The Optokinetic Cervical Reflex in Pilots of High-Performance Aircraft

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Background: For over 60 yr, researchers and engineers have based investigations and the design of cockpit displays and structures upon the presupposition that during flight the pilot maintains a head alignment coincident with the aircraft's vertical axis (z-axis). Recent simulator studies have verified the existence of a pilot neck reflex which refutes this long-standing assumption. This reflex, named the opto-kinetic cervical reflex (OKCR), occurs during visual flight and is theorized to be an attempt by the pilot to stabilize a retinal image of the horizon to maintain spatial orientation. As a result, during initial banking maneuvers, pilots view a fixed-horizon image and not a moving-horizon. The research objectives were to determine if the OKCR occurs during actual flight of high performance jet aircraft and to model the response. ***Hypothesis:*** Pilots of high performance aircraft will exhibit the OKCR. Additionally, the OKCR is dependent on the phase of banking (entering into or exiting from a banked position). ***Methods:*** This was an observational study in which the head positions of nine pilots were recorded during actual F-15 aircraft flight and subsequently analyzed. ***Results:*** Objective data indicate the OKCR caused pilots to tilt their heads during aircraft bank ($p < 0.0001$). Also, the reflex was found to be independent of the bank phase. ***Conclusion:*** The OKCR was shown to be a strong, natural response and the flight results correlated closely with simulator results. The effect of these results on pilot training, spatial disorientation, physiological injury and safety, and the redesign of displays for aircraft attitude and virtual reality are discussed.

RECENT FLIGHT simulator studies concerning pilot head orientation during flight have refuted a previous, long-standing assumption that pilots always align their head and body vertically with the aircraft (in the z-axis) throughout all flight maneuvers. Poppen (6) stated this original premise in 1936 following the successful implementation and employment of the first attitude indicator display. The statement was merely an educated observation and was not based on scientific evidence or testing.

The persistence of the assumption for the past six decades has been due to a number of issues. Primarily, the assumption had never been challenged by actual scientific studies involving pilot head alignment. Secondly, the assumption had been propagated via pilot training and education which discourage motion of the head during flight. This training leads pilots to "believe" they do not tilt their heads during flight. Finally, no direct link had been established between aircraft mishaps, aircraft displays, and the possibility that Poppen's 1936 statement was incorrect. The closest attribution to that link is that of spatial disorientation (SD). SD is typically attributed as a cause, in and of itself, of human error (and mishaps) but not as a result from a conflict between aircraft displays and the reality of pilot head alignment during flight.

Two recent investigations (5,7) have documented the existence of a pilot reflex currently named the optokinetic cervical reflex (previously: optokinetic collic reflex), or OKCR (5). Using helmet-mounted trackers in dome simulators, both studies found that pilots naturally tilt their heads during aircraft bank in an apparent attempt to align their eyes with the visible horizon. This reflex occurs during visual flight but not during instrument (no external visual stimuli) flight. The discovery of the OKCR is important since pilots have been trained to minimize their head motion during flight. Both studies were completed in nonmotion aircraft simulators. Until this time, no studies have objectively investigated the existence of the OKCR during actual flight.

Research Objective

The purpose of this research is to determine if the optokinetic cervical reflex occurs during actual flight of high performance jet aircraft. The focus is on the lateral flexion reflex (left and right angle of head tilt) in response to aircraft bank (or roll) angle. The connection between these variables will provide information as to which environmental sensory cues are important to the pilot in order to maintain the aircraft's attitude. Increased understanding of this subject can be used to more accurately design aircraft attitude displays—specifically, the design and choice of symbology used in helmet-mounted displays (HMD) and in head-up displays (HUD). Further, other flight-related topics such as training and physiological effects should be re-evaluated in light of the results.

Common sense indicates that during human develop-

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* Posthumously.

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ment the human body attempts to maintain vestibular order by keeping the head vertical with respect to the Earth's gravitational acceleration. As a self-mobile being on the Earth's surface, the human is equipped with visual, vestibular and other sensory organs which provide the necessary feedback to deal with normal physical events. But these events are usually limited to activities such as crawling, standing, walking, running, climbing, etc. The sensory information input to the visual, vestibular and other sensory channels for these activities is relatively low in frequency and magnitude when compared with more complex activities. Therefore, it should not be surprising that during highly dynamic motion, the visual and vestibular systems have difficulty bringing order to an overwhelming, chaotic influx of sensory information. This is especially true when this activity involves the unnatural occurrence of motion in the coronal plane (roll plane) such as occurs during flight.

Today's high performance jet fighter aircraft can approach speeds in excess of 2 Mach, perform rolls at rates greater than $360° \cdot s^{-1}$, and subject its occupant(s) to acceleration forces over 12 times the force of Earth's gravity. These extremely foreign conditions force the human system to compensate using reflexes and abilities developed on the Earth's surface. These reflexes are typically inadequate for the extreme conditions, resulting in injury, fatality, or the necessary re-design of the aircraft. Often, new reflexes are found as a result of placing a human in a foreign environment. This is believed to be the case in the discovery of the OKCR.

