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Release from Masking in Virtual Auditory Space During Sustained Positive Acceleration

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ORIGINAL RESEARCH

Release from Masking in Virtual Auditory Space During Sustained Positive Acceleration

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Background: The use of a three-dimensional (3-D) auditory display to significantly lower subject detection level while maintaining comprehension under sustained positive G-stress was explored in this study ***Methods:*** Auditory threshold levels were measured for detecting a band limited pulsed signal in the presence of a broadband diotic masker at both $+1$ G_z (rest position) and under sustained $+3$ G_z. The pulsed signal was presented diotically and was spatialized at one of four static azimuth positions on the horizontal plane. ***Results:*** Results showed that auditory thresholds were not significantly affected by sustained $+3$ G_z stress. Compared with a diotic presentation, subjects reached an average of 6.8 dB lower auditory threshold at $+1$ G_z and under sustained $+3$ G_z when the pulsed signal was spatialized at a static position of 90° azimuth on the horizontal plane ***Conclusion:*** The implication of these results and suggestions for further research are discussed.

Keywords: auditory thresholds, 3-D audio display, sustained positive acceleration.

ONE OF THE CURRENT STRATEGIES to combat erroneous visual and vestibular cues associated with spatial disorientation is to instruct pilots to follow accepted instrument cross-check procedures during flight. However, vision can be degraded in circumstances such as high visual workload, limited ambient light, vibration, and hypoxia. Dimming, peripheral light loss, greyout, and blackout during increased $+G_z$ acceleration have been documented (2). There is also a significant decrease in visual pursuit performance in the centrifuge at frequencies greater than 0.4 Hz during sustained $+3$ G_z acceleration (7). Given the limitations of vision under sustained positive acceleration the use of other senses to prevent and recover from spatial disorientation, a major contributor to aviation accidents (8,15), needs to be explored. In particular, the auditory sense needs to be further investigated. This study addressed whether subjects who are under sustained $+3$ G_z can reach a significantly lower auditory threshold using a 3-D audio display compared with a diotic (the same sound presented to both ears) presentation. A sustained $+3$ G_z level was chosen in order to avoid introducing the complication of blackout or G-induced loss of consciousness (G-LOC) given that all but two of the subjects in this study had not experienced increased positive acceleration. From an operational perspective, exposure to $+4$–7 G_z is brief (in seconds) while exposure to sustained $+2$–3 G_z is more prevalent and of longer duration (e.g., during prolonged banking in high performance jets).

A 3-D auditory display has been explored both independent of and in combination with visual cues to provide orientation (1). It has been proposed that a 3-D auditory display can support situational awareness and spatial orientation by providing veridical spatial cues to the positions of targets, threats and beacons (10,14,23). This application is sometimes referred to as the "auditory radar display." During an inflight study, pilots reported that a 3-D audio display decreased target acquisition time and visual workload while increasing communication capability and situational awareness (18). The reception of visual cues requires that one's gaze be fixed in a certain direction, whereas the reception of audio cues carries no such limitation. Thus, auditory inputs could serve as concordant orientation cues to the pilot when visual input is limited or unavailable. Moreover, reaction time to auditory signals remains superior to that of visual signals for all levels of acceleration stress (5,25).

Recently Nelson et al. (19) investigated one's ability to localize virtual auditory cues on the horizontal plane under six levels of sustained $+G_z$ acceleration (1.0, 1.6, 2.5, 4.0, 5.6 and 7.0). They found that no significant increases in average localization error were made between $+1.0$ and $+5.6$ G_z. However, they did occur at the $+7$ G_z level. Sound localization is a measure of central auditory function, while hearing thresholds depend on peripheral (cochlear) processing of sound (16). Hence the study by Nelson et al. (19) is a test of central auditory function. If virtual auditory cues are to serve as auditory warnings (3,4,11), then their ability to be detected under sustained positive acceleration needs to be

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investigated. The effects of sustained positive acceleration on auditory thresholds (measures of peripheral processing of sound) in a 3-D audio display were investigated in this study.

