Audiogravic Illusion

Induced by Acceleratory Force Fields

by

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ABSTRACT

This thesis work investigates the audiogravic illusion induced in subjects when they are subjected to an acceleratory force field. The term “audiogravic illusion” refers to the effect on auditory localization in azimuth caused by the high force field. Although previous studies have indicated the presence of such an illusion, further investigation is required to devise ways to compensate for the illusion and thus lay the foundations for the use of auditory cues in combating spatial disorientation that occurs in such force fields.

Subjects are positioned a bed that is oriented perpendicular to the radius of the rotating room. Such an orientation will allow the rotation of the gravitoinertial force vector (GIF) in the azimuthal plane of the subjects’ heads as the room rotates. The gravitoinertial force vector is the resultant of the gravity and the centrifugal force due to the rotation. Subjects are asked to control the auditory spatial cues of a source presented over headphones so that the source appears to be straight ahead relative to the subjects’ heads. By controlling the speed of the room and the tilt angle of the bed, the magnitude and angle of the GIF can be controlled.

The results indicate that an increase in GIF magnitude with the angle from the median plane held constant requires a rightward shift of an acoustic stimulus for it to be perceived in the median plane. The degree of the required shift varies with the angle at which GIF is tilted away from the median plane. In general, it was observed that the degree of shift increases with increasing tilt of the GIF from the median plane.
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1. INTRODUCTION

1.1 GENERAL OBJECTIVE

Spatial disorientation (SD) in flight leads to many flight disasters every year. The acceleratory force fields in the aerial environment introduces novel features that are unknown to our sensorimotor systems. SD in flight may involve misperceived orientation of one's own body, of the aircraft, of isolated visual objects, or of the entire visual panorama. Accordingly, prior work on alleviating SD have focused primarily on the visual system, on the vestibular system, and on non-vestibular kinesthesia, as well as on interactions among these systems. In contrast, this project explores the use of auditory stimulation to reduce SD by providing the aircrew members with orientation information coded in non-speech auditory signals. The use of the auditory channel for SD reduction may be substantially more effective than the use of additional or modified visual displays because of differential effects of acceleratory forces on these two sensory modalities and simply because of "visual overload".

In order to assess the feasibility of combating the SD problem with auditory localization and to develop an operational system that makes use of auditory-localization cueing, it is necessary to determine the extent to which and the manner in which auditory localization is affected by inertial changes and acceleratory force fields. Furthermore, the effects of acceleratory force fields on other signal parameters such as pitch, loudness, and subjective duration must also be studied since an effective auditory cueing system is likely to require the use of such parameters as well. However, initial work will focus primarily on the perception of sound source direction, and more specifically on the perception of sound source azimuth (normally determined primarily by inter-aural differences in phase and amplitude). Furthermore, in order to obtain information that is suf-
ficiently analytic to facilitate development of models that can be used to reliably predict performance under a wide variety of circumstances, it is necessary to first examine the influence of acceleratory fields on auditory perception without any background interference and visual inputs.

There are a variety of visual and postural illusions that occur during angular and linear acceleration. The oculogyral illusion occurs during angular acceleration and refers to apparent displacement of visual objects in the direction of acceleration; the oculogravic illusion refers to the apparent tilt of the visual field experienced during exposure to a gravitoinertial force field greater than 1 g. The somatogyral and somatogravic illusions are the postural counterparts of the oculogyral and oculogravic illusions. These illusions represent examples of spatial disorientation that this project hopes to combat by providing veridical orientation information via auditory cues.

Past studies have demonstrated audiogyral and audiogravic illusions comparable to oculo- gyral and oculogravic illusions. During and after rotation about their body axis, subjects misjudge the position of a sound source that is always stationary in regard to their body. The displacement components of this audiogyral illusion are in the opposite direction to those of the oculogyral illusion. Studies have also shown that the displacements in auditory localization that occur during rotation of the visual field and physical rotation of the subject are opposite in sign. Similarly, an analogue of the oculogravic illusion in the auditory domain, audiogravic illusion, has also been studied to some extent.

This thesis work primarily investigates the audiogravic effects on subjects subjected to gravitoinertial force. The experiments examine the influence on head-relative localization of the same set of acoustic stimuli during exposure to different linear accelerations of the whole body in a centrifuge. It has been known that interaural timing, phase and amplitude spectra are especially
important for judging the angle relative to the median plane of the head (azimuth) of a single broadband sound. The transformations produced by a sound passing through the air and interacting with the head and pinna can be described with a single linear filter, called the head-related transfer function (HRTF). Pairs of HRTFs for the two ears have been measured for a range of sound source directions, and this set of HRTF pairs filtering broad spectrum sound have been shown to provide potent cues for localizing sources relative to the head.

1.2 NORMAL AUDITORY LOCALIZATION

In normal environment, the direction of an isolated sound source is determined primarily by comparing the signals received at the two ears to determine the interaural amplitude ratio and the interaural phase difference as a function of frequency. For high frequency signals, interaural amplitude ratio provides the dominant cue while interaural phase difference provides the dominant cue for low-frequency signals. At low frequencies, the effects of head shadow are relatively small because of diffraction; at high frequencies, measurement of time delay suffers from phase ambiguities unless there is sufficient bandwidth to eliminate these ambiguities. Therefore, for wide band signals, interaural phase difference also plays a significant role at high frequencies.