METHODS

Subjects

The subject pool consisted of nine USAF operational fighter test pilots. Each volunteer was male with 6 to 12 yr experience flying high-performance fighter aircraft and was currently actively flying the F-15 aircraft. All pilots were instrument-qualified. The pilots read and signed a consent form explaining all risks and benefits of the investigation. In addition, the pilots were advised that the purpose of the study was to evaluate normal pilot reflexive actions during various phases of flight. This was a single blind investigation and, therefore, subjects were not briefed on the actual variables until the completion of the study. There was no remuneration for participation in the study.

Apparatus

The subjects piloted McDonnell-Douglas F-15C fighter aircraft based at Nellis AFB, NV. As this investigation involved actual (not simulated) flights in high-performance fighter aircraft, it was imperative that non-invasive methods of data collection were employed. Two F-15 aircraft were pre-equipped with Polhemus® MAGNETRAK magnetic head tracker systems which allowed the collection of pilot's head motion parameters without interfering with the pilot's tasks. This satisfied the requirement for passive, non-invasive data collection techniques. The head tracker has a resolution of 0.088° based upon 12-bit accuracy.

Procedures

This was an observational study and, therefore, no experimental task was designed. All data were collected from normal, day-to-day aircraft sorties and missions flown at Nellis AFB. All missions occurred during VMC (visual meteorological conditions) flight. These sorties and missions were not specific to this study. Pilot subjects flew sorties during which various maneuvers and engagements took place. Both aircraft position data and pilot head orientation data were simultaneously recorded via telemetry during the flights. Coincidentally, the Nellis AFB air ranges were the same scenario in the Patterson (5) and Smith (7) studies in which the subjects flew simulated F-15 aircraft. Thus this investigation matched the basic flight environment conditions and data collection techniques of previous related studies.

Data Collection

During flight, pilot head orientation and aircraft dynamic parameters were continuously sent from the aircraft to ground stations via near-real-time electronic telemetry signals. These parameters were then stored as raw data on magnetic tapes for each pilot and mission. The data sampling rate was ~10 samples per second (or approximately one data point every 100 ms).

The raw data tapes were then used with a graphics workstation to playback the mission. The application on the workstation projected a three-dimensional (3-D) view of the ground and airspace showing all active aircraft on the flying range. The software allows the "observer" free movement of the point-of-view (POV) in three-space to observe the mission scenario from any vantage point (including a bird's-eye view). In addition, the observer can "attach" the POV to the tail of any aircraft in the scenario and follow that aircraft throughout the mission essentially "viewing" what the pilot had seen from the cockpit.

In order to replicate as closely as possible the task conditions used in the simulator studies (5,7), the investigator made every attempt to discard data during which the pilot was obviously engaged in active pursuit of another aircraft. The investigator studied the mission to isolate time periods during which the pilot had performed basic, simple flight maneuvers, preferably when the pilot was not engaged in a mode where the primary visual stimulus was another aircraft in the airspace. Since it was impossible to know where the pilot was looking in every instance, some of the time periods may have included part or all of an engagement. These time periods were recorded as a list for each pilot/mission.

Finally, the time intervals were used in conjunction with data reduction techniques to create blocks of data for which only the orientation parameters of interest (aircraft and pilot head) were retained.

Variables

The dependent variable, ROLL, was the pilot head tilt angle as measured from body vertical; negative ROLL values corresponded to a lateral flexion tilt to the left. The two independent variables were BANK and PHASE. BANK was the aircraft angle of bank with respect to the

TABLE I. SINGLE FACTOR ANOVA RESULTS.

Source	df	MS	F	p
BANK	36	2082.951	23.19	0.0001
Subject × BANK	288	89.838		

Earth's horizon; negative BANK values corresponded to a left aircraft bank. The second independent variable, PHASE, was a qualitative variable with two values: INTO and OUT_OF. To investigate whether subjects' head tilt response may have been dependent upon the phase of the aircraft turn, the data was divided into two categories: head tilt while entering (INTO) the banked turn and head tilt while exiting (OUT_OF) the turn.

The nine pilots in the study were considered to be a sample from the population of possible pilots. The aircraft bank angle was divided into 5° increments.

RESULTS

Subject Data

All nine subjects completed a sufficient number of maneuvers (aircraft banking turns) to provide a quantity of raw data equivalent to or greater than that used in the simulator studies. Using the process described above, data were converted into a 2 × 37 matrix for each pilot (2 levels for phase: bank angle increasing vs. decreasing; 37 levels for bank angle: 5° increments between −90° and +90° of aircraft bank). These matrices were then used for analysis. The mean head tilt for each pilot at each aircraft bank angle was the dependent variable in the matrices for two reasons: 1) this method provided a balanced ANOVA approach via one head ROLL observation per aircraft BANK angle; and 2) this was the method used to analyze the simulator study results. Level of significance was 0.05 for all analyses.

Missing Data Points

As there was no control over specific angles of bank during aircraft turns, the subjects employed each of the 37 levels of BANK (±90°) differently. In most cases there was a minimum of one head tilt (ROLL) data point for each of the 5° levels of BANK. However, overall there were 7 missing data cells of a total 333 (37 × 9). Although this was a small percentage (2%) of missing data points, only 326 observations were included in the analysis.

