Pitch-Plane Angular Displacement Perception During Helicopter Flight and Gondola Centrifugation

Arne Tribukait; Eddie Bergsten; Ola Eiken

BACKGROUND: During hovering with a helicopter, an involuntary change in attitude (during brownout) results in reduced lifting force and a horizontal acceleration component. This movement pattern is difficult to perceive via the otolith organs. If the angular displacement occurs rapidly, it will, however, activate the semicircular canals. The major aim of this study was to establish to what extent pitch-plane angular displacements can be perceived based on canal information when there is no tilt stimulus to the otoliths.

METHODS: In a helicopter, 9 nonpilots (N) and 8 helicopter pilots (P) underwent 5–6 pitch-forward displacements (magnitude 14–33°, angular velocity 2–7° $\cdot$ s^{-1}). In a swing-out gondola centrifuge, 9 N and 3 P were exposed to a similar canal-otolith conflict (acceleration, seated centripetally) with four displacements of 25° and two of 60°. The visually perceived eye level (VPEL) was continuously recorded using an adjustable luminous dot in darkness. For each helicopter dive and centrifuge run the gain was calculated as the ratio (VPEL deflection)/(displacement of helicopter or gondola).

RESULTS: In the helicopter there was no difference between N (0.28 $\pm$ 0.13) and P (0.36 $\pm$ 0.22). In the centrifuge the gains were 0.34 $\pm$ 0.18° (25° displacements) and 0.30 $\pm$ 0.16° (60° displacements). Values obtained in the helicopter did not differ significantly from those in the centrifuge. There was a correlation between data obtained during the 25° and 60° displacements in the centrifuge.

CONCLUSION: There was a pronounced underestimation of pitch angular displacements in a helicopter. The interindividual variability was considerable. Gains for perceived displacement were similar in helicopter and centrifuge.

KEYWORDS: sense of balance, spatial orientation, spatial disorientation, vestibular psychophysics.

Tribukait A, Bergsten E, Eiken O. *Pitch-plane angular displacement perception during helicopter flight and gondola centrifugation*. Aerosp Med Hum Perform. 2016; 87(10):852–861.

The present study concerns the ability to perceive, on the basis of vestibular information, changes in attitude of a helicopter. Helicopter missions comprise, to a relatively large extent, low altitude flight whereby the pilot maintains spatial orientation by means of visual contact with external landmarks. When airspeed is low, the helicopter is inherently unstable, which requires continuous adjustments by the pilot. During hovering, recirculation of dust (brownout) or snow (whiteout) can cause sudden loss of external visual information. The practical significance of spatial disorientation in rotary-wing operations has been reviewed by Braithwaite et al.[3]

When visual cues are poor there is a tendency to rely, instinctively, on information from the vestibular organs. Several movement patterns that are common during flight cannot, however, be adequately detected by the sense of balance.[13] One instance is the entering of a coordinated turn. Since the resultant gravitoinertial force vector is persistently acting in the head and body median plane, the otolith organs cannot detect that the aircraft is tilted in roll with respect to the surface of the Earth. If the change in roll attitude is performed rapidly it will, nevertheless, constitute a stimulus to the semicircular canals, similar to that elicited by a lateral head tilting in the static 1-g environment.[25]

From the Swedish Aerospace Physiology Centre, Department of Environmental Physiology, Royal Institute of Technology, KTH, School of Technology and Health, Solna, Sweden.

This manuscript was received for review in March 2016. It was accepted for publication in June 2016.

Address correspondence to: Arne Tribukait, M.D., Ph.D., Department of Environmental Physiology, Swedish Aerospace Physiology Centre, School of Technology and Health, KTH, Royal Institute of Technology, Berzelius v. 13, SE-171 65 Solna, Sweden; arne.tribukait@sth.kth.se.

DOI: 10.3357/AMHP.4627.2016

During hovering with a helicopter, this kind of intravestibular conflict may occur in pitch as well as in roll. Consider a helicopter hovering geostationary out of ground effect, i.e., at a height exceeding two times the radius of the rotor.[14] An involuntary angular displacement from the upright orientation (as might occur in a brown-out situation) will generate a horizontal acceleration component while the lifting force is reduced. The resulting pattern of tilt, drift, and height loss cannot be sensed by the graviceptive systems, whose message is that the pilot remains upright (see **Fig. 1**). Thus, the G vector acting on the pilot is persistently aligned with the shaft of the main rotor. If the change in attitude occurs rapidly, it will, nevertheless, stimulate the semicircular canals.

Such otolith-canal conflicts can also be created in a large swing-out gondola centrifuge.[6] The tangentially pivoted gondola is deflected in the direction of the resultant gravitoinertial force vector. Thus, if the test subject is seated forward in the gondola, acceleration of the centrifuge will result in a roll (frontal plane) angular displacement. Similarly, acceleration with the subject facing the center of the centrifuge (centripetally) causes a pitch- (sagittal-) plane angular displacement.[18] Except for deviations related to tangential accelerations (during changes in angular velocity of the centrifuge), the G vector does not change direction with respect to the subject.

Orientation with respect to the Earth-horizontal plane can be studied quantitatively by means of visual indicators. Concerning orientation in roll, the test subject is asked to adjust a luminous line, in otherwise complete darkness, so that it is perceived as horizontal or vertical. This measure of spatial orientation is denoted the subjective visual horizontal (SVH) or vertical (SVV).[11,16] Analogously, orientation in pitch can be studied using a luminous dot, adjustable in the vertical direction;

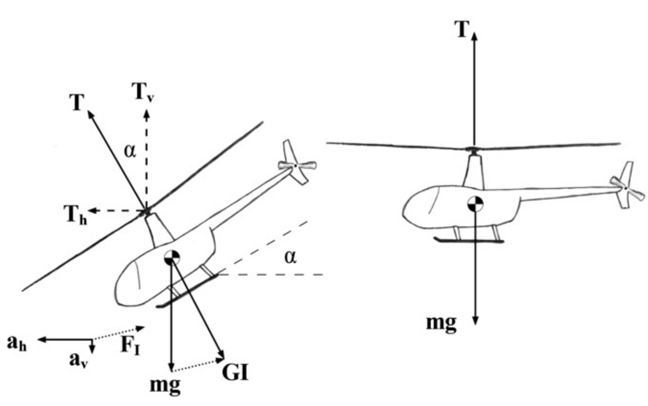

Fig. 1. During hovering, or when air speed is low and constant, the main rotor thrust (lifting force, T) balances the helicopter's weight (force of gravity = mg). The main rotor thrust can be resolved into one component acting vertically and one acting horizontally. If T is constant, i.e., if the pilot does not move the collective lever, a change in attitude implies that the vertical component is reduced to $T \cdot \cos\alpha$ while the horizontal component is increased from zero to $T \cdot \sin\alpha$. Thus, there will be a vertical acceleration component, a_v (corresponding to the difference $mg - T \cdot \cos\alpha$) and a horizontal acceleration component, a_h (corresponding to $T \cdot \sin\alpha$). These acceleration components generate an inertial force, F_I. The vectorial sum of the force of gravity and F_I, the gravitoinertial force (GI), has the same direction with respect to the pilot as the force of gravity (mg) when the helicopter is in the upright position.