Head movements and monaural processing provide additional cues for sound source localization. Changes in auditory cues with head movement can differentiate between source positions that give rise to very similar binaural cues. These are positions directly in front of and directly behind the listener. Directional information from monaural processing is obtained by estimating properties of the direction dependent filtering of the transmitted signal that occurs when the transmitted signal propagates from the signal source to the eardrum. However, monaural information depends strongly on the listener’s a priori knowledge of the source spectrum and the existence of high-frequency energy in the signal so that the listener’s pinnae can have a strong directional
effect on the spectrum of the received signal.

In environments where there are reflections such as echoes and reverberation, sound source direction identification tends to be degraded. However, this degradation is limited by the tendency of the auditory system to enhance perception of the direct acoustic wave and suppress the late arriving echoes.

Perception of sound source distance is poor even in normal settings. The ability to determine the distance of a sound source is based on three changes in the received signal as source distance is increased: a decrease in intensity, an increase in high frequency attenuation, and an increase in the ratio of reflected to direct energy. Since all of the above cues are influenced by factors other than distance, distance perception is poor. Although distance perception is poor, sound sources are perceived to be located outside the head under normal circumstances. In-head localization becomes a problem only in special circumstances, such as when sounds are presented through earphones.

1.3 BACKGROUND

Clark and Graybiel (1949) demonstrated an illusion in the auditory realm analogous to oculogyral illusion. During and after rotation about their body axis, subjects misjudge the position of a sound source that is always stationary in regard to their body. During the subject's initial acceleration, he or she hears the sound move off in the direction opposite rotation. After rotation, there is a consistent tendency for sounds to be heard too far in the direction of previous body rotation.

It has also been known that head movements can play an important role in the localization of sound. Wallach (1940) showed that head movements enable a blindfolded subject to determine accurately the locus of a sound source because the pattern of change in the auditory cues at his
ears, in conjunction with knowledge of the direction and extent of his head movement, are sufficient to uniquely specify source location. For instance, the auditory cues at a subject's ears, resulting form a sound source in front of him and 30 degrees to the left of his median plane are the same as those generated by a sound source in back of his head at an angle 30 degrees to the left. However, if the subject turns his head to the left, the arrival times and intensities of the sound at his ears will tend to be equalized if the sound source is in front but the interaural differences will tend to increase if the sound source is in back.

Graybiel and Niven (1951) used a centrifuge to demonstrate that auditory localization in azimuth is affected by linear acceleration, the audiogravic illusion. Radial centrifugal forces combine with gravity to generate a resultant gravitoinertial force (GIF) vector greater than either component and oriented between the two. The resultant rotates around a subject who is held in a fixed orientation relative to the centrifuge axis, and subjects tend to orient relative to it. Graybiel and Niven fixed observers facing the axis of a centrifuge and had them lean over 90 degrees laterally so that rotation of the GIF would occur in azimuth during rotation. They placed a ring of speakers around the head in azimuth and asked subjects to select the (unseen) speaker that appeared to emit a click in the apparent horizontal plane. When the centrifuge was still and the head's median plane was horizontal, the subject chose a speaker located straight ahead. During rotation, the subject was reoriented laterally with nose-up relative to the gravitoinertial horizontal, and perceived the nose-up attitude change and chose a speaker below the median plane. The magnitude of change in selected sound source was about 76% of the angular displacement of the GIF up to 29.2 degrees, for auditory settings in the apparent horizontal plane, 15 degrees and 30 degrees above it and 15 degrees below.

Howard and Templeton (1966) and Howard (1981) deny that this effect is a meaningful
audiogravic illusion, calling it simply constant orientation relative to a changed external, gravito-inertial reference frame. According to this explanation, only 76% of the change in GIF orientation was registered by the subjects; in other words, the GIF had rotated 29.2 degrees but the subjects registered and compensated for only 22.2 degrees. However, the failure of the auditory setting to change exactly as much as the orientation of the GIF could be due to mislocalization of the sound relative to the head, which qualifies as a true audiogravic illusion. For example, if the GIF tilted 29.2 degrees relative to a subject and a sound actually at 22.2 degrees of azimuth were heard as being at 29.2 degrees, then the subject would only compensate 76%.

A series of initial experiments have indicated that a change in the magnitude and azimuthal orientation of \( G \) produces an auditory localization shift in the same plane. Subjects that were subjected to a 2.0 g force field inclined 60 degrees to subjects’ right perceived as straight ahead (in the median plane) sounds that were heard to their right when they were stationary. In another set of experiments, subjects prepositioned 60 degrees in 1.0 g (so that during rotation the 2.0 g force field would be parallel to median plane) showed no difference in auditory settings from that in 1.0 g with the body earth horizontal. The second set of experiments indicate that change in \( G \) magnitude without a change in \( G \) orientation is not sufficient to produce an auditory localization shift. A third set of experiments run in normal 1.0 g conditions showed no effect of tilt on sound localization, thus indicating that change in azimuthal orientation relative to normal 1.0 g field is not sufficient to produce an auditory localization shift.