Aircraft Bank Phase Interaction and Main Effects

The main effect for PHASE of the aircraft turn, characterized by an increasing or decreasing angle of aircraft bank, was not found to be statistically significant (F(1,8) = 0.14, p = 0.7169). Furthermore, there was no significant interaction between BANK and PHASE (F(36,288) = 1.22, p = 0.1924). Therefore, data were pooled leaving a single-factor, repeated measures model design.

Aircraft Bank Angle Main Effects

There was a significant effect of aircraft BANK angle upon the subjects' head ROLL angle: (F(36,288) = 23.19, $p < 0.0005$). See **Table I** for the pooled data ANOVA results. The plot in **Fig. 1** shows the overall mean head tilt (for all subjects) at each level of aircraft bank angle. The maximum and minimum subject data at each aircraft bank angle level is also annotated via high/low bars.

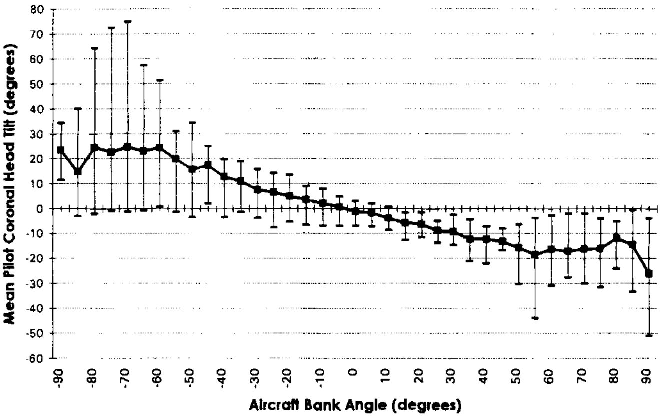

Fig. 1. Mean pilot head tilt in the coronal plane as a function of F-15 aircraft bank angle flight data (■). Maximum and minimum subject head tilt angles annotated by hi/lo bars (–).

Regression Analysis Results

Data from simulator studies suggested the OKCR response is sigmoidal in shape with a linear phase between ~±45° at which point it levels-off asymptotically. Trend analysis was used to determine the components of the model. Initially four forms were tested: linear, quadratic, cubic, and quartic. These were chosen since the sigmoid shape has a linear trend as well as two-reverse points. An F-test involving each of the four fundamental forms was accomplished. It was hypothesized that the F-test would be significant for the linear and cubic components, but not for the quadratic or quartic forms.

Following the significant results of aircraft BANK upon the pilot head ROLL angle (tilt of head), a regression procedure was used to determine the coefficients of the response. As predicted, the linear and cubic parameters were found to be statistically significant (p = 0.0002 and p = 0.0013, respectively), while the quadratic and quartic components were not statistically significant (p = 0.1550 and p = 0.0992, respectively). These results were produced via the POLYNOMIAL option in the SAS GLM procedure. The equation used to fit the model was:

$$\mathrm{ROLL} = \beta_0 + \beta_1 \times \mathrm{BANK}_1 + \beta_2 \times \mathrm{BANK}_2 + \beta_3 \times \mathrm{BANK}_3$$

The results of the regression procedure are in **Table II** (ANOVA) and **Table III** (parameter estimates). **Fig. 2** shows the plot of the predicted polynomial response based on the regression analysis.

TABLE II. REGRESSION ANALYSIS ANOVA RESULTS.

Source	df	MS	F	p
Regression Model	3	2679.313	300.879	0.0001
Error	33	8.905		
R^2			0.9647	
Adjusted R^2			0.9615	

TABLE III. REGRESSION ANALYSIS PARAMETER ESTIMATES.

Variable	df	Parameter Estimate	Standard Error	T for H_0: $\beta_x = 0$	Prob > |T|
INTERCEPT	1	−0.04403	0.7363	−0.598	0.5540
$BANK_1$	1	−0.3998	0.0230	−15.622	0.0001
$BANK_2$	1	0.000419	0.000193	2.176	0.0368
$BANK_3$	1	0.000017	0.000004	4.122	0.0002

DISCUSSION

The OKCR Effect During Actual Flight

The results of this study indicate that the OKCR is an irrefutable behavior of pilots in high performance jet aircraft. This validates the objective results of the simulator studies (4,6) and objectively confirms subjective observations (4). **Fig.** 3 shows a plot of the four OKCR models. Each line is a plot of head angle versus aircraft bank angle. The four models are this study's third-order model, Patterson's third-order model (5) and Smith's active and passive fourth-order models (7). Graphical inspection indicates a good match between all four models.

In order to compare the actual flight data against the simulator models, the method of standardized residuals was utilized. Each subject's mean head tilt response at every aircraft bank angle increment (from actual flight data) was compared with the predicted head tilt from the (simulator) models. A minimum of 95% of all the standardized residuals fell within the normal range for each of the three models considered. Therefore, the OKCR flight data was found to be statistically comparable to the results from the previous simulator studies.