the subject is requested to adjust the position of the dot so that it appears to be gravitationally at the level of the eyes. This measure of spatial orientation has been termed the visually perceived eye level (VPEL).[9]

In healthy subjects, seated upright, the SVH or VPEL rarely deviates by more than a few degrees from the true horizontal plane.[16,20] During moderate ($< 30°$) static head and body tilt, the values for SVH and VPEL remain close to the values for the upright position, reflecting the functioning of the otolith organs.[16,20] If a change in head orientation is performed rapidly, the brain will also receive information from the semicircular canals. The angular velocity signal from the canals can be integrated over time, resulting in an estimate of angular displacement.[4,10] Consequently, the measure of perceived head tilt will be greater if the angular displacement is performed rapidly than if tilting is made with an angular velocity below the stimulus threshold of the canals.[15]

In recent studies we have recorded, in gondola centrifuges and fixed-wing aircraft, the ability to perceive the roll attitude during coordinated turns. Briefly, if the subject is seated facing forward, acceleration of the centrifuge causes a sensation of head and body tilt toward the center of the centrifuge. This sensation is reflected in a tilt of the SVH with respect to the horizontal plane of the gondola.[19,22] In nonpilots, the initial SVH tilt is, on average, approximately 30% of the roll inclination of the gondola and it often declines with a time constant of 1–2 min. Pilots show a different pattern with a greater SVH tilt that does not usually decline with time.[23] There is a large interindividual variability. Nevertheless, repeated testing suggests the existence of persistent individual characteristics in spatial orientation.[17] Furthermore, data obtained in the centrifuge correlate with those obtained during coordinated turns with an aircraft.[24]

Analogous experiments on orientation in pitch, i.e., recordings of the VPEL with the subject facing centripetally or centrifugally in the gondola, confirm that the graviceptive systems predominate over the semicircular canals. The influence on the VPEL of oppositely directed displacements suggests that in both nonpilots and helicopter pilots the perceived displacement is only 10-15% of the real displacement.[21] Notably, in fighter pilots, the magnitude of this influence on the VPEL was significantly greater. Thus, it seems that orientation in roll and pitch are to some extent independent functions and also that angular displacements in pitch might constitute a greater challenge to helicopter pilots.

There are, however, several inescapable differences between the vestibular stimulus encountered during a pitch-forward angular displacement and "dive" in a helicopter and that created by acceleration of a swing-out gondola centrifuge (with the subject heading centripetally). In the centrifuge the pitch-plane angular displacement is accompanied by considerable angular velocity components in yaw (the head transversal plane) and roll.[21] Further, the resultant gravitoinertial force vector will increase in magnitude during acceleration of the centrifuge, whereas in the helicopter it will remain close to 1 G even for considerable changes in pitch attitude. Thus it is possible that the measurement of perceived angular displacement (deflections in VPEL) obtained in the centrifuge does not correspond to the dilemma met in real flight situations.

The primary aim of the present study was to establish, via continuous recording of the VPEL during pitch-forward "dives" in a helicopter, to what extent pitch-plane angular displacements can be perceived based on semicircular canal information when there is no tilt stimulus to the otolith organs, i.e., in a situation similar to that encountered by a helicopter pilot who involuntarily changes the pitch attitude of the aircraft. A secondary aim was to compare helicopter pilots and nonpilots in terms of the ability to perceive such changes in attitude. Finally, we wanted to recreate, using a large gondola centrifuge, the pitch-plane stimulus profile occurring during forward dives with the helicopter and determine whether factors like the angular-velocity components in yaw and pitch or the increase in resultant G vector, which are inevitable in the centrifuge, influence the perception of the pitch stimulus.

METHODS

Subjects

Nine nonpilots (one woman and eight men), ages 19–66 yr, and eight helicopter pilots (one woman and seven men), ages 26–48 yr, with flight experience of 250–5000 h, were recruited to the helicopter experiments. Nine nonpilots (one woman and eight men) and three male helicopter pilots (with 250 flight hours) were recruited to the centrifuge experiments. Four of the subjects (one nonpilot and three pilots) participated in both experiments. The subjects participated with their informed consent and were free to withdraw at any time. The test procedures were in accordance with the declaration of Helsinki and were approved by the human ethics committee in Stockholm.

Equipment

The helicopter experiments were carried out in a four-seat single main rotor helicopter (Robinson R44, Robinson Helicopter Company Inc., CA). The subject was seated in the left rear seat. On board were, in addition to the test subject and pilot, the experimenter and a technician managing the data collection. All wore head sets and could freely communicate with each other.

In front of the subject (at a distance of 35 cm from the subject's eyes) there was a screen with a vertical column of 61 red light-emitting diodes. The screen formed a circular segment in the pitch plane so that all diodes were at the same distance from the subject's eyes. The distance between two adjacent diodes was 1.0°. The screen was adjusted so that its center was at the level of the subject's eyes. At a given point in time, the subject could only see one single luminous dot, but using a remote control he or she could make adjustments so that the dot was at the perceived eye level. The remote control consisted of a small box, which the subject held in the left hand, and a rotary control knob (diameter 40 mm), which was held in the right hand, so that it could be rotated in the pitch plane. The control knob was mounted on an angular encoder (ERN 1020, Heidenhain, Schaumburg, IL). The control knob did not have any tactile landmarks, it was nearly frictionless, and without physical end-points. Via a USB card (USB 6218), the angular encoder was connected to a HP ProBook 6570b (Intel Core i5, 2.60 GHz) where the signal from the encoder was converted into a signal to the diode screen. Rotation of the knob changed the position of the luminous dot in the same direction; to facilitate fine adjustments of the luminous dot and to avoid effects of involuntary movements, there was a 6:1 ratio between rotation of the knob and deflection of the dot. Thus, rapid or short-lasting changes in perceived pitch attitude could be indicated in an intuitive manner. Recording frequency was 10 Hz. Programming for converting the signal from the encoder and for recording of data was performed in LabView (National Instruments Corporation, Austin, TX).