The above experimental results show that a combination of both a change in magnitude and a change in azimuthal orientation of \( G \) is required to produce an auditory localization shift. The nature of the dynamics of this relation is yet to be studied. This thesis work will investigate this relationship by running a series of experiments in which subjects are exposed to acceleratory
force fields that are greater in magnitude than 1 G and that are inclined at various angles to the
median plane.
2 METHODS

2.1 EXPERIMENTAL APPARATUS

The experimental apparatus used in this project allow a finer degree of control and larger range of acoustical and acceleratory stimuli to be used than in previous studies of vestibular-auditory interactions. Auditory signals will be generated by acoustical virtual-environment technology and presented over headphones. Acceleratory stimulation will be generated through the use of a large, computer-controlled, rotating room.

The experiment was performed in the rotating room in the Graybiel Laboratory at Brandeis University. The room is an approximately circular enclosure 6.7 meter in diameter riding on a 7 ft. diameter central bearing. The room is powered by electric motors and a dedicated controller with a computer interface that permits the programming of virtually any angular velocity profile. The onboard equipment includes a tiltable bed with a system for restraining a subject, a system for generating spatial sound sources, and a joystick which can be used for subject responses.

The bed was constructed to hold the subject supine, with the long body axis tangent to the walls of the room, 2.5 meter from the center of the room, and the right ear toward the center. The bed includes a stiff, tight fitting foam mold that surrounds the back and sides of the head, with elastic straps across the forehead. The rest of the body was supported beneath with a stiff foam pad and from above with foam lined straps with Velcro closures. The tilting bed is controlled by a motor system capable of tilting the bed in the axis along which the gravitoinertial vector changes with room rotation. Since the sound source localization in azimuth is expected to be affected by rotation of the gravitoinertial force field in azimuth, the bed is built to hold the subject’s long axis tangent to the wall of the room and to tilt in azimuth.
A Crystal River Convolvotron II board was plugged into a PC to create the acoustic signals that were presented over earphones to the subjects. The input to the system was a continuous, single channel Gaussian white noise (500 Hz - 20 kHz) from a Sony digital audio tape (DAT) player. Inside the Convolvotron resides a set of filter pairs (HRTFs) containing all the spatial cues normally present in the signals reaching the ears from sources at different positions around an average listener’s head. The PC in which the Convolvotron resides selects the HRTF pair for the Convolvotron to use at every point in time and also gates the output. Gating permits the spatialized white noise signal to be square-wave modulated (4 Hz), which provides more salient auditory localization cues, and to be turned on and off at the appropriate times in an experimental run. The Convolvotron generates signals for the left and right ears by convolving the input signal with the pair of filters associated with the desired location of the simulated sound. This stimulus could be adjusted by the manipulation of a multi-purpose joystick to the PC through an A/D converter. When the subject applies isometric torque to a sleeve around the handle of the joystick, the PC instructs the Convolvotron to increment the azimuthal angle of the HRTF pair. Holding constant torque moves the acoustic signal at set speed, and releasing torque stops it.

The HRTF pair in the Convolvotron are minimum phase, i.e. the phase lag of these filters is the smallest possible among all filters which have the same magnitude response. Minimum phase filters have the shortest possible impulse response, which is desirable for real-time processing. The minimum phase HRTFs are supplemented by an interaural delay, which adjusts the overall filter characteristic so that its group delay accurately reproduces the differential delays between sounds arriving at the closer and more distant ears.

Distance from the center of the head to the localized source is modeled via an atmospheric absorption filter and spreading loss gain coefficient. This filter is applied before the HRTF filter-
ing, and can be augmented or disabled to simulate different atmospheric conditions. To provide smooth dynamics, samples are overlapped. Extra samples are computed at the end of each block, and are overlapped into the next block, insuring smooth transitions in case of head or source motion.

The joystick, in addition to being used to control the auditory stimulus as described above, was used in a different mode to provide for haptic indications of the head's perceived median plane. An adjustable cantilever anchored on the bed positioned the whole joystick so that a pivot at one end of the handle was in the mid-sagittal plane, and the subject could comfortably grasp it and align it with the head's perceived median plane. A potentiometer and associated circuitry connected to the A/D board registered joystick position. All tactile cues about joystick position were removed, and sufficient friction was added to the pivot to prevent haptic discrimination of the pendant or anti-pendant positions of the handle. A thumb switch at the free end of the joystick could be depressed to indicate when the subject was satisfied with an auditory or haptic setting.

2.2 EXPERIMENTAL SETUP

In the only previous investigation of audiogravic effects (Graybiel and Niven, 1949) subjects matched the location of an acoustic source with the apparent horizon. In addition, subjects were subjected to gravitointertial vectors \( G \) up to only 1.14 \( g \) in magnitude, causing a displacement of the resultant vector by 29.2 degrees.