METHODS

Subjects

There were seven paid subjects consisting of five females and two males, ranging in age from 20–44 yr (mean age was 28.3 yr), who participated in this study. All were medically screened and found to be in good general health. A Békésy audiometric test was administered to each subject. All had less than a 20 dB bilateral hearing loss at frequencies between 125 Hz and 8 KHz. One of the subjects had previously participated in psychoacoustics studies while two other subjects had previously been exposed to centrifugation at sustained + 3G_z. The DCIEM Human Ethics Committee approved the experimental protocol and informed consent was obtained from the subjects.

Human Centrifuge

The study took place in the DCIEM human centrifuge. The centrifuge consists of a rotating arm, which measures 6.1 m long from the center axis of rotation to the gondola. The gondola is passively coupled to the G_z vector and pivots on self-aligning trunnion bearings. During rotation, the gondola swings out freely so that the resultant vector of gravitational and centrifugal acceleration is always orthogonal to the floor of the gondola. Consequently, subjects inside the gondola experience an increased downward-pulling force aligned with their spine (z-axis) and achieve a +G_z centrifugation. In this study the resultant force either equaled the earth's gravitational pull (+1 G_z) with the gondola stationary, or exceeded it by a factor of 3 (+3 G_z). At +3 G_z, the gondola rotated at approximately 20 rpm. Subjects were seated and secured in the gondola facing the direction of rotation. The interior of the gondola was illuminated throughout the study.

Acoustic Stimulus

The acoustic stimulus consisted of pulsed white noise band limited from 12.5 Hz to 8 KHz and had an equal on-off duration of 100 ms without ramping. Care was taken to ensure that no transient characteristics were audible in the signal. A 5-s segment of the signal was digitally stored on the hard disk of a 486 personal computer (PC) that served as the host computer. This signal was spatialized in real-time through convolution with specialized filters termed head-related transfer functions (HRTFs). HRTFs encode the binaural and spectral cues used by humans in sound localization and discrimination. They are derived from a series of impulse measurements performed at the ears of an observer in response to a sound source placed at various locations in the vicinity of the head. The HRTFs used in this study were obtained from the Aeronautical and Maritime Research Laboratory, Melbourne, Australia.

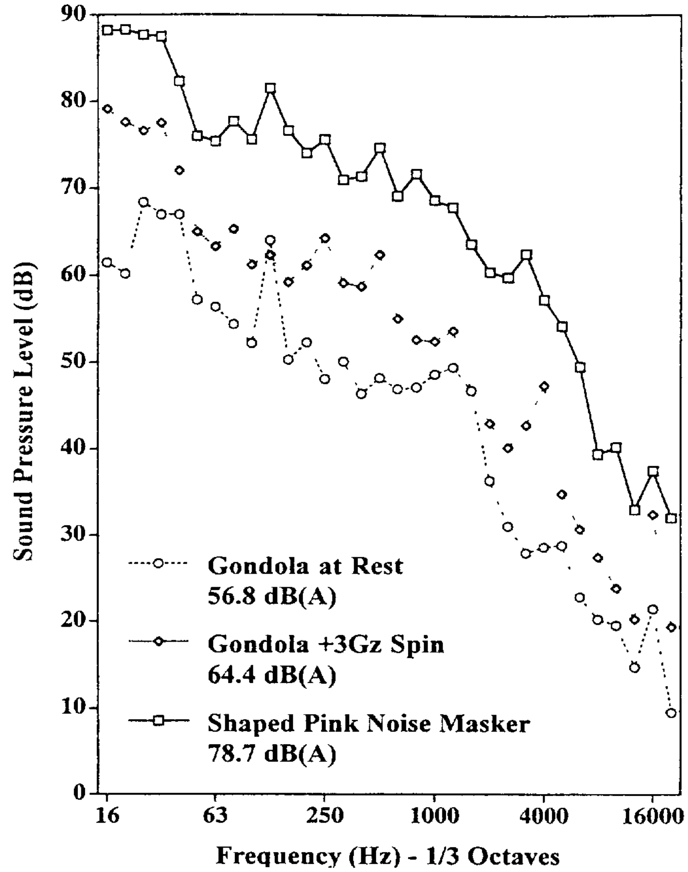

Fig. 1. Centrifuge noise frequency spectra

Their measurement technique and psychoacoustic validation is described in Pralong and Carlile (21), and Carlile and Pralong (6), respectively. The HRTFs were measured on an individual who was not a subject in this study.

