localization error did not occur until participants were exposed to 7.0 $+G_z$. In addition, both the magnitude of localization errors and the percentage of reversal confusions were found to be consistent with results reported by Valencia, Calhoun, Ericson, and Agnew (1990) who employed a similar localization task and response procedure at 1.0 G. These outcomes provide strong empirical evidence that one's ability to localize virtual auditory cues will not be degraded significantly in high $+G_z$ environments. Accordingly, it does not appear as though the efficacy of virtual 3-D audio interfaces will be compromised by the extreme accelerations to which pilots are subjected in modern tactical air combat environments.

ACKNOWLEDGMENTS

Portions of this research were sponsored by the Air Force Office of Scientific Research. The authors wish to acknowledge the technical contributions of Steve Bolia, Ron Dallman, Dennis Allen, and David Ovenshire of Veridian, Dayton, OH.

REFERENCES

Barer, A. S. & Grishanov, V. E. (1976). Aeyrwbjyfkmyjt cjcnjzybt fyfkbpfnjhf xtkjdtrf ghb ecrjhtybb $+G_x$ [Functional state of the human auditory analyzer following $+G_x$ acceleration]. *Rjcvbxtcrfz <bjkjubz b Fdbfrjcvbxtcrfz Vtlbwbyf* 10%41-47.

Begault, D. R. (1993). Head-up auditory displays for traffic collision avoidance system advisories: A preliminary investigation. *Human Factors*, *35*, 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*, 79-93.

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

Calhoun, G. L., Valencia, G., & Furness, T. A. (1987). Three-dimensional auditory cue simulation for crew station design/evaluation. *Proceedings of the Human Factors Society's 31st Annual Meeting* (pp. 1398-1402). Santa Monica, CA: Human Factors Society.

D'Angelo, W. R., Bolia, R. S., McKinley, R. L. & Perrott, D. R. (1997, June). Auditory guided search with visual distractors. *Paper presented at the 134th Meeting of the Acoustical Society of America.* State College, PA.

Doll, T. J. (1986). Synthesis of auditory localization cues for cockpit applications. *Proceedings of the Human Factors Society's 30th Annual Meeting* (pp. 1172-1176). Santa Monica, CA: Human Factors Society.

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. 593-609). Mahwah, NJ: Lawrence Erlbaum Associates.

Furness, T. A. (1986). The super cockpit and its human factors challenges. *Proceedings of the Human Factors Society 30th Annual Meeting* (pp. 48-52). Santa Monica, CA: Human Factors Society.

Goodman, A. (1965). Reference zero levels for pure-tone audiometer. *American Speech and Hearing Association, 7*, 262-263.

Grishanov, V. E. (1976). Bccktljdfybt cke[jdjq aeyrwbb ghb gjgthtxyj yfghfdktyyjv ecrjhtybb. [Study of auditory function following transverse acceleration]. Abpbjkjubz xtkjdtrf 2%247-252.

Johnson, R. E., Allen, J. R., Schultz, T., Liening, D. A., & Bell, A. F. (1998). The effects of linear acceleration on distortion product otoacoustic emissions in human ears. *Aviation, Space, and Environmental Medicine*, *69*, 40-44.

Koehnke, J., Besing, J. M., Abouchacra, K. S., & Tran, T. V. (February, 1998). Speech recognition for known and unknown target message locations. Presented at the *1998 Mid-Winter Meeting of the Association for Research in Otolaryngology*. St. Petersburg, FL.

McKinley, R. L., Ericson, M. A., D'Angelo, W. R. (1994). 3-dimensional auditory displays: Development, applications, and performance. *Aviation, Space, and Environmental Medicine*, *May*, 31-38.

Nelson, W. T., Ericson, M.A., Bolia, R. S., & McKinley, R. L. (1998). Monitoring the simultaneous presentation of spatialized speech signals in a virtual acoustic environment. *Proceedings of the 1998 IMAGE Conference* (pp. 1-8) Chandler, AZ: The IMAGE Society, Inc.

Nelson, W. T., Hettinger, L. J., Cunningham, J. A., Brickman, B. J., Haas, M. W., McKinley, R. L. (in press). The effects of localized auditory information on visual target detection performance using a helmet-mounted display. *Human Factors*.

Perrott, D. R., Cisneros, J., McKinley, R. L., & D'Angelo, W. R. (1996). Aurally aided visual search under virtual and free field listening conditions. *Human Factors, 38,* 702-715.

Ricard, G. L., & Meirs, S. L. (1994). Intelligibility and localization of speech from virtual directions. *Human Factors*, *36*, 120-128.

Stinnett, T. A. (1989). Human factors in the super cockpit. In R. Jensen (Ed.), *Aviation psychology* (pp. 1-37). Brookfield, VE: Gower Publishing.

Valencia, G., Calhoun, G., Ericson, M. A., & Agnew, J. (1990). Localization performance with synthesized

directional audio. *Technical Report No. AAMRL-TR-90-025*.
Wenzel, E. M. (1992). Localization in virtual acoustic displays. *Presence*, *1*, 80-106.
Wightman, F. L., & Kistler, D. J. (1989). Headphone simulation of free-field listening. II: Psychophysical validation. *Journal of the Acoustical Society of America*, *82*, 868-878.