In the experiments performed in this project, the magnitude of \( G \) ranged up to 2.0 \( g \), causing a displacement of the resultant vector by 60 degrees. The size of the resultant force is closer to those experienced by pilots in-flight. Positioning subjects on the bed which was oriented perpendicular to the radius of the rotating room allowed us to rotate the gravitoinertial vector \( G \) in the azimuthal plane of the subjects' heads. As the room rotates, gravity and centrifugal force \( (F_{\text{cent}}) \)
which is proportional to the square of the room angular velocity, combine to produce a gravitoinertial force, as illustrated in Figure 1. The magnitude and direction of this force depends on the angular velocity of the room. As the room accelerates, the magnitude of the GIF increases while its direction moves away from the median plane. In all the auditory localization experiments, the subjects are asked to control the auditory spatial cues of a source presented over headphones so that the source appears to be straight ahead relative to the subject's head. This response method differs from that used by Graybiel and Niven (1949) in that localization is to be judged relative to the listener's head rather than to the apparent horizon or some other exocentric reference.

\[
\text{Gravitoinertial Force (GIF)} = g^2 + F_{\text{cent}}^2
\]

\[
\angle \text{GIF} = \arctan \left( \frac{F_{\text{cent}}}{g} \right)
\]

*Figure 1. Gravitoinertial Force*

In addition to responding by controlling the auditory spatial cues, the same conditions were run with subjects responding by pointing the manual control to the apparent direction of straight ahead. These results allow us to compare the effects of changes in the resultant force vector on auditory localization cues with those on felt position cues. Both the auditory localization experiments and the manual pointing experiments were performed with subjects blindfolded.

### 2.3 PROCEDURE

Blindfolded subjects placed supine on the tilting bed were asked to make auditory and haptic settings to the median plane of their head in two separate sets of runs in which the magnitude and orientation of GIF was manipulated. Each set has five runs with identical GIF magnitude
but varying orientation achieved by tilting the bed to different angles. All runs have the same five phases in which the subject is always kept at an orientation such that the GIF is set at a fixed angle off the subject’s median. In the pre-rotation phase, the room is stationary for 100 sec providing a normal, 1 g force in the set angle. In the second phase, the room is accelerated for 150 seconds such that the GIF magnitude increases linearly. In the third phase, the room kept at 150 degree/sec for 100 sec. In the fourth phase, the room is decelerated at the same rate for 150 seconds until it comes to a stop. At the peak angular velocity of 150 degrees/sec, the resultant GIF is 60 degrees right of the earth vertical and has a magnitude of 2.0 g. During the final phase, the room is kept stationary for 200 sec. Figure 2 illustrates the velocity and lGl profile of the room.

![Figure 2. Room Velocity and Gravitoinertial Force (GIF) Profile](image)

As the room accelerates, the bed tilts such that the angle between the subject’s median plane and the GIF orientation remains constant. This setup is illustrated in Figure 3. Five runs with different angles (0, 15, 30, 45, 60 degrees) between the subject’s median and the GIF are carried out in each set of experiments. During the run when the angle is 0 degrees, the bed is earth
horizontal in the pre-rotation phase. During runs when the angle is more than 0 degrees, the bed has to be pre-tilted to the angle such that the GIF is off from the subject’s median by that angle to begin with. As the room picks up speed, the bed tilts towards the center of the room since the GIF will start to have some angle. Since at peak velocity, the GIF direction is 60 degrees off the earth vertical, the bed rotates a total of 60 degrees too. In the 0 degrees case, the bed tilts towards the center of the room by 60 degrees when peak velocity is attained. In the 60 degrees run, the bed ends up earth horizontal when peak velocity is attained.

Figure 3. As the GIF changes in magnitude and direction, the bed tilts accordingly to keep the angle between the subject’s median and the GIF (θ) constant.

At pre-selected times prior to, during, and after room rotation, the blindfolded subject is asked to indicate straight ahead relative to his or her head. In the auditory localization runs, the subject responds by positioning a virtual auditory source (i.e., controlling the auditory spatial cues of an acoustic signal processed by the Convolvotron) so that it appears to be straight ahead. In then manual pointing runs, the subject responds by pointing straight ahead with the manual
pointer.

For runs using the acoustic pointer response, the sound comes on in the azimuthal plane at a random angle between $75^0$ right and left of the median plane. The subject’s task is to adjust it until it sounds like it is in the median plane, and then press the thumb switch to indicate completion. The subject controls the apparent location by turning the sleeve of the joystick (which works as a three-position switch). When the switch is off to one side, the HRTFs used by the Convovotron to process the input source signal are changed to cause the apparent location of the acoustic source to move in the indicated direction. The initial HRTF filter pair used to spatialize the acoustic signal is chosen at random on each trial. Each trial ends when the subject depresses a button at the thumb switch, or after 15 seconds, whichever come first. If the thumb switch is not pressed in 15 seconds, the location of the sound source at that time gets recorded. The computer initiates new trials every 20 seconds. With the room velocity profile illustrated in Figure 2, subjects are given five trials in the pre-rotation phase, seven each during the acceleration and deceleration phases, six during the constant velocity phase, and ten during the post-rotation phase.