As expected, most of the extreme outliers occurred at the tail ends of the aircraft bank angle—those angles between ±80 and 90°. There was greater variance of the data at the higher bank angles due to the smaller number of observations. An exception was a single subject who had numerous extreme outliers in the left aircraft bank data cells. This subject appears to have exhibited extremely high head tilt angles during aircraft banks to the left. Further investigation into this subject's data determined that this range (extreme left aircraft bank) was the only region for which this anomaly existed. Any number of confounding variables could explain this response: e.g., poor data collection, pilot was visually tracking (or engaging) another aircraft, or the helmet system rotated during flight and was subsequently uncalibrated for part of the mission. The extreme tail end, for left aircraft bank, of this study's third-order model is, therefore, suspect and should be interpreted as a possible product of the extreme outlier data.

Strength of the OKCR Effect

Despite the many confounding factors (see previous section) possible in an observational study such as this, the OKCR was significant enough to overcome these extraneous variables. An approximation of the simulator studies results was predicted, but the actual level of coincidence between the three studies was extremely surprising. The fact that the OKCR can be induced in a motionless simulator, without the true physical and vestibular effects of actual flight, also suggests that the reflex is a powerful, natural behavior based primarily on visual inputs.

Significance of Aircraft Bank Phase Results

The results of this investigation suggest that the OKCR response is not dependent upon whether the pilot is en-

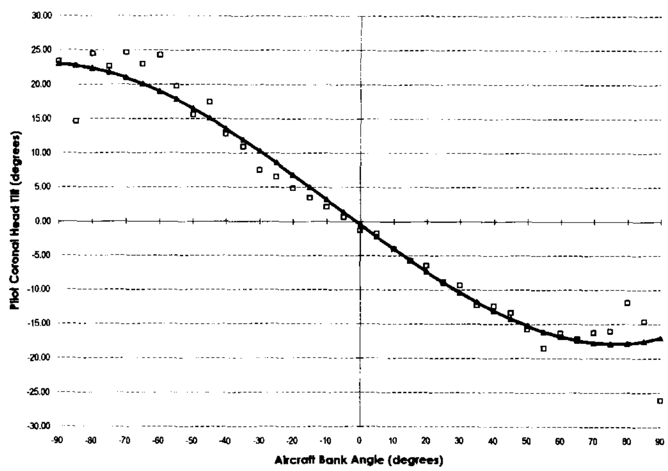

Fig. 2. Opto-kinetic cervical reflex (OKCR) model from flight data (▲). Mean pilot head tilt is also indicated (☐).

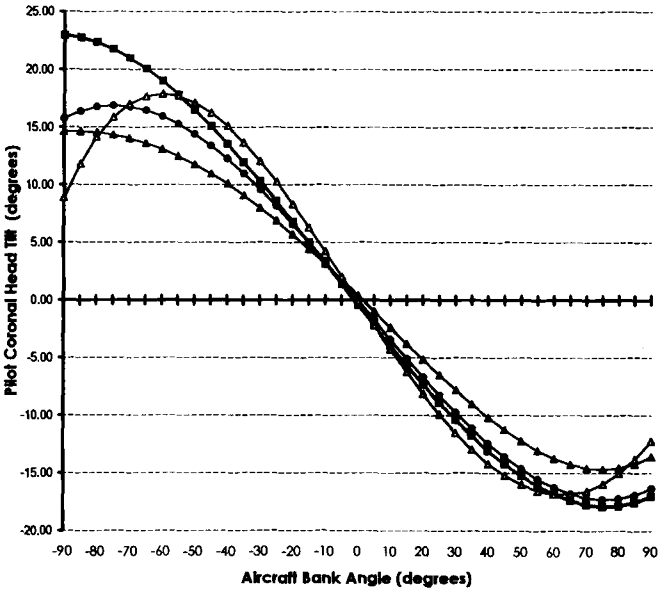

Fig. 3. Plot of four OKCR models from flight and simulator studies. ■ = OKCR Model (Merryman, 1995); ● = OKCR Model (Patterson, 1995); ▲ = OKCR Model (Smith [Active Subject], 1994); △ = OKCR Model (Smith [Passive Subject], 1994).

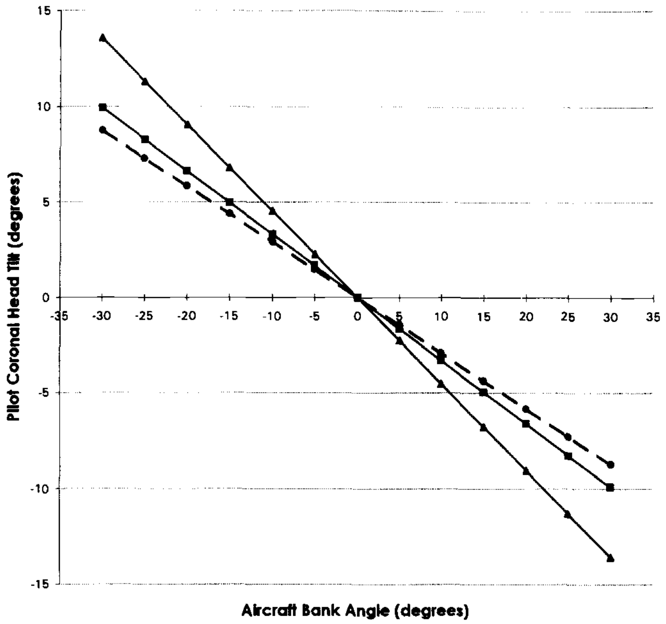

Fig. 4. Comparison of linear segments (±30° aircraft bank) between flight data and simulator data OKCR response models. †p < 0.01 from Smith [Passive Subject]. ● = Linear OKCR Model (Merryman, 1995); ■ Linear OKCR Model (Smith [Active Subject], 1994); △ Linear OKCR Model (Smith [Passive Subject], 1994).