Masking Signal

The pulsed signal was masked by continuous diotic noise. The amplitude and shape of the masker were selected to render the ambient noise in the gondola (stationary or in motion) inaudible to the subjects. To accomplish this, a wideband (16 Hz to 20 KHz) pink noise signal produced by a Brüel & Kjær model 1405 noise generator was shaped in a Brüel & Kjær model 5612 Spectrum Shaper and presented via headphones. The shape of the masker was closely aligned with that of the ambient noise measured at the subject's head position in the gondola by means of a Brüel & Kjær model 4145 1-in microphone and model 2231 digital signal analyzer. To achieve sufficient masking, the presentation level was approximately 14 dB above the A-weighted level of the ambient noise in the gondola. The spectrum of the noise masker in relation to the gondola ambient at rest and at sustained +3 G_z is shown in **Fig. 1**.

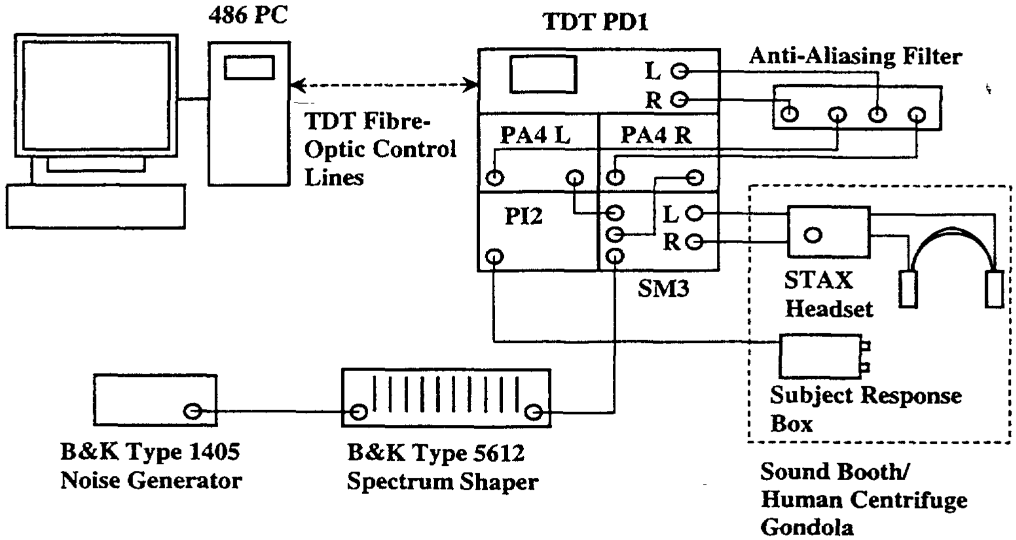

Fig. 2. Experimental apparatus.

Apparatus

The apparatus used in this experiment was a suite of digital and analog audiometric equipment manufactured by Tucker-Davis Technologies (TDT), Gainesville, FL, that was controlled by the host computer. This system was used for generating and presenting the auditory stimuli and for collecting responses from the subjects. A block diagram of the apparatus is shown in **Fig. 2**. The acoustic stimulus was spatialized using the TDT PD1 processor in conjunction with the HRTFs described above. The left and right channels from the PD1 processor were sent to a two-channel Kemo Type VBF/23 low-pass elliptic filter set to 8 KHz, in order to remove the alias products resulting from digital-to-analog conversion. For a diotic presentation of the pulsed signal the TDT PD1 was set to an inactive state so that the left and right channel signals were identical. The left and right channel filtered outputs were routed to two TDT PA4 programmable attenuators that were used to vary the amplitude of the pulsed signal. The diotic masking signal was mixed equally into the left and right outputs of TDT PA4s in a TDT SM3 stereo signal mixer, which in turn drove a Stax SRM-T1 headphone amplifier. The mixed signals were then presented over Stax electrostatic headphones (model SR- λ Signature).