For runs using the manual pointer response, each trial begins when the controlling PC emits a beep. At this point the subject’s task is to position the joystick parallel to the head’s median plane and press the thumb switch when satisfied with the setting. As in the acoustic trials, the trial ends either when the subject presses the switch or when 15 seconds elapses, whichever occurs first.

When each trial finishes, the computer saves the time and the azimuthal angle of the stimulus chosen as appearing straight ahead (for auditory trials) or the angle of the joystick relative to the median plane (for haptic settings). Angles of $0^0$ indicate median plane settings and wherever the direction right or left of the median plane is not indicated, positive angles designate rightward
tilt and negative angles designate leftward tilt relative to the medina plane.

A total of four subjects participated in the experiments. The only selection criteria were self reports of normal hearing, balance, and posture and no general health restriction that would make exposure to 2.0 g hazardous. Subjects were warned that they would feel supine when the room was stationary and tilted left when the centrifugal force component produced rightward rotation of the resultant. They were cautioned to make all settings relative to the midline of the head rather than to the perceived zenith. They were also told that their body weight would double when GIF equaled 2.0 g and not to be distracted by the stresses and strains this would induce. Subjects were given practice trials before each set of runs.

The order of trials was the same for all the subjects. First the auditory trials were carried out in the following order in tilt angle: 0, 30, 60, 15, 45 degrees. The same order was then followed for the haptic trials. Subjects were not allowed to do more than 3 trials in one day.
3 RESULTS

3.1 AUDITORY TRIALS

The average results across subjects for the auditory settings for trials with different GIF angles (0, 15, 30, 45, 60 degrees) relative to the median plane are shown in Figures 4 - 8. Refer to the appendix for individual results. The y-axes in the plots show auditory-setting angles in degrees relative to the median plane. Auditory settings to the right of the median plane are positive while those to the left are negative. The x-axis in each plot is the time duration in seconds. The error bars show the standard deviation across the individual results.

Figure 4 shows the results for the GIF vector 0 degrees off the subjects’ median plane. During pre-rotation, an auditory stimulus at 1.06° (sd = 1.24) to the left was perceived as straight ahead. During acceleration, an auditory stimulus at 2.45° (sd = 1.71) to the right was perceived as straight ahead. At constant velocity (GIF equal 2.0 g), an auditory stimulus at 2.89° (sd = 2.68) to the right of the median plane was perceived as straight ahead. During deceleration, an auditory stimulus at 2.17° (sd = 2.73) to the right of the median plane was perceived as straight ahead. In the immediate post-rotation period an auditory stimulus at 0.56° (sd = 2.03) to the left of the median plane was perceived as straight ahead. During the final post rotation period, an auditory stimulus at 0.39° (sd = 2.51) to the right was perceived as straight ahead.

Figure 5 shows the results for the GIF vector 15 degrees off the subjects’ median plane. During pre-rotation, an auditory stimulus at 0.08° (sd = 1.63) to the left was perceived as straight ahead. During acceleration, an auditory stimulus at 7.26° (sd = 1.04) to the right was perceived as straight ahead. At constant velocity (GIF equal 2.0 g, tilted 15 degrees right), an auditory stimulus
at $5.34^0$ (sd = 1.39) to the right of the median plane was perceived as straight ahead. During deceleration, an auditory stimulus at $5.33^0$ (sd = 1.19) to the right of the median plane was perceived as straight ahead. In the immediate post-rotation period an auditory stimulus at $1.45^0$ (sd = 1.11) to the right of the median plane was perceived as straight ahead. During the final post rotation period, an auditory stimulus at $1.33^0$ (sd = 0.57) to the right was perceived as straight ahead.

Figure 6 shows the results for the GIF vector 30 degrees off the subjects’ median plane. During pre-rotation, an auditory stimulus at $1.06^0$ (sd = 1.31) to the left was perceived as straight ahead. During acceleration, an auditory stimulus at $7.75^0$ (sd = 1.16) to the right was perceived as straight ahead. At constant velocity (GIF equal 2.0 g, tilted 30 degrees right), an auditory stimulus at $4.23^0$ (sd = 2.47) to the right of the median plane was perceived as straight ahead. During deceleration, an auditory stimulus at $1.30^0$ (sd = 0.96) to the right of the median plane was perceived as straight ahead. In the immediate post-rotation period an auditory stimulus at $3.37^0$ (sd = 0.77) to the left of the median plane was perceived as straight ahead. During the final post rotation period, an auditory stimulus at $1.50^0$ (sd = 1.31) to the left was perceived as straight ahead.