tering into a bank or returning from one. The data plots graphically indicated that there are no hysteresis effects between the two phases. This result should be accepted cautiously. Since this was a relatively non-controlled, observational study, other confounding variables may have prevented any phase effect from becoming apparent. A controlled experimental task in which pilots flying actual aircraft follow a prescribed flight path should provide a better set of data from which the bank phase effect can be studied.

However, if the bank phase is, as this study has shown, independent of the OKCR, then this is a critical finding since it can reduce the complexity of future display design. Attitude displays which will compensate for OKCR effects will be much simpler if the only inputs are the aircraft's and the pilot head's orientations—bank phase effects would greatly complicate any design.

Analysis of Linear Segment of OKCR Response

Fig. 4 shows a plot of the linear segment of the OKCR response between ±30° of aircraft bank. The three lines represent the linear regressions from the actual flight data and from Smith's simulator data (7). The simulator data has two lines: one is the OKCR exhibited by the subject actively controlling the simulator; the other is the reflex exhibited by the subject who was passively observing the auto-piloted flight. Smith found a significant difference between the slopes of the passive and active simulator data. Since the F-15 flight data for this investigation involves pilots flying single-seat fighter jets, it was hypothesized that the linear regression line would match Smith's active data and not the passive data. Graphically, the flight data correlates well with the active data.

Two *t*-tests were conducted comparing the mean linear regression slopes from each pilot to each of Smith's active and passive slopes. **Table IV** summarizes the *t*-test procedures and results. The *t*-tests revealed a significant difference between the flight data and the passive simulator data (p = 0.0023), while the difference between the flight data and the active simulator data was found to be not significant (p = 0.4762). These results indicate that the actual flight data corresponds extremely well with the appropriate simulator data, further validating the OKCR simulator research.

Analysis of Asymptotic Effects in the OKCR Response

According to Patterson (5), the OKCR is a natural attempt to stabilize a retinal image of the horizon to provide a reference stimulus. This true horizon image is theorized to provide the primary spatial reference for maintaining spatial awareness. The OKCR response behaves in a linear fashion at smaller angles of aircraft bank. During these low angles (<40°) the pilot maintains an almost fixed visual orientation with respect to the horizon—the aircraft and pilot's body act as a separate "system," moving independently from the pilot's head. But, as higher angles of aircraft bank (>40°) are encountered, the OKCR response begins to level and the pilot's head begins to move with the aircraft and against the horizon image. This reflects a significant transition in visual orientation cues and reference frame.

The asymptotic limit of the pilots' head tilt was in the range of 15 to 20° of latero-flexion (reference Fig. 2). Recent studies have found the mean maximum latero-flexion angle for males (non-military) to be 41° with a standard deviation of 7° (8). There is at least a 20° difference between the maximum mean OKCR head tilt and that of the Woodson, et al. research (8). The question then posed. What are the mechanisms for the limited head tilt and why does it occur at approximately 40° of aircraft bank? Patterson (5) has suggested that the asymptotic limit is an anatomical limit—that pilots reach a maximum neck flexion in the coronal (mid-frontal) plane. But, in light of the anthropometry findings, there appears to be other mechanisms since the pilots are far from the mean male extreme head tilt angle. The remaining part of this section will present proposed interpretations behind the asymptotic effect.

The proposed interpretations fall under two categories: physiological/physical and cognitive (4). The physiological and physical explanations will be discussed first.

Physiological/Physical Interpretations of the OKCR Asymptotic Response

The exhibited limit to head tilt is not a true physical limit as much as it may be a comfort level limit. The anthropometry results (8) were for extreme head tilt, not a "comfortable" head tilt. It may be true that, if asked to tilt their head to a comfortable angle, subjects would exhibit a head tilt in the range of 15 to 20°. This should be investigated. An alternative interpretation is that of normal acceleration-attenuated neck flexion. At extreme aircraft angles of bank (AOB), the normal accelerations on the pilot may be greater than 6 g. It is possible that the high G-loading on the neck prevents full flexion of

TABLE IV. *t*-TEST RESULTS FROM COMPARISON OF LINEAR REGRESSION SLOPES BETWEEN FLIGHT AND SIMULATOR OKCR MODELS FOR AIRCRAFT BANK ANGLES ± 30°.