Threshold Tracking

The subject's auditory threshold of the pulsed signal, with respect to the diotic masking signal, was measured using a modified Békésy tracking procedure. Subject responses were recorded using a custom-built button box that contained two paddle switches and was interfaced to the TDT system through a PI2 module. The response box (measuring approximately 11 cm X 7 cm X 3 cm) was secured to the subject's left thigh so the subject's left hand could be positioned comfortably over the paddle switches. This arrangement freed the subject's right hand to operate the gondola's "dead-man" switch. Subjects reported that they had no preference in handedness. The left-hand paddle switch of the subject's response box controlled the amplitude of the pulsed signal. Depressing the switch caused the amplitude of the pulsed signal to decrease, while releasing it resulted in an amplitude increase. Each subject was instructed to depress the left switch when the pulsed signal was audible over the masking noise and to release it when the signal became inaudible. At the beginning of the tracking procedure the pulsed signal was clearly audible over the masker (greater than 4 dB signal-to-noise ratio). The rate of change of the pulsed signal was 2 dB $\cdot$ s^{-1} until the occurrence of the first reversal (i.e., first "valley") was reached. At that point the rate was changed to 1 dB $\cdot$ s^{-1}. Although there was a potential range of 100 dB over which the amplitude of the pulsed signal could be varied, there was no more than a 20 dB difference between all consecutive reversals for each subject. The auditory threshold was taken as the average of the difference in the amplitude of the pulsed signal between the last three "peaks" and the last three "valleys" of each acoustic stimulus condition. The relative thresholds, representing the algebraic difference between diotic and spatial thresholds for each trial-type, were calculated from the raw thresholds.

Experimental Design and Procedure

A 4 (+G_z) level × 5 (acoustic stimulus) × 4 (session) within-subject repeated measures design was employed to assess the effects of sustained acceleration on the subject's auditory threshold in virtual acoustic space. The +G_z component comprised a single centrifuge run that consisted of the following: Pre (+1 G_z), Test (+3 G_z), Post1 (+1 G_z) and Post2 (+1 G_z). The acoustic stimulus was spatialized on the horizontal plane at the following static azimuth positions: 60°, 90°, 270° and 300°. In this paper, azimuth increases clockwise on the horizontal plane with 0° positioned directly in front of the listener. The acoustic stimulus was also presented diotically, which served as the control condition. Each of the five acoustic stimulus conditions was presented at every $+G_z$ level in a counterbalanced order across subjects and sessions. An analysis of variance (ANOVA) and Scheffé post hoc procedures were used to analyze the relative auditory thresholds.

All subjects were trained in threshold tracking in an Industrial Acoustic Company (IAC) double-walled sound-attenuating booth. The training session consisted of eight trials separated from one another by approximately 3 min. The duration of each training session was approximately 1 h. Subjects were given two training sessions. Naive subjects were also familiarized with the sensations of G-stress in the human centrifuge through one exposure to 3 min of sustained +3 G_z.

The threshold at each acoustic stimulus condition (diotic plus the four static spatial positions) was determined during each centrifuge run. An alerting signal in the headphones worn by the subject indicated the beginning of each acoustic stimulus condition. Subjects were then required to simultaneously press both paddle switches on the response box to indicate that they were ready to begin the trial. The time allotted for each acoustic stimulus condition was fixed at 40 s. On completion of one acoustic stimulus condition subjects proceeded onto the next, until all five were completed. The duration of each trial was approximately 4 min. The Pre, Test, Post1 and Post2 G_z trials during each session were separated by a 3 min rest period.