Figure 7 shows the results for the GIF vector 45 degrees off the subjects’ median plane. During pre-rotation, an auditory stimulus at $1.48^0$ (sd = 1.33) to the right was perceived as straight ahead. During acceleration, an auditory stimulus at $7.54^0$ (sd = 1.90) to the right was perceived as straight ahead. At constant velocity (GIF equal 2.0 g, tilted 45 degrees right), an auditory stimulus at $7.42^0$ (sd = 2.34) to the right of the median plane was perceived as straight ahead. During deceleration, an auditory stimulus at $6.66^0$ (sd = 2.34) to the right of the median plane was perceived as straight ahead. In the immediate post-rotation period an auditory stimulus at $3.85^0$ (sd = 2.34) to the right of the median plane was perceived as straight ahead. During the final post rotation
period, an auditory stimulus at $3.26^\circ$ (sd = 1.49) to the right was perceived as straight ahead.

Figure 8 shows the results for the GIF vector 60 degrees off the subjects’ median plane. During pre-rotation, an auditory stimulus at $4.17^\circ$ (sd = 2.17) to the right was perceived as straight ahead. During acceleration, an auditory stimulus at $11.8^\circ$ (sd = 3.80) to the right was perceived as straight ahead. At constant velocity (GIF equal 2.0 g, tilted 60 degrees right), an auditory stimulus at $12.6^\circ$ (sd = 1.38) to the right of the median plane was perceived as straight ahead. During deceleration, an auditory stimulus at $9.31^\circ$ (sd = 1.94) to the right of the median plane was perceived as straight ahead. In the immediate post-rotation period an auditory stimulus at $2.0^\circ$ (sd = 2.57) to the right of the median plane was perceived as straight ahead. During the final post rotation period, an auditory stimulus at $2.34^\circ$ (sd = 2.16) to the right was perceived as straight ahead.
Figure 4. Auditory setting angle relative to median plane averaged over all the subjects with the GIF vector fixed on the median plane of the subjects. The error bars show the standard deviation across the individual results.
Figure 5. Auditory setting angle relative to median plane averaged over all the subjects with the GIF vector fixed at 15 degrees to the right of the median plane of the subjects. The error bars show the standard deviation across the individual results.
Figure 6. Auditory setting angle relative to median plane averaged over all the subjects with the GIF vector fixed at 30 degrees to the right of the median plane of the subjects. The error bars show the standard deviation across the individual results.
Figure 7. Auditory setting angle relative to median plane averaged over all the subjects with the GIF vector fixed at 45 degrees to the right of the median plane of the subjects. The error bars show the standard deviation across the individual results.
Figure 8. Auditory setting angle relative to median plane averaged over all the subjects with the GIF vector fixed at 60 degrees to the right of the median plane of the subjects. The error bars show the standard deviation across the individual results.
3.2 HAPTIC TRIALS

The average results across subjects for the haptic settings for trials with different GIF angles (0, 15, 30, 45, 60 degrees) relative to the median plane are shown in Figures 9 - 13. Refer to the appendix for individual results. The y-axes in the plots show haptic-setting angles in degrees relative to the median plane. Haptic settings to the right of the median plane are positive while those to the left are negative. The x-axis in each plot is the time duration in seconds. The error bars show the standard deviation across the individual results.

Figure 9 shows the results for the GIF vector 0 degrees off the subjects’ median plane. During pre-rotation, a haptic position at 3.380 (sd = 1.04) to the left was perceived as straight ahead. During acceleration, a haptic position at 0.9650 (sd = 1.41) to the left was perceived as straight ahead. At constant velocity (GIF equal 2.0 g), a haptic position at 1.780 (sd = 2.29) to the left was perceived as straight ahead. During deceleration, a haptic position at 5.810 (sd = 0.92) to the left of the median plane was perceived as straight ahead. In the immediate post-rotation period a haptic position 3.150 (sd = 1.22) to the left of the median plane was perceived as straight ahead. During the final post rotation period, a haptic position at 3.930 (sd = 1.41) to the left was perceived as straight ahead.

Figure 10 shows the results for the GIF vector 15 degrees off the subjects’ median plane. During pre-rotation, a haptic position at 2.420 (sd = 1.41) to the right was perceived as straight ahead. During acceleration, a haptic position at 0.630 (sd = 0.80) to the right was perceived as straight ahead. At constant velocity (GIF equal 2.0 g, tilted 15 degrees right), a haptic position at 1.060 (sd = 0.59) to the right of the median plane was perceived as straight ahead. During deceleration, a haptic position at 0.120 (sd = 1.14) to the right of the median plane was perceived as
straight ahead. In the immediate post-rotation period a haptic position at $1.14^0$ (sd $= 1.35$) to the right of the median plane was perceived as straight ahead. During the final post rotation period, a haptic position at $2.80^0$ (sd $= 0.40$) to the right was perceived as straight ahead.

Figure 11 shows the results for the GIF vector 30 degrees off the subjects’ median plane. During pre-rotation, a haptic position at $1.99^0$ (sd $= 1.04$) to the right was perceived as straight ahead. During acceleration, a haptic position at $2.33^0$ (sd $= 1.24$) to the right was perceived as straight ahead. At constant velocity (GIF equal 2.0 g, tilted 30 degrees right), a haptic position at $3.69^0$ (sd $= 0.98$) to the right of the median plane was perceived as straight ahead. During deceleration, a haptic position at $3.49^0$ (sd $= 1.65$) to the right of the median plane was perceived as straight ahead. In the immediate post-rotation period a haptic position at $3.40^0$ (sd $= 1.33$) to the right of the median plane was perceived as straight ahead. During the final post rotation period, a haptic position at $1.64^0$ (sd $= 0.55$) to the right was perceived as straight ahead.