Complete darkness was attained in the following way: the subject wore a modified diver's mask, the glass of which had been removed. The mask was connected to the screen with diodes via flexible light-proof material, consisting of an external layer of reflecting plastic and aluminum foil and an internal layer of black velvet. The shape of this construction was maintained by a skeleton of thin steel rods. The mask was equipped with light-proof ventilation channels, permitting breathing through the nose. Partly for safety reasons no head rest was used, but the elasticity of the construction provided some support, making it easy for the subject to avoid head movements.

The movements of the helicopter with respect to the Earth were recorded with 10 Hz using a 3DM-GX3-45 miniature GPS-aided inertial navigation system (LORD MicroStrain®, Williston, VT). Any deviation of the G vector relative to the z-axis of the helicopter could be noted by the experimenter using a digital water level (Bosch DNM 60L, Robert Bosch GmbH, Stuttgart, Germany) mounted in the helicopter. For the purpose of verifying, afterwards, that the recordings of the helicopter pitch were adequate, two video cameras were installed in the helicopter. One of these was directed sideways, surveying the Earth horizon. The other was monitoring the display of the digital water level.

The centrifuge experiments were performed in the Dynamic Flight Simulator (Wyle Laboratories, Inc., El Segundo, CA) at the Aviation Physiology Laboratories in Linköping. The radius of this centrifuge is 9.1 m. In the swing-out gondola, the subject was positioned centripetally (facing the center of the centrifuge) and fixed by means of safety belts and a head support.

The device for recording of the VPEL was similar to that used in the helicopter. However, to permit recording of responses to greater pitch angular displacements (i.e., during acceleration to 2 G), the screen with diodes subtended a visual angle of 90°. The control knob was mounted on a rotary encoder (E6A2-CW3C, OMRON Electronics, Kyoto, Japan). The encoder was connected to a microprocessor (Arduino UNO with the program made in C), where the signal from the encoder was converted into a signal to the diode screen. The ratio between knob rotation angle and deflection of the luminous dot was 8:3. Recording frequency was 20 Hz. Measurement data were transmitted from the microprocessor via slip rings to a HP ProBook 6570b (Intel Core i5, 2.60 GHz). During the tests the gondola was completely darkened, but the subject was observed in infrared light by means of a video camera and he/she always had the possibility to communicate with the experimenter via a two-way intercom system.

Procedure

The subject was instructed to imagine the horizon of the external world and adjust the luminous dot so that it appeared to be at the same height as the horizon. He or she was asked not to "freeze" the dot, but to persistently make small movements up and down about the perceived height of the horizon. In case of any sensation of angular displacement in pitch, the subject should indicate the horizon in relation to which he or she felt displaced (i.e., the response to a pitch-forward angular displacement of the helicopter or gondola would be an upward displacement of the luminous dot and conversely). Otherwise, the subject was encouraged to trust his or her spontaneous impressions rather than thinking or calculating. The height of the screen was adjusted to each subject prior to the experiment.

In the helicopter experiments, the face mask was donned prior to takeoff. Recording of the VPEL commenced at an altitude of $>$250 m ($>$820 ft). The pilot was hovering against the wind or maintained a speed of approximately 15 kn with respect to the air. Then a series of pitch-forward "dives" were performed during a time span of 3–3.5 min. The pilot made these angular displacements with constant collective, i.e., without changing the lifting force in the main rotor, and with a minimal change in the direction of the gravitoinertial force field within the helicopter. The magnitude of each angular displacement was 15–30° with an angular velocity of approximately $5° \cdot s^{-1}$. The pilot then leveled off, gained height, and stabilized the helicopter for at least 10 s prior to the next dive. Each subject underwent 5–6 displacements.

The centrifuge experiment comprised six runs; four with acceleration from 1 g (stationary) to 1.1 G (pitch angular displacement 25°) and two runs with acceleration from 1 g to 2 G (60°). After a period with constant G level (4.3 s and 5.4 s, respectively) the centrifuge was decelerated to 1 G. Planetary acceleration and deceleration was $8° \cdot s^{-2}$ (with a slight damping by the end of the acceleration period); the 1.1-G level was attained in 5 s and the 2-G level in 11 s.

The runs were grouped in blocks of two stimuli in the following sequence: 1.1 G–1.1 G–2 G–2 G–1.1 G–1.1 G. After the second and fourth runs, there were pauses of 5 min; the gondola was opened and the light was turned on. Otherwise the intervals at 1 g were 35 s. For each pair of runs, recording of the VPEL commenced 30 s before the first acceleration and continued for 30 s after the second deceleration.

Analysis

Pitch-forward angular displacement (of the helicopter or gondola as well as of the VPEL) is denoted negative. Recordings from the helicopter experiments (of helicopter pitch and VPEL) were filtered using a Savitzky-Golay filter with two side-points. VPEL recordings from the centrifuge were filtered with four side-points. In recordings from the helicopter, the time points when displacements began were determined via visual scrutiny of the curves representing the helicopter's pitch attitude (see **Fig. 2**). For both the pitch attitude and the VPEL, baseline values were then calculated as the mean of the data points obtained during the 5-s intervals preceding the displacements (zero for the helicopter pitch was defined as the attitude of the helicopter when it was standing on the ground). The magnitude of a given displacement was defined as the minimum with respect to the preceding baseline. Similarly, the subject's response was defined as the maximum deflection of VPEL relative to the baseline value. As regards data obtained in the centrifuge, for each separate run, the baseline value for the VPEL was calculated as the mean for the 10-s interval preceding acceleration of the centrifuge.

For each displacement, a gain value was calculated as the ratio between the response and the magnitude of the displacement. Since the responses were always in the opposite direction with respect to the stimulus, we have, for simplicity, omitted the minus sign where gain values are mentioned. For the individual, a mean gain value was calculated for all displacements undergone in the helicopter. Based on these individual means, differences between nonpilots and pilots were evaluated using unpaired *t*-test. In an analogous way, gain values for the responses in the centrifuge were determined for the 25° and 60° displacements, respectively. Individual means for each pair of 25° displacements were also calculated.

For the centrifuge data, differences between the responses (gain values) to the 25° (mean of four responses) and 60° (mean of two responses) displacements were evaluated using paired *t*-test. Also, comparison between the responses to the first two and last two 25° displacements was done using paired *t*-test; for each individual the means of the first two and last two responses were first calculated.