The subjects did not wear any anti-G garments. A gradual onset rate of 0.1 $G \cdot s^{-1}$ was employed until the gondola reached the target acceleration of +3 G_z. Approximately 1 min was required for the gondola to stabilize at +3 G_z and for the vestibular sensation of rotation to subside. Sustained +3 G_z was maintained for approximately 4 min (the duration of the test trial). At the end of the trial the subject was decelerated at 1 $G \cdot s^{-1}$. After the gondola returned to the rest position, Post1 and Post2 trials were administered. These two trials were carried out to separate the effects and aftereffects of hypergravity from purely time-related phenomena such as fatigue or learning. All subjects were able to perform the four consecutive trials without undue fatigue in a time span of approximately 25 min. Subjects participated in one practice session in addition to four experimental sessions. Each session was performed on a separate day. Performance feedback was not provided to the subjects but they were debriefed following the completion of the study. The subjects' heart rates were monitored continuously throughout the centrifuge sessions using a Marquette ECG system, Model Case 12 (Milwaukee, WI) to indicate $+G_z$-stress. A skull cap, attached by straps to the head rest of the gondola's seat, was worn by subjects to keep the Stax headphone securely in position over the ears under sustained +3 G_z and to stabilize the head.

RESULTS

The relative auditory thresholds at each spatial stimulus condition for the different trial-types averaged across subjects are shown in **Fig. 3**. As observed, the subjects' auditory thresholds were not significantly affected by sustained +3 G_z. Compared with a diotic presentation, subjects reached an average of 6.8 dB lower auditory threshold at +1 G_z and under sustained +3 G_z when the pulsed signal was spatialized at a static position of 90° azimuth on the horizontal plane.

The data reported in this study do not include the data collected during the two training sessions and the practice session in the human centrifuge. These sessions were designed to familiarize subjects with threshold tracking. The training and practice sessions' data revealed that all subjects learned the task well and produced consistent threshold measurements. The reported analyses do not include the data of subject 4, as this subject experienced G-LOC on the final +3 G_z trial However, results of analyses performed on the first three sessions for all seven subjects were essentially identical to the results reported for the six subjects across four sessions.

A three factorial within-subjects repeated measures design analysis of variance (ANOVA) showed that the relative auditory thresholds were not significantly affected by sustained +3 G_z, $F(3,15) = 1.98$, $p > 0.16$. However, there was a statistically significant effect of acoustic stimulus condition across-trial types, $F(4,20) = 24.04$, $p < 0.01$. As observed in Fig. 3, the greatest reduction in auditory threshold was 6.8 dB which occurred when the pulsed signal was spatialized at 90° azimuth. A Scheffé post hoc analysis at the 0.01 alpha level revealed no statistical significance between 90° and 270° azimuth. However, the thresholds at 90° and 270° azimuth were significantly lower than at the remaining acoustic stimulus conditions. Only the 60° azimuth condition was not statistically significant from the diotic stimulus condition. There was no significant effect of session.

The only significant interaction was trial-type × stimulus condition, $F(12,60) = 3.80$, $p < 0.01$. This interaction can be observed in Fig. 3. At each spatial stimulus condition, performance across the trial-types varied as much as 2 dB. However, the test trial-type that had the largest improvement was not consistent across the spatial stimulus conditions.

The heart rate measurements for each trial-type averaged across subjects and within-subjects were also analyzed. A two factorial (trial-type × session) within-subject repeated measures ANOVA revealed that the only statistical significance was trial-type, $F(3,12) = 40.04$, $p < 0.01$. A Scheffé post hoc analysis at the 0.01 alpha level showed heart rate measurements in the +3 G_z trial were significantly larger than in the other trials.

DISCUSSION

This study found insignificant effects of sustained +3 G_z on auditory thresholds when the stimulus was presented in a 3-D audio display on the horizontal plane. The magnitude of the auditory thresholds was found to be consistent with those collected in the two training sessions. Similarly, Nelson et al. (19) reported that the magnitude of localization errors and the percentage of reversals (i.e , perceiving the mirror image of the presented sound source) were consistent with the results reported in