Figure 12 shows the results for the GIF vector 45 degrees off the subjects’ median plane. During pre-rotation, a haptic position at $2.33^0$ (sd $= 0.70$) to the right was perceived as straight ahead. During acceleration, a haptic position at $2.79^0$ (sd $= 1.03$) to the right was perceived as straight ahead. At constant velocity (GIF equal 2.0 g, tilted 45 degrees right), a haptic position at $5.86^0$ (sd $= 1.12$) to the right of the median plane was perceived as straight ahead. During deceleration, a haptic position at $4.90^0$ (sd $= 1.92$) to the right of the median plane was perceived as straight ahead. In the immediate post-rotation period a haptic position at $4.12^0$ (sd $= 2.01$) to the right of the median plane was perceived as straight ahead. During the final post rotation period, a haptic position at $5.13^0$ (sd $= 1.03$) to the right was perceived as straight ahead.

Figure 13 shows the results for the GIF vector 60 degrees off the subjects’ median plane.
During pre-rotation, a haptic position at $1.54^0$ (sd $= 1.96$) to the left was perceived as straight ahead. During acceleration, a haptic position at $3.51^0$ (sd $= 2.05$) to the left was perceived as straight ahead. At constant velocity (GIF equal 2.0 g, tilted 60 degrees right), a haptic position at $1.20^0$ (sd $= 1.32$) to the left of the median plane was perceived as straight ahead. During deceleration, a haptic position at $6.34^0$ (sd $= 1.88$) to the right of the median plane was perceived as straight ahead. In the immediate post-rotation period a haptic position at $2.11^0$ (sd $= 3.59$) to the right of the median plane was perceived as straight ahead. During the final post rotation period, a haptic position at $1.03^0$ (sd $= 1.26$) to the left was perceived as straight ahead.
Figure 9. Haptic setting angle relative to median plane averaged over all the subjects with the GIF vector fixed on the median plane of the subjects. The error bars show the standard deviation across the individual results.
Figure 10. Haptic setting angle relative to median plane averaged over all the subjects with the GIF vector fixed at 15 degrees to the right of the median plane of the subjects. The error bars show the standard deviation across the individual results.
Figure 11. Haptic setting angle relative to median plane averaged over all the subjects with the GIF vector fixed at 30 degrees to the right of the median plane of the subjects. The error bars show the standard deviation across the individual results.
Figure 12. Haptic setting angle relative to median plane averaged over all the subjects with the GIF vector fixed at 45 degrees to the right of the median plane of the subjects. The error bars show the standard deviation across the individual results.
Figure 13. Haptic setting angle relative to median plane averaged over all the subjects with the GIF vector fixed at 60 degrees to the right of the median plane of the subjects. The error bars show the standard deviation across the individual results.
4 DISCUSSION

The results from the five auditory trials indicate that an increase in GIF magnitude with the angle from the median plane held constant requires a rightward shift of an acoustic stimulus for it to be perceived in the median plane. The degree of the required shift varies with the angle at which GIF is tilted away from the median plane. In general, it can be observed that the degree of shift increases with increasing tilt of the GIF from the median plane.

Figures 14 - 19 illustrate the average auditory setting angles relative to the median plane for each stage during the trial plotted against the tilt angle of the GIF. The slope of the plots during the acceleration stage (Figure 15) and the constant-velocity stage (Figure 16) is higher than the slope of the plot during the pre-rotation stage (Figure 14). This trend indicates that at GIF magnitude higher than 1.0 g, the shift in the auditory setting angle is bigger for higher GIF tilt angles compared to the 1.0 g baseline for the respective tilt angles. Furthermore, by comparing the points for 0 tilt angle across all the stages, it can be verified that an increase in just the GIF magnitude is sufficient to produce a shift in auditory perception.

Relative to the pre-rotation stage, during the constant-velocity stage, the auditory setting angles shift by 3.94, 5.43, 5.29, 5.94 and 8.38 degrees to the right for GIF tilt angles 0, 15, 30, 45 and 60 degrees respectively. The relative shift is highest when the tilt angle is 60 degrees. Relative to the pre-rotation stage, the shift during the acceleration stage are 3.51, 7.34, 8.81, 6.27 and 7.66 degrees to the right of the median for GIF tilt angles 0, 15, 30, 45 and 60 degrees respectively. Similarly, during the deceleration stage (Figure 17), the shift angles relative to the pre-rotation stage are 3.23, 5.41, 2.36, 5.18 and 5.14 degrees to the right for GIF tilt angles 0, 15, 30, 45 and 60 degrees respectively. During the immediate post-rotation (Figure 18) and final post-rotation (Figure 19) stages, the auditory shift angles return close within 2 degrees of the baseline of the
pre-rotation stage.