Linear regressions were performed to establish whether there was any correlation between the two pairs of 25° displacements or between the 25° and 60° displacements. Comparison between responses in the helicopter and those to the 25° displacements in the centrifuge was done using unpaired *t*-test.

RESULTS

The subjects found the task unambiguous and responded in a consistent manner to the angular displacements. In the centrifuge, one subject experienced moderate nausea after the first 60° displacement; in this case the second 60° displacement was omitted.

Fig. 2A-D shows, for four of the subjects, recordings from the helicopter. The pitch attitude of the helicopter is also shown. Although the movements of the helicopter display a notable variation, the responses of a given individual are consistent and synchronous with the helicopter displacements.

The average baseline for the helicopter pitch was $-0.1 \pm 2.7°$ ($N = 90$). The amplitude of the helicopter's pitch-forward

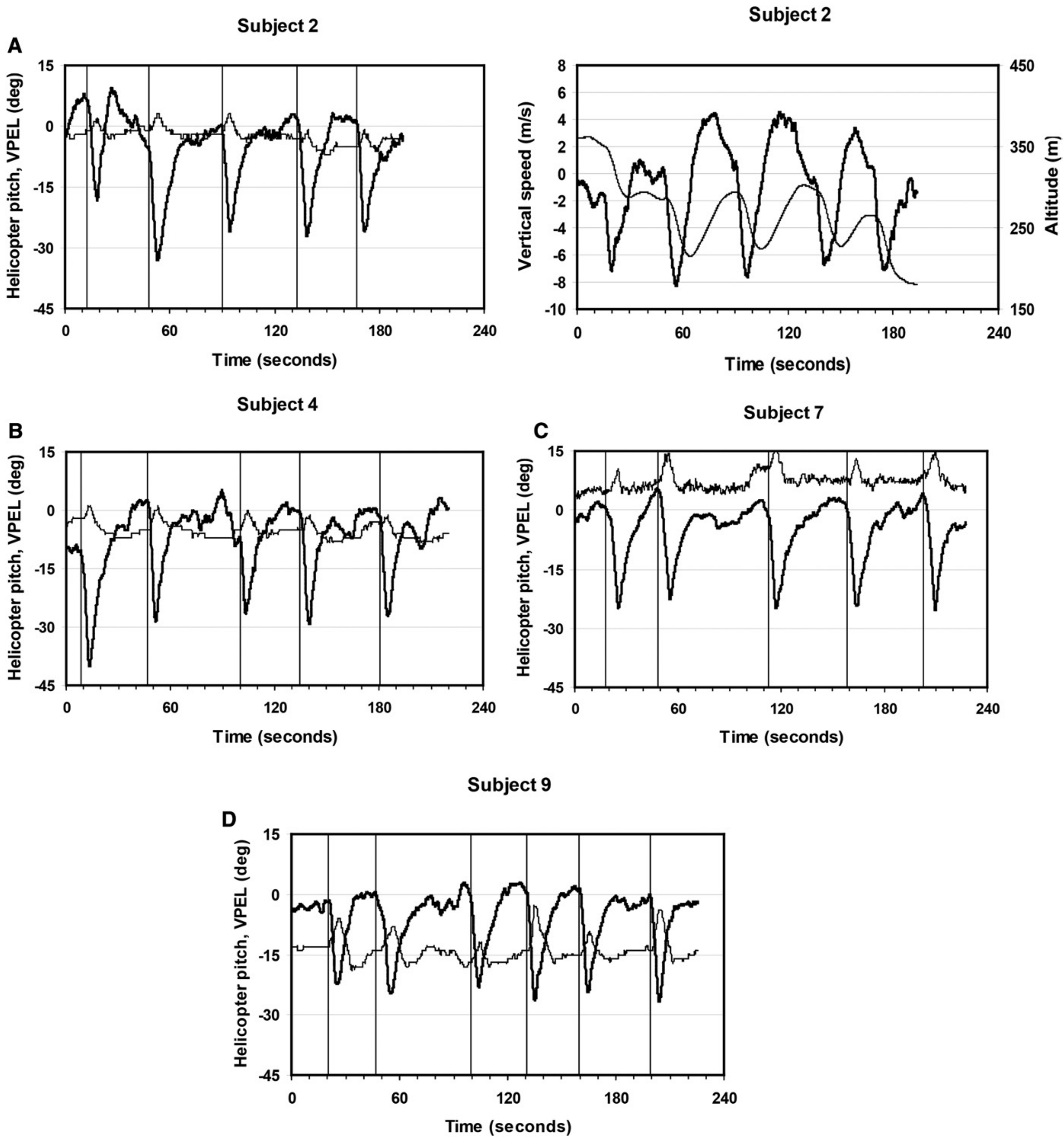

Fig. 2. Recordings from the helicopter for four of the subjects. Bold curves represent the pitch attitude of the helicopter, thin curves represent the VPEL. The top right diagram for Subject 2 shows vertical speed (bold curve) and altitude (thin curve); for the sake of brevity vertical speed and altitude are not shown for Subjects 4, 7, and 9.

displacements was $-23.9 \pm 3.7°$ ($N = 90$), with a mean angular velocity (from the end of the baseline period to the time point where the pitch-forward tilt attained its maximum) of $4.1 \pm 1.2° \cdot s^{-1}$ ($N = 90$).

Typically, the vertical descent rate attained a maximum approximately 1 s after the peak of the pitch-forward displacement. On average, the maximum descent rate was 5.8 ± 1.3 $m \cdot s^{-1}$ (19 ± 4.3 $ft \cdot s^{-1}$; $N = 90$), with a resulting height loss of 51 ± 17 m (167 ± 56 ft; $N = 90$).

As regards the VPEL, a mean baseline has been calculated for each individual. In the group of nonpilots the baseline was $-0.6 \pm 6.0°$ ($N = 9$). In the pilots it was $-14.2 \pm 4.3°$ ($N = 8$). The difference between these two means is highly significant [unpaired t-test, $t(15) = 5.28$, $P < 0.001$].

Individual gains for the responses in the helicopter are shown in **Fig. 3**; in addition to mean values, the gains for each single displacement are also shown. In general, the variability within subjects was considerably smaller than the interindividual variability. The group mean for the responses (gain values) was 0.28 ± 0.13 (SD) in the nonpilots and 0.36 ± 0.22 in the pilots. These values are statistically similar [unpaired *t*-test, $t(15) = 0.89$, $P = 0.39$]. There was no relationship between gain and the baseline for VPEL (linear regression, $r = 0.31$, $P = 0.23$, $N = 17$).