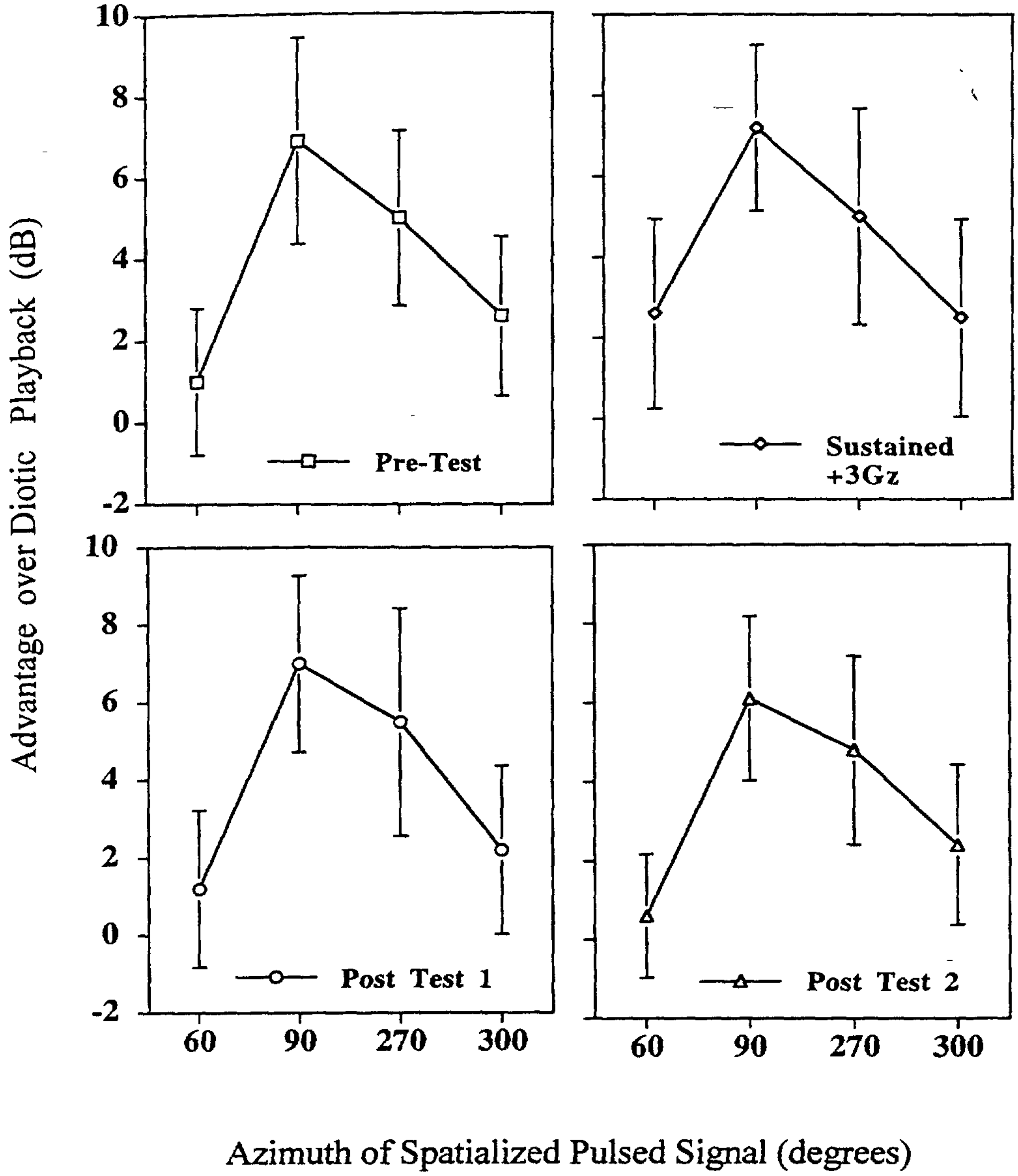

Fig. 3. Relative auditory thresholds for each trial-type. Data are averaged across sessions and subjects except subject 4. Standard error bars represent one standard deviation from the mean.

a study that employed a similar task at +1 Gz (24). The findings reported in the present study and from Nelson et al. (19) suggest that neither peripheral (cochlear) processing nor central auditory function are significantly effected by low levels of sustained acceleration.