Subject	Flight Data Regression Slope	Difference between Flight Slope and Active Subject* Slope	Difference between Flight Slope and Passive Subject† Slope
1	−0.29	0.04	0.17
2	−0.09	0.24	0.36
3	−0.34	0.00	0.12
4	−0.23	0.10	0.22
5	−0.31	0.02	0.14
6	−0.33	0.00	0.12
7	−0.38	−0.05	0.07
8	−0.45	−0.11	0.01
9	−0.34	−0.01	0.11
	Mean	0.02	0.15
	S_d^2	0.01	0.01
	t_8	0.75	4.40
	$t_{\alpha/2}$	1.86	1.86
	p-value	0.4762	0.0023‡

* From Smith (7) involving pilots actively flying a simulator (slope = −0.33).
† From Smith (7) involving pilots passively observing a simulator flight (slope = −0.45).
‡ Indicates a significant difference.

the neck. Additionally, the helmet's weight may further inhibit full latero-flexion. However, since the OKCR asymptotic limitation was observed in simulators without acceleration forces, this interpretation warrants investigation. It is possible that the simulator pilots anticipated a G-load from experience and reacted accordingly. A simulator investigation using subjects without flight experience (never flown, never used a flight simulator or computer flight program) should be accomplished to resolve the flight experience factor as applied to OKCR in simulators.

The actual visual limitations imposed by the frame of the aircraft may be another factor to consider. In both this investigation and the simulator studies the aircraft flown was an F-15. The cockpit structures in the simulator were very close in position and size to those actually found in the F-15's used in this investigation. Also, the HUD field-of-view (FOV) was comparable between actual aircraft and simulator. Due to this similarity, if aircraft structures forced a limitation on OKCR-induced head tilt, then the same asymptotic limits should be seen in both studies—which is what occurred. Further, it is possible that the asymptotic value of head tilt would be greater or less in other aircraft which have a cockpit structure much different from the F-15. For example, in the F-16 aircraft the pilot sits much higher above the aircraft frame and experiences less visual blocking by cockpit structures. Since the OKCR is primarily a visually driven response, any differences of a visual nature may affect the magnitude of the reflex.

Cognitive Interpretation of OKCR Asymptotic Response

There is an interesting angular lag between the OKCR head tilt response and the aircraft AOB (4). Prior to the asymptotic limit of head tilt, the image of the horizon upon the pilot's retina is slowly rotating as the aircraft increases AOB. The plot in **Fig. 5** shows the retinal horizon image angle of rotation as a consequence of the OKCR (■). With the assumption that the OKCR is a reflex to maintain a fixed head-horizon orientation, it is reasonable to predict counterbalance: an aircraft bank of 10° should result in an OKCR tilt of 10°. If there was perfect compensation for the aircraft bank, the OKCR response would be equivalent in magnitude (opposite in direction) to the aircraft AOB until "maximum" head tilt was encountered—at approximately 20–25° of head tilt. This would bring the difference between OKCR and the horizon much closer to zero during low AOB as indicated by the second plot (△) in Fig. 5. However, this is not the case and a lag exists in reality.

The asymptotic limit occurs around 40–45° AOB. At

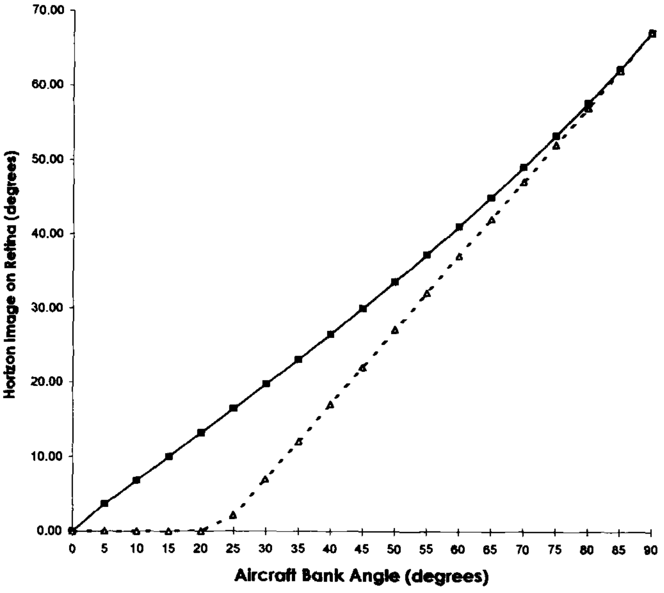

Fig. 5. Angular displacement of horizon image on pilot's retina as a result of the OKCR (■). 0° retinal image is assumed for "normal" view of horizon while head is vertical in the z-axis. Dashed line (△) indicates a proposed model of pilot's horizon retinal image if OKCR compensated perfectly for aircraft bank angle. Neither plot reflects any eye rotation (or torsion), if existent.

this AOB the retinal horizon image is approximately 30° (see Fig. 5). It is proposed that, at this point, the pilot can no longer normalize the image of the horizon. Normalizing refers to the cognitive recognition that the horizon (rotated or not) represents a horizontal frame of reference. This is predicated on the supposal that the human visual system is not a rotationally invariant pattern recognizer (3). The "pattern" in this case is a straight line across the eyes. When the horizon is displaced from its normal, ground-viewed orientation of 0°, at some point (perhaps at 30°) it is no longer a "horizon" and consequently cannot be used as the primary visual cue to maintain spatial orientation.