Fig. 4 shows, for the nonpilots and pilots, respectively, gain values plotted against angular velocity for each single displacement. It is obvious that neither differences between individuals nor the variability within subjects can be explained by the variation in mean angular velocity of the helicopter (which was always in the interval between 2 and $7° \cdot s^{-1}$). Linear regression analysis of all 90 data points gives $r = 0.15$, $P = 0.16$. Analogously, there was no correlation between the gain for the responses and the magnitude of the displacements of the helicopter (linear regression: $r = 0.13$, $P = 0.22$, $N = 90$), the latter ranging between 14 and 33°.

Fig. 5 shows, for a representative subject, recordings from the centrifuge. For the 25° displacements the VPEL baseline was −3.5 ± 3.7° ($N = 12$); for the 10-s interval following centrifugation the VPEL was −3.3 ± 4.6°. There was a tendency [paired *t*-test ($N = 12$): $t(11) = 2.17$, $P = 0.053$] to smaller gains for the 60° displacements (0.297 ± 0.161) than for the 25° displacement (0.345 ± 0.181). There was no significant difference [paired *t*-test: $t(11) = 0.95$, $P = 0.36$] between the first two (0.363 ± 0.218) and last two (0.327 ± 0.163) 25° displacements.

Individual gains for the responses to the 25° displacements in the centrifuge are shown in **Fig. 6**. In addition to mean values the gains for each single displacement are also shown. Like in the helicopter, the variability within subjects was considerably smaller than the interindividual variability.

There was a significant correlation ($r = 0.91$, $P < 0.001$, $N = 12$) between the responses to the 25° and 60° displacements.

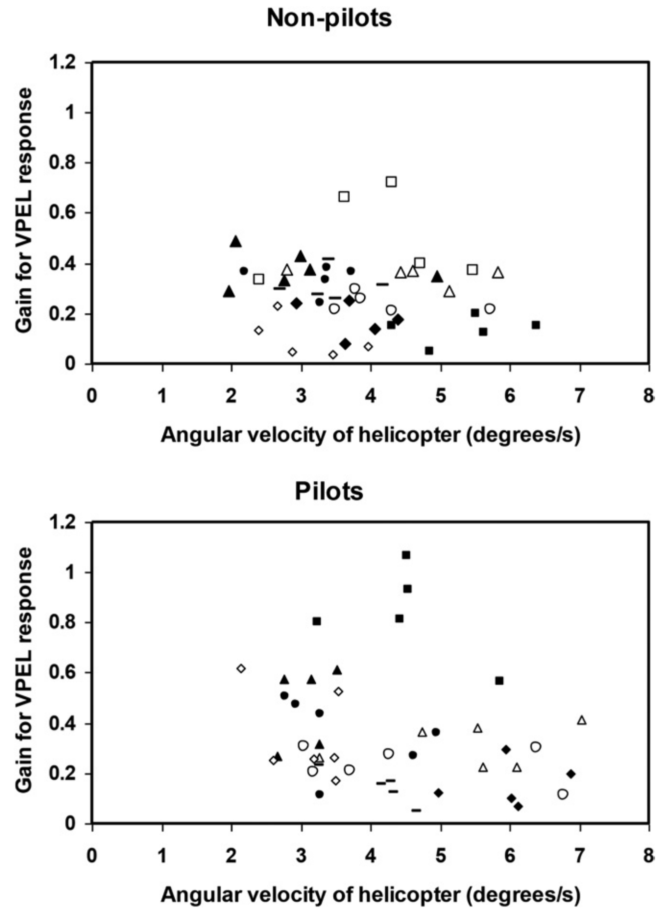

Fig. 4. Gain values plotted against angular velocity of the helicopter. Each data point represents the response to a single displacement. Individuals are represented by different symbols. It is obvious that the response gain is independent of the magnitude of the helicopter's pitch angular velocity and also that differences between individuals cannot be explained by differences in the helicopter's angular velocity.

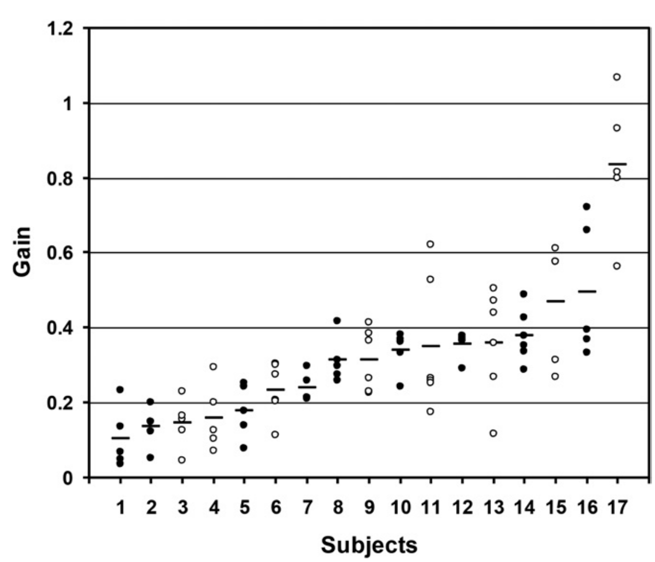

Fig. 3. Gain values for the responses to the helicopter's pitch-forward angular displacements. Subjects have been ranked according to their average responses (horizontal bars). Round symbols (black, nonpilots; white, pilots) represent the responses to single displacements.

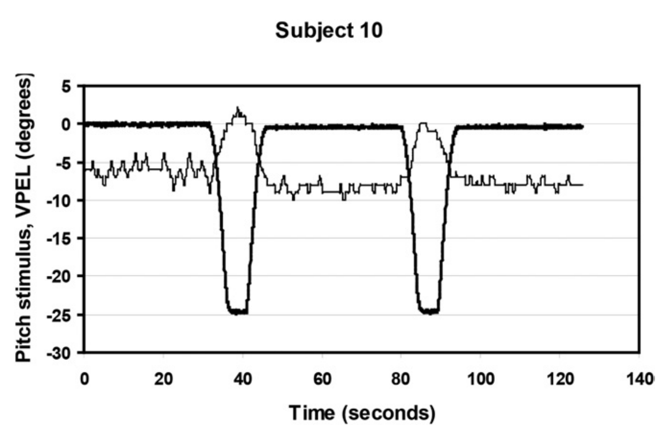

Fig. 5. Recording from the centrifuge (one subject). The bold curve represents the orientation of the gondola, the thin curve represents the VPEL.