The general rightward shift of the auditory setting angles during high GIF conditions does not necessarily guarantee the presence of audiogravic illusion. Because the auditory stimuli were adjusted by the subjects relative to their perceived median, an equivalent rightward change of the perceived median plane under the same GIF conditions could mean that the auditory shift reflected just the reorientation to a new frame of reference. The shifts in the auditory angle setting must take into account this shift in the frame of reference.

The haptic setting results illustrated in Figures 9 - 13 don’t indicate any sort of definite shift in the perceived median. In trials with the GIF tilted at 0, 15, 30 and 45 degrees, the haptic settings stays nearly constant with the maximum shift relative to the pre-rotation settings at about 5 degrees. Although there seems to be a leftward shift of the haptic setting during acceleration and a rightward shift during deceleration in the trial with the GIF tilt angle set at 60 degrees, the shift does not quite stabilize at constant-velocity stage. Therefore the apparent shift in this trial could be attributed to acceleration factor, and not a shift in the frame of reference. Overall, the shift in the auditory setting angle can be attributed to audiogravic illusion solely. Figures 20 - 25 show the average haptic setting angles relative to the median plane for each stage during plotted against the tilt angle of the GIF. These plots don’t show much change in the haptic setting angles as the tilt angle changes. This observation further leads us to believe that there is not a significant change in the frame of reference caused by a change in the magnitude or the direction of the GIF.

The upward slope of the plot of the pre-rotation stage in Figure 14 indicates the presence of audiogravic illusion in 1.0 g condition, as long as the GIF is tilted away from the median plane. This contradicts earlier results from similar studies. To investigate this apparent shift in normal 1.0 g condition, three trials were run win 1.0 g condition. In the first trial, the subjects lay flat on
the bed with the headphone place normally. In the second trial, the left phone was pressed close to the ear while the right phone was placed farther away from the ear. In the third trial, the right phone was pressed close to the ear while the left phone was placed farther away. Between the three trials, when the left ear was pressed, the average auditory setting angle shifted right relative to the normal condition of the first trial; when the right ear was pressed, the average auditory setting angle shifted left relative to the normal condition. When one side of the phone is pressed against the ear, that side of the phone is louder than the other side. Consequently, subjects have to place the auditory stimuli further towards the weaker side for the it to be perceived in the median plane. When the subjects were tilted at 45 and 60 degree angles, the left phone got pressed against their ears more than the right phone. This accounted for the shift in the 1.0 g baseline condition in higher tilt angles.

The results clearly show a shift in auditory setting angle that is not due to a shift in the perceived median plane, but due to an actual shift in auditory perception -- audiogravic illusion. The audiogravic illusion joins the oculogravic illusion in the class of GIF-related alterations in head-centric spatial localization. These results bear directly on how to combat spatial disorientation in pilots. Since pilots are already working under a visual overload, an alternative to visual instrument to combat spatial disorientation is needed. One such alternative is to present the pilot with a virtual sound around the head in azimuth as a gauge of aircraft roll angle. In such a setting, the sound would be placed straight ahead to indicate straight and level flight or displaced left to indicate roll left. However, with the presence of audiogravic illusion, such a system should make appropriate corrections depending on the magnitude and the direction of the GIF.
Figure 14. Average auditory setting angle relative to the median plane during the pre-rotation stage.
Figure 15. Average auditory setting angle relative to the median plane during the acceleration stage.
Figure 16. Average auditory setting angle relative to the median plane during the peak-velocity stage.
Figure 17. Average auditory setting angle relative to the median plane during the deceleration stage.
Figure 18. Average auditory setting angle relative to the median plane during the immediate post-rotation stage.
Figure 19. Average auditory setting angle relative to the median plane during the final post-rotation stage.
Figure 20. Average haptic setting angle relative to the median plane during the pre-rotation stage.
Figure 21. Average haptic setting angle relative to the median plane during the acceleration stage.
Figure 22. Average haptic setting angle relative to the median plane during the peak-velocity stage.
Figure 23. Average haptic setting angle relative to the median plane during the deceleration stage.
Figure 24. Average haptic setting angle relative to the median plane during the immediate post-rotation stage.
Figure 25. Average haptic setting angle relative to the median plane during the final post-rotation stage.
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6 REFERENCES


7 APPENDIX

The following graphs plot the results of each subject for the auditory and the haptic trials. The y-axes in the plots show auditory-setting angles for the auditory trials and the haptic-setting angles for the haptic trials. Settings to the right of the median plane are positive while those to the left are negative. The x-axis in each plot is the time duration in seconds.
Auditory Trial with 0 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4
Auditory Trial with 15 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4
Auditory Trial with 30 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4
Auditory Trial with 45 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4
Auditory Trial with 60 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4
Haptic Trial with 0 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4
Haptic Trial with 15 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4
Haptic Trial with 30 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4
Haptic trial with 45 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4
Haptic Trial with 60 degrees tilt

Subject #1

Subject #2

Subject #3

Subject #4