This supports Patterson's (5) proposal that, upon reaching the asymptotic limit, the primary and secondary visual cues are switched. At low AOB the horizon can be normalized and, therefore, used as a primary cue. At higher AOB the pilot no longer sees a horizon, but senses the motion (rotation) of the horizon in the peripheral vision (secondary visual cue) and aircraft structures become primary for maintaining spatial orientation. While not investigated, eye torsion and aircraft control-response ratio may also influence the apparent OKCR angular lag.

CONCLUSIONS

OKCR in the Actual Cockpit

This investigation verified the opto-kinetic cervical reflex does occur in the cockpit of high performance aircraft. It is a seemingly natural response to a very unnatural stimulus: rotation in the roll (coronal) plane during airborne motion. As Patterson (5) stated, it is theorized that this response is an attempt to stabilize the retinal image of the visible horizon. The stabilized image becomes the primary source of visual information used to maintain spatial orientation. OKCR is a logical reflex considering, to a pilot flying in an aircraft, there is only one physical visual stimulus which can be used to determine body orientation: the Earth. The best discriminator on the Earth's surface is the horizon, the natural divider between the ground and the sky—the pilot's medium. Therefore, it appears the pilot reflexively seeks to maintain a relatively fixed head-horizon orientation as long as possible. While this accounts for spatial orientation of the human portion of the system, the pilot is still attached to an aircraft. Keeping the aircraft from impacting the ground is a primary concern for the pilot and, therefore, the pilot must also account for the spatial orientation of the airframe with respect to the Earth. Patterson (5) has suggested that the aircraft wing tips (and other aircraft structures) act as peripherally viewed secondary sources of information by which pilots detect the independent motion of the aircraft relative to their own head.

In summary, it is theorized that during low angles of bank (AOB) pilots maintain a head-horizon orientation from which spatial awareness is established. Once the maximum OKCR head tilt is exceeded (corresponding to high AOB), the pilot's head becomes "re-attached" to the pilot's body (and aircraft). This complete system is now rotating during the aircraft bank. The pilot is now maintaining a head-aircraft orientation. In the process of returning to a "wing's level" attitude, the pilot maintains a head-aircraft orientation until the aircraft AOB is about ±45° at which time the pilot seeks a head-horizon orientation. The transition between head-aircraft and head-horizon orientations represents a critical change in the pilot's cognitive view of the world since the frame of reference changes instantaneously.

The results of this study and the previous studies impact many aspects of flight. The following is a synopsis of those issues and suggested approaches.

The OKCR in Pilots of Large Aircraft

Although Smith (7) suggested that the aircraft experience of the pilot (fighter or transport) was not a significant factor in the OKCR response, actual data from transport aircraft has not been studied. This study and the previous simulator studies have documented the OKCR in a high-performance aircraft system. The control-response time lag in high-performance jets is small and aircraft roll is almost instantaneous when the flight stick is moved. In contrast, the time lag in large aircraft such as transport jets and commercial airliners is greater. The aircraft does not roll (or bank) as quickly as a jet fighter. While the OKCR is hypothesized to exist in all aircraft, the actual magnitude and frequency response may be affected by control-response time lag.

Impact on the Use of Simulators and Simulated Flight

The fact that the OKCR response was found (from head tracker data) to be almost equivalent between the actual flight data and the simulator data lends credibility to the use of simulators for realistic training and as experimental research tools. Given the high cost and logistical difficulties involved in actual flight testing, the use of simulated flight methods is a necessary and desirable alternative. Since the simulators used were full 360° dome-style units and the effect of reducing field-of-view on the OKCR is not known, the recommendation to use simulators is limited to full field-of-view, dome simulators.

Impact on HMD and Display Design

The recognized existence of the OKCR should, at a minimum, be a principal consideration in the design of all aircraft attitude displays. Current HMD attitude symbology sets still reflect the old assumption of static pilot head orientation during flight. Applying the traditional attitude display to HMDs may result in the serious consequences of pilot spatial disorientation and control reversal error. Since HMDs are now in their infancy, the correct design of attitude symbology today can save aircrew lives and prevent costly re-engineering in the future. The most important issue is the fact that HMDs have a relative frame of reference, mainly the pilot's head, and that the pilot's head is subject to the OKCR response which changes the pilot's cognitive frame of reference during flight. We would be remiss not to take full advantage of the head position data provided by modern head-mounted trackers (HMT) in the cockpit. This information, in conjunction with physiological and human factors models of the OKCR, can result in attitude display formats which are compatible with the pilot's spatial orientation cues and could increase pilot spatial awareness, reducing the incidences of spatial disorientation.

Effect on Training Issues

The first step of the training process should be education: education in the research community, the engineering community and, most importantly, the pilot community. An incorrect presupposition has persisted for over 60 yr, and this will be a difficult obstacle to overcome. First, pilots need to be trained that it is natural to tilt the head during VMC banking maneuvers and furthermore, that this OKCR head tilt should not induce cross-coupling (the Coriolis effect) during IMC flight. If pilots are aware of this reflex, it may reduce the incidence of spatial disorientation as they transition between external and internal (cockpit displays) visual spatial orientation cues.