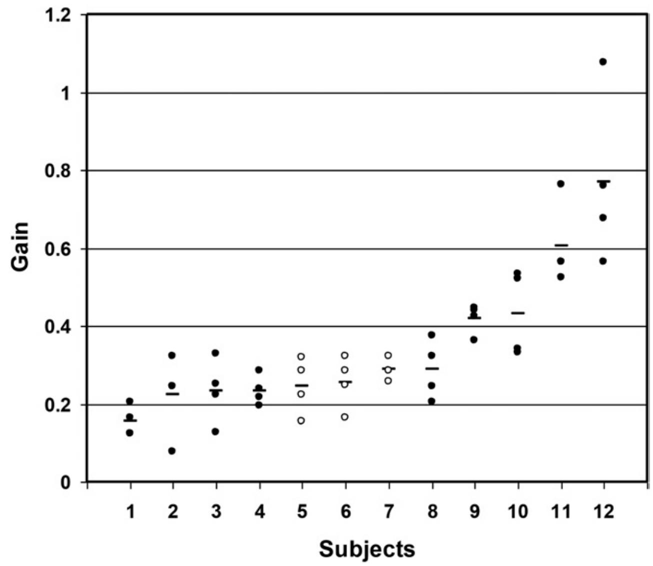

Fig. 6. Gain values for responses to 25° pitch-forward angular displacements in the centrifuge. Subjects have been ranked according to their average responses (horizontal bars). Round symbols (black, nonpilots; white, pilots) represent responses to single displacements.

Likewise, there was a significant correlation ($r = 0.81$, $P < 0.01$, $N = 12$) between the first two and last two 25° displacements. There was no significant difference [unpaired *t*-test, $t(27) = 0.41$, $P = 0.69$] between the responses to 25° displacements in the centrifuge (0.345 ± 0.181, $N = 12$) and those recorded in the helicopter (0.318 ± 0.176, $N = 17$).

DISCUSSION

The visual measure of perceived pitch-forward angular displacement was, on average, approximately 30% of the real displacement. A principal question is whether this underestimation is related to limitations of the semicircular canal system, including stimulus thresholds for angular velocity and velocity-to-position integration at the central nervous level, or whether it is due to the fact that the canal signal for change in head orientation is contradicted by graviceptive information. Judging from the literature, however, it appears unlikely that the underestimation is due to limitations in the semicircular canal system.

The ability of humans to perceive semicircular canal stimuli has been studied using a variety of motion profiles and recording techniques. As regards angular displacements, one method is to ask subjects to express the perceived magnitude of various stimuli in terms of fractions or multiples of an easily sensed "standard" stimulus, to which they have been acquainted prior to the experiment. Mergner et al.[10] exposed subjects, seated upright on a Bárány chair, to constant angular velocity steps; velocities ranged between $5° \cdot s^{-1}$ and $40° \cdot s^{-1}$ and were maintained for between 1 s and 16 s. One standard stimulus was a displacement of 40° performed during 4 s. All displacements of this magnitude or smaller were, on average, perceived close to veracity, even when the intensity was as low as $5° \cdot s^{-1}$. In a similar study Becker et al.[1] used sinusoidal oscillations in the horizontal plane. Perceptions of angular velocity and angular displacement were estimated for a wide range of frequencies; peak angular velocities ranged between $4° \cdot s^{-1}$ and $64° \cdot s^{-1}$ with peak-to-peak amplitudes between 11° and 180°. The standard stimulus had a peak velocity of $16° \cdot s^{-1}$ and its amplitude was 45°. Displacements of 11°, 22°, and 34° (with peak angular velocities of, respectively, $4° \cdot s^{-1}$, $8° \cdot s^{-1}$, and $12° \cdot s^{-1}$) were as accurately perceived as the standard stimulus.

Angular displacements of moderate amplitude can be more directly quantified via recording of voluntary eye movements toward a memorized starting point (a light presented at a straight ahead position prior to displacement). Using this paradigm, Israël et al.[8] measured the responses to displacements with magnitudes ranging between 5° and 50°, performed during 2 s. At the group level, the ratio between the magnitude of the eye movement and the preceding angular displacement was close to unity for the whole range of stimuli. In a later study, Israël et al.[7] found that the ability to estimate the magnitude of angular displacements is essentially independent of the plane of canal stimulation. Seated on a rotating chair, subjects were passively displaced by 30-180° (stimulus) and were then required to rotate back to the starting position (response) using a joystick. Subjects were also able to return to the starting position with great accuracy in experiments where the head position was changed from upright to hyperextended backward, or vice versa, between stimulus and response. As regards the perception of angular-displacement stimuli to the vertical semicircular canals, a noteworthy investigation was performed by Owens and Guedry,[12] who recorded the perception of angular displacements in the roll plane. In the supine position subjects were rotated about an Earth-vertical axis passing through the center of the head. The magnitude of displacements ranged from 10° to 375°. After each displacement the subject gave an estimate by means of a pointer on a dial. Although there was a very large interindividual variability, the group means for perceived displacements were close to the ideal.

Since the above-mentioned findings suggest that angular displacement stimuli like in the present helicopter experiments can be adequately perceived via the semicircular canal system, we will next examine the alternative explanation, namely that the under-estimation of pitch-forward angular displacements found in both the centrifuge and the helicopter is due to the conflicting graviceptive message. In the static 1-g environment, head-centric rotation about an Earth-vertical axis does not result in otolithic cues, whereas changes in head orientation with respect to gravity may be detected both by the semicircular canals and the otolith organs. Concerning canal-related effects of angular oscillation in pitch, it has been found that the gain for the vestibulo-ocular reflex is higher for rotation about an Earth-horizontal than about an Earth-vertical axis;[2] in the former case the canal message is "assisted" by otolithic input, whereas in the latter it is "gravity-neutral," i.e., the graviceptive systems neither confirm nor contradict the canal signal. During a pitch-forward dive with the helicopter, the subject will experience a third kind of otolith-canal interaction: the otolith organs persistently deny that there is a change in head orientation. Taken together, the findings that 1) angular displacements of magnitudes and velocities similar to those created in the helicopter can be adequately perceived by the canal system, and that 2) otolithic input can influence the response to a canal stimulus are reasons to believe that the underestimation of pitch-forward displacements found both in the helicopter and the centrifuge is due to the fact that the canal message is contradicted by graviceptive information.