The average relative 6.8 dB threshold reported in this study is consistent with threshold magnitudes collected at rest conditions in the free-field by Ebata, Sone and Nimura (12) and Saberi et al. (22). These studies have also shown that the effectiveness of a masker decreases as it is separated in space from the signal. Saberi et al. (22) for example, reported that subjects obtained a 7 dB lower auditory threshold level when the signal was positioned at 50° and 310° azimuth on the horizontal plane. Moreover, subjects in the present study reported that they perceived the virtual auditory cues at the four spatial positions in spite of using HRTFs that were not their own.

The findings reported in this study suggest that it is possible for pilots to detect auditory warnings in a 3-D audio display under sustained positive acceleration. Furthermore, the findings suggest that auditory warnings may be lowered in amplitude by as much as 6 dB compared with a diotic presentation. This represents an approximate 50% reduction in the acoustic amplitude of the stimulus. The overall amplitude level of the communication system can be reduced without sacrificing detectability. This would present many advantages. A lower headphone amplitude could reduce the risk of hearing loss. At present, the level of auditory warnings presented over the communication system used by aircrew is frequently too loud (20). Many of the existing auditory warnings disrupt thought and verbal communication among crewmembers (20). In addition, continuous loud sounds hold the crew's attention beyond the point where the problem has been identified, often incapacitating aircrew (20).

A possible explanation for the lack of a significant effect of sustained +3 G_z on auditory thresholds in a spatial auditory display is that sustained +3 G_z acceleration for 3–4 min has very little effect in inducing stagnant hypoxia. Hypoxia is unlikely under a short duration of sustained +3 G_z, as the brain contains sufficient oxygen reserves to function for several seconds in the absence of blood flow. However, no published data are available to substantiate these statements. In the present study the subjects experienced physiological stress during sustained +3 G_z as indicated by the significant increase in their heart rate measurements. None of the subjects reported sustained dimming of the visual field, and only subject 4 experienced G-LOC. The subjects reported in the study by Nelson et al. (19), who donned G-suits, also reported no sustained dimming of the visual field or G-LOC at the tested six +G_z levels. A significant effect of sustained positive acceleration on average localization error above 5.6 +G_z was found (19). However, it should be noted that average localization errors were corrected for reversals. For example, a sound source presented in the front hemisphere could be perceived in the rear hemisphere. Such a reversal is referred to as a front-back confusion. It is common practice in localization studies to resolve reversals by coding the subject's response as if it was indicated in the correct hemisphere (26). Thus it is possible that G-stress might not have been significant on average localization errors if these errors were not corrected for reversals. In any event, the present study and that of Nelson et al. (19) suggest that moderate levels of sustained +G_z will not compromise virtual auditory cues.

There is a diminution in auditory acuity and reaction time at high +G_z levels (5,25). This may persist for some minutes after the cessation of G-stress (9). The +G_z level where this occurs is close to the level at which consciousness is lost. The two are nearly identical and can be treated as such (9,13). Moreover, exposures to sustained high +G_z have been shown to produce injury to the cochlea (17). Consequently, it would serve no purpose to investigate whether auditory thresholds in a 3-D audio display are significantly affected by sustained positive acceleration under conditions in which subjects are likely to suffer injury or G-LOC.

CONCLUSIONS

The environment in a modern military aircraft cockpit is highly dynamic and complex. Aircrews are often subjected to high workload and are required to maintain situational awareness while making quick decisions and prompt responses. The accurate detection of messages in the communication systems of military aircraft is critical especially under sustained acceleration. Spatial disorientation remains a major cause of life-threatening accidents during peacetime (8,15). The data presented in this study suggest that the efficacy of a 3-D auditory display for detecting auditory warnings in a spatial auditory display will not be compromised by the cardiovascular stress induced by modern tactical maneuvers at low G-levels. Continued research on localization in a 3-D auditory display under sustained +G_z is required. In particular, further research is required to investigate the limits of localization under sustained +G_z as misinterpreting the signals as reversals could lead to fatal conditions.

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