For the research community, the existence of the OKCR should be recognized in the design of future experiments involving flight. Subjects should be allowed full freedom of head motion to permit the OKCR to occur naturally. This holds true for both actual and simulated flight. It is critical that the natural spatial orientation cues are not blocked or altered, unless that is the primary intent of the study.

For the engineering community, the design of future displays, especially virtual reality (VR) and helmet-mounted displays (HMD), must include provisions for adapting to the OKCR. Current attitude displays, when coupled with the OKCR response, can magnify spatial disorientation effects and induce control reversal errors (5). New attitude display symbology of the moving aircraft (outside-in) type or a frequency-separated type may help by providing a frame of reference which matches that seen by the pilot. The area of display design is mired in the convention of old theories regarding pilot head alignment. While modifications of the cockpit attitude displays are unlikely to occur in the near future, the ease by which the symbology of new displays (i.e., helmet-mounted displays) can be changed makes them the prime candidates for "OKCR-friendly" design changes. Caution must be taken, however, since multiple attitude displays of differing types may prevent resolution or add to spatial disorientation. Therefore, all attitude displays within the vehicle should be compatible with a singular frame of reference and this frame of reference should be determined experimentally and include the OKCR response.

Effect on Pilot Injury and Safety

While spatial disorientation remains a paramount concern, the existence of the opto-kinetic cervical reflex may affect the physiological aspects of flying as well. There are numerous physiological effects possible as a result of the OKCR. In particular, if pilots tilt their heads during normal accelerations greater than 1 g, this may place additional strain on the lateral muscles of the neck. With helmet-mounted displays, the combined head + helmet system center of gravity (CG) may be different than the pilot's normal head CG. This difference could cause significantly greater strain during OKCR-induced head tilt and high-G maneuvers. Cervical damage has been cited as another possible source of OKCR-induced injury in pilots (5).

Another physiological effect centers on the methods pilots use to combat the deleterious results of enduring high levels of g-forces. Pilots can only endure a certain level of normal acceleration before losing consciousness due to hypoxia—the severe reduction in oxygen concentration in the brain tissues. The high-Gs prevent the blood from reaching the brain and, therefore, the pilot "passes out." This is known as G-induced loss of consciousness (G-LOC). G-suits are just one method pilots may use to raise their G-tolerance. Another method is called the "L-1 procedure," or "anti-G straining maneuver" (AGSM). By rhythmically taking short breaths, grunting, constricting muscles in the neck and abdomen, and holding a column of air in the trachea, a pilot can usually gain up to an extra 2–3 g of tolerance. Since the OKCR occurs during aircraft turns and, therefore, under higher-G conditions, this may reduce the effectiveness of these techniques. During OKCR, the pilot's trachea and blood vessels may be constricted, thus preventing maximum AGSM effect.

Future Work

This investigation and the two previous simulator studies are the proverbial "tip of the iceberg" with respect to aviation spatial orientation. Although the optokinetic cervical reflex has been shown to be a real effect during flight, additional work is required to focus on the specific details of the reflex.

Numerous studies are documented in the literature regarding eye motion resulting from changes in body orientation and the external environment. The countertorsion of the eyes resulting from tilting the head is one such effect found in a laboratory setting (1,2). It is desirable to know if eye movement and eye scan patterns play a part in the OKCR. Eye tracker studies would answer many questions regarding the actual visual and vestibular mechanisms driving the OKCR.

A variable not measured to this point is that of upper body tilt. Does the pilot supplement head tilt by rotating the torso as well? Head tracker systems only measure the overall orientation of the head within the cockpit, but this is not necessarily the actual tilt angle between the neck and head. This information is important in order to determine the effects of G_z loading on the cervical spine region.

The effects of G-forces on the OKCR needs to be studied as well. Since G-forces are highly correlated with aircraft angle of bank, another method of investigation needs to be devised. The interaction of G-forces and OKCR with the L-1 procedure should also be studied. One possible experiment would be to expose subjects to higher levels of G-forces in centrifuges and determine the objective or subjective effectiveness of the L-1 procedure at head tilt angles similar to those resulting from the OKCR.

As was alluded to above, each of the three OKCR studies provided the subjects with full 360° field-of-view (FOV). It may be true that with a reduced FOV pilots will not exhibit the same magnitude of OKCR, perhaps altogether absent. Simulator studies involving modification of the field-of-view are required to clarify the relationship between OKCR and FOV. The results of such studies would be applicable to night vision goggle and virtual reality research where the user's FOV may be reduced or modified.

Finally, other methods of analyzing the OKCR should be investigated. One such method would involve frequency analysis. This method can be used to study the time effects of the OKCR. Possible results could include response latency (the time difference between initiation of aircraft bank and the subsequent OKCR response), and the frequency response of the OKCR head tilt (head roll rate). These results may lend insight into OKCR mechanisms as well as provide the necessary inputs for new aircraft/spacecraft attitude and virtual reality display designs.

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