Experiments analogous to those of the present study have also been performed for the roll plane.[24] When the subject is facing forward, acceleration of the centrifuge or entering a coordinated turn with a fixed-wing aircraft results in a roll-plane canal-otolith conflict; while the otolith organs persistently signal that the head is upright, the roll tilting of the gondola or aircraft is a stimulus to the semicircular canals.[25] Recordings of the subjective visual horizontal have also revealed that in this stimulus situation most subjects make considerable under-estimations of the angular displacement.[22,24] There is, however, a difference between nonpilots and pilots—both fighter pilots and helicopter pilots indicated a significantly larger perceived roll tilt (on average approximately 50% of the physical roll tilt) than nonpilots.[23]

In the present study, the VPEL was significantly lower in the group of helicopter pilots than among the nonpilots, a difference that could possibly be explained by the pilots' experience of viewing the surface of the Earth from a higher viewpoint. Nevertheless, when it comes to the ability to perceive the angular displacements of the helicopter, there was no difference between nonpilots and helicopter pilots. Thus, it appears that experience of maneuvering a helicopter, where changes in roll and pitch attitude can often also be recognized via visual contact with the surroundings, does not result in an improvement in the ability to interpret the vestibular stimuli. In an earlier centrifuge study we recorded the ability to perceive forward and backward pitch angular displacements of 60°. In that study, experienced helicopter pilots also showed results very similar to those obtained in nonpilots. The indicated pitch angular displacements were, however, considerably greater among fighter pilots.[21]

The interindividual variability in the present material was substantial. In the helicopter, the individual mean gain ranged between 10% and 60%. The within-subject variability was, in general, notably smaller. In the centrifuge, where the stimulus could be repeated in an accurate way and always commenced with a tangible jerk (when planetary acceleration of the centrifuge started), there was also considerable interindividual variability, suggesting that the interindividual variability in the helicopter is not merely a consequence of poor precision or predictability in the stimulus profile. In addition, the correlation between the responses to 25° and 60° displacements in the centrifuge confirms that the response variability is not simply due to uncertainties in the measurement procedure.

It is beyond the scope of the present study to provide an explanation of the differences between individuals. A few possible sources of variation will, nevertheless, be briefly discussed. These are: 1) the sensitivity of the semicircular canal system to angular velocity stimuli; 2) the central nervous velocity-to-position integration of canal signals; 3) the relative dependence, or weighting, of input from the canals and otolith organs; 4) the idiotropic vector; and 5) cognitive factors.

Vision plays an important role in updating the responses to vestibular stimuli.[5,26] In the laboratory there is, nevertheless, often a substantial interindividual variability among young and healthy subjects, even when it comes to visual or oculo-motor responses. For example, in the study by Owens and Guedry,[12] there was a 10-fold variation (total range among 26 subjects) in the ability to indicate roll-plane angular displacements about an Earth-vertical axis. This finding might suggest that the variability in perceived pitch displacement found in the helicopter and centrifuge can be related to rather basic mechanisms of the canal system which govern perceived angular velocity or velocity-to-position integration. Nevertheless, since the stimulus situation in the present experiments is rather different, it is warranted to also reflect upon other possible causes of the differences between individuals.

In conditions where there is a conflict between two sensory inputs, the brain has to make a weighting operation. As long as the otolith organs and semicircular canals provide unanimous information regarding changes in head orientation with respect to gravity, as is often the case during natural head movements in the static 1-g environment, the relative dependence of an individual on these two receptor systems is not likely to be of major significance for spatial orientation and balance. This order of things would permit differences between individuals in the relative dependence on canal and otolith information. In conditions where the two sources of information are in conflict with each other, however, such variation would contribute to differences in the perception of angular displacements. Thus, during the otolith-canal conflict encountered in the helicopter or centrifuge, otolith-dependent individuals would experience smaller angular displacements than individuals who are more sensitive to canal signals.

The canal-induced deflections of the VPEL are not just counteracted by input from the otolith organs. According to Mittelstaedt's theory on human spatial orientation, there is also a tendency, inherent in the central nervous system, to localize the subjective zenith on one's own head and body long (z) axis.[11] This tendency can be represented by a vector, termed the idiotropic vector, whose magnitude might be an individual constant.

In the present experiments, subjects were instructed not to make any conscious efforts to estimate the angular displacements, but to indicate what they spontaneously perceived as the height of the horizon. It cannot be excluded, however, that there are individuals who are still prone to respond in a cognitive manner in spatial orientation tasks. In such a hypothetical subject, a cognitive tendency to displace the luminous dot upwards would be added to the more instinctive response. If this were a major cause of interindividual variability, then large individual gain values would also be associated with a greater variability. Although there was no obvious such trend in the present material, it can be noted that the three individuals who had the greatest gains in the helicopter also displayed a comparatively large variability in their responses (Fig. 3). Two of these individuals were pilots.

The gain values found in the centrifuge were similar to those obtained in the helicopter. This pertains not only to the group means, but also to the interindividual variability. Considering only the pitch plane, the stimulus experienced in the helicopter can be recreated in a gondola centrifuge with the subject facing centripetally. In both systems there is an intravestibular conflict with an otolithic message contradicting the canal signal for pitch-forward angular displacement. Displacements as created in the centrifuge are, however, accompanied by an increasing G vector. For displacements with greater amplitude, this might result in a smaller gain for perceived displacement. Nevertheless, the gain value was only slightly smaller for the 60° displacements than for those of 25°.

Perhaps a more tangible characteristic of the stimulus situation in the centrifuge is the pronounced angular-velocity stimuli in yaw and roll. Presumably, these stimulus components may constitute a distraction, interfering with the task of responding to the displacements in pitch. That this was not the case suggests that subjects are able to "single out" and focus on a single component of a complex motion pattern. On the other hand, it might be argued that the distinct temporal pattern of the centrifuge stimulus, including the jerk associated with the beginning of the stimulus, would alert the subject, making him or her attentive to the pitch angular displacements, whereas in the helicopter the pitch stimulus profile is rather unpredictable and not accompanied by other tangible cues. Thus, it is possible that a distraction caused by yaw and roll angular velocity would be counterbalanced by the more distinct stimulus profiles in the centrifuge.

The present data and those of previous experiments in centrifuge and aircraft confirm that measurement of the perceived horizontal plane can be used for elucidating vestibular mechanisms for spatial orientation in certain elementary flight situations. For the detection of short-lasting phenomena, continuous recording is warranted. The device used in this study enables the test subject to indicate rapid or transient shifts in perceived eye level. The substantial interindividual variability is not the consequence of random noise or uncertainties regarding the task. This fact, as well as the similarity between data obtained in the helicopter and centrifuge, raises questions regarding the feasibility of testing and training. Firstly, the individual pilot might benefit from being aware of his or her own limitations. Secondly, there seems to be a possibility of using a centrifuge-based flight simulator for recreating the vestibular dilemma encountered by helicopter pilots during an involuntary change in attitude (as might happen in a brownout situation). Finally, recording the perceived horizontal plane might be used to establish the effects of training programs or whether certain components of spatial orientation can be improved by training in a centrifuge-based flight simulator.

ACKNOWLEDGMENTS

The study was supported by the Swedish Armed Forces (AF.9220907) and by a grant from the Fraenckel Foundation. The authors sincerely thank Scandinavian Helicopter Center, Västerås, where the in-flight experiments were performed.

Authors and affiliations: Arne Tribukait, M.D., Ph.D., Eddie Bergsten, and Ola Eiken, M.D., Ph.D., Department of Environmental Physiology, Swedish Aerospace Physiology Centre, Royal Institute of Technology, KTH, School of Technology and Health, Solna, Sweden.

REFERENCES

1. Becker W, Jürgens R, Boss T. Vestibular perception of self-rotation in different postures: a comparison between sitting and standing subjects. Exp Brain Res. 2000; 131(4):468–476.
2. Bockisch CJ, Straumann D, Haslwanter T. Human 3-D aVOR with and without otolith stimulation. Exp Brain Res. 2005; 161(3):358–367.
3. Braithwaite MG, Durnford SJ, Crowley JS, Rosado NR, Albano JP. Spatial disorientation in U.S. Army rotary-wing operations. Aviat Space Environ Med. 1998; 69(11):1031–1037.
4. Clark BJ, Taube JS. Vestibular and attractor network basis of the head direction cell signal in subcortical circuits. Front Neural Circuits. 2012; 6:7.
5. Guedry FE. Visual control of habituation to complex vestibular stimulation in man. Acta Otolaryngol. 1964; 58:377–389.
6. Guedry FE, Oman CM. Vestibular stimulation during a simple centrifuge run. Pensacola (FL): NAMRL; 1990.
7. Israël I, Bronstein AM, Kanayama R, Faldon M, Gresty MA. Visual and vestibular factors influencing vestibular "navigation". Exp Brain Res. 1996; 112(3):411–419.
8. Israël I, Rivaud S, Pierrot-Deseilligny C, Berthoz A. "Delayed VOR": an assessment of vestibular memory for self motion. In: Requin J, Stelmach GE, editors. Tutorials in motor neuroscience. Dordrecht (The Netherlands): Kluwer Academic Publishers; 1991:599–607.
9. Matin L, Fox CR. Visually perceived eye level and perceived elevation of objects: linearly additive influences from visual field pitch and from gravity. Vision Res. 1989; 29(3):315–324.
10. Mergner T, Rumberger A, Becker W. Is perceived angular displacement the time integral of perceived angular velocity? Brain Res Bull. 1996; 40(5–6): 467–70; discussion 470–471.
11. Mittelstaedt H. A new solution to the problem of the subjective vertical. Naturwissenschaften. 1983; 70(6):272–281.
12. Owens GG, Guedry FE. Assessment of semicircular canal function. II. Individual differences in subjective angular displacement produced by triangular waveforms of angular velocity. Pensacola (FL): Naval Aerospace Medical Institute; 1969. Report No.: NAMI-1074; USAARL 69-13.
13. Parmet AJ, Ercoline WR. Spatial orientation in flight. In: Davis RD, Johnson R, Stepanek J, Fogarty JA, editors. Fundamentals of aerospace medicine, 4th ed. Philadelphia: Lippincott Williams & Wilkins; 2008: 142–205.
14. Seddon J, Newman S. Basic helicopter dynamics, 2nd ed. An account of first principles in the fluid mechanics and flight dynamics of the single rotor helicopter. London (UK): Blackwell Science; 2002.
15. Stockwell CW, Guedry FE. The effect of semicircular canal stimulation during tilting on the subsequent perception of the visual vertical. Acta Otolaryngol. 1970; 70(3):170–175.
16. Tribukait A. Subjective visual horizontal in upright posture and asymmetry in roll-tilt perception: independent measures of vestibular function. J Vestib Res. 2006; 16(1–2):35–43.
17. Tribukait A, Bergsten E, Eiken O. Variability in perceived tilt during a roll plane canal-otolith conflict in a gondola centrifuge. Aviat Space Environ Med. 2013; 84(11):1131–1139.
18. Tribukait A, Eiken O. Semicircular canal contribution to the perception of roll tilt during gondola centrifugation. Aviat Space Environ Med. 2005; 76(10):940–946.

19. Tribukait A, Eiken O. Roll-tilt perception during gondola centrifugation: influence of steady-state acceleration (G) level. Aviat Space Environ Med. 2006; 77(7):695–703.
20. Tribukait A, Eiken O. The human sense of the head's polarity is influenced by changes in the magnitude of gravity. Brain Cogn. 2007; 63(1):24–30.
21. Tribukait A, Eiken O. Flight experience and the perception of pitch angular displacements in a gondola centrifuge. Aviat Space Environ Med. 2012; 83(5):496–503.
22. Tribukait A, Eiken O. On the time course for short-term forgetting: a human experimental model for the sense of balance. Cogn Neurodyn. 2016; 10(1):7–22.
23. Tribukait A, Grönkvist M, Eiken O. The perception of roll tilt in pilots during a simulated coordinated turn in a gondola centrifuge. Aviat Space Environ Med. 2011; 82(5):523–530.
24. Tribukait A, Ström A, Bergsten E, Eiken O. Vestibular stimulus and perceived roll tilt during co-ordinated turns in aircraft and centrifuge. Aerosp Med Hum Perform. 2016; 87(5):454–463.
25. Young LR. Perception of the body in space: mechanisms. In: Geiger SR, editor. Handbook of physiology III/1. Bethesda (MD): American Physiological Society; 1984.
26. Zennou-Azogui Y, Xerri C, Leonard J, Tighilet B. Vestibular compensation: role of visual motion cues in the recovery of posturo-kinetic functions in the cat. Behav Brain Res. 1996; 74(1–2):65–77.