SPATIAL DISORIENTATION & AVIATION SAFETY

Howard Jaslow
ORIGINAL RESEARCH PROJECT
OUTLINE

- Background
- Objectives
- General Disorienting Effects
- Motion Perception Cues
- Inner Ear Mechanism
- Motion Perception Model
- SD Accident Prevention
- Conclusions
U.S. Accidents Initiated by Pilot Error

Source: "Why Airplanes Crash" ~ NTSB Accident Data
PILOT ERROR ???

• Is pilot error truly the cause of “pilot error”?

• Pilot errors can be due to:
  - poor judgment
  - oversight
  - exhaustion
  - schedule pressure
  - negligence

• Should spatial disorientation be labeled pilot error?
WHAT IS SPATIAL DISORIENTATION?

• False perception of actual orientation.
• Misperceived attitude, motion & distances.
• Operating in environment foreign to innate sense of perception.

• Is SD a real problem?
  YES → Complete Disorientation
  → False Sense of Security
“Do not be misled into believing that only pilots of high-performance aircraft suffer the illusion of pitching up after takeoff.”

“That pilots can realize being disoriented, see accurate information on the attitude indicator, and still fly in the ground always strains the credulity of nonaviators.”

“Why so many disoriented pilots, even those who know they are disoriented, are unable to recover their aircraft has mystified aircraft accident investigators for decades.”
IS SPATIAL DISORIENTATION A REAL PROBLEM?

Source: "FAA Office of Aviation Medicine" (1996)
Spatial Disorientation Accidents
- 1987-1996
- Average of 37.6 SD accidents per year
- 33.9 fatal (over 90%)
- One fatal SD accident every 11 days
GENERAL AVIATION SD ACCIDENTS

- 1994-2003
- 202 accidents
- 184 fatal
• Spatial disorientation (SD) in flight wastes millions of dollars worth of defence capability and continues to kill aircrew.

• A number of surveys have identified SD as the most detrimental of all listed aircraft and human factor issues in terms of its effects on flight safety and operational effectiveness.
SHOULD SPATIAL DISORIENTATION BE LABELED PILOT ERROR?

NO!!!

• Pilot Error $\Rightarrow$ Pilot Fault $\Rightarrow$ Career Stigma

• Spatial Disorientation
  $\Rightarrow$ Need to Understand and Overcome

• What can be done about it?
SD CATEGORY

• Type 1. Unrecognized
• Type 2. Recognized
• Type 3. Incapacitating
Source: "Spatial Disorientation in Aviation"
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OBJECTIVES

• Provide an understanding of why SD occurs.
• Demonstrate that it is a real problem to aviation safety.
• Show that SD can be quantitatively analyzed and evaluated.
• ID how SD hazards can be reduced by:
  - Training
  - Flight path planning
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DISORIENTING EFFECTS

• EQUIPERCEPTION
  - different stimuli → same receptor reaction

• AFTEREFFECTS
  - selective, temporary impairment of receptor

• ADVERSE INPUTS
  - above/below receptor normal operating range

• SENSORY CONFLICT
  - different stimuli → perception conflict
SENSORY RECEPTORS
INTERFACE WITH OUTSIDE WORLD
SENSORY RECEPTORS

**Mechanoreceptors**
- Auditory
- Vestibular
- Muscular
- Articular (joints)
- Cutaneous (skin)

**Chemoreceptors**
- Taste
- Smell

**Photoreceptors**
- Visual

**Thermoreceptors**
- Cutaneous (skin)
<table>
<thead>
<tr>
<th>Receptor Location</th>
<th>Receptor</th>
<th>Stimuli</th>
<th>Process</th>
<th>Perception</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye</td>
<td>Photo-receptors</td>
<td>Light</td>
<td>Chemical</td>
<td>• Color</td>
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<td>• Rods</td>
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<td>• Motion</td>
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<td>• Cones</td>
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<td>• Depth</td>
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<td></td>
<td>• Distance</td>
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<td></td>
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<td></td>
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<td>• Orientation</td>
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<tr>
<td>Inner Ear</td>
<td>• Otoliths</td>
<td>Gravitoinertial</td>
<td>Physical displacement</td>
<td>• Motion</td>
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<tr>
<td></td>
<td>• Semi-circular Canals</td>
<td>• Acceleration</td>
<td></td>
<td>• Tilt</td>
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<td></td>
<td></td>
<td>• Gravity</td>
<td></td>
<td>• Orientation</td>
</tr>
<tr>
<td>Middle Ear</td>
<td>Tympanic Membrane (eardrum)</td>
<td>Sound</td>
<td>Membrane vibration</td>
<td>• Source direction</td>
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<td></td>
<td></td>
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<td></td>
<td>• Frequency/Amplitude</td>
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<td></td>
<td></td>
<td>• Communication</td>
</tr>
<tr>
<td>Skin</td>
<td>Cutaneous receptors</td>
<td>• Pressure (static/dynamic)</td>
<td>• Mechano-reception</td>
<td>• Touch</td>
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<td>• Vibration</td>
<td>• Thermo-reception</td>
<td>• Heat/Cold</td>
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<td>• Temperature</td>
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<td>• Pain</td>
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<td></td>
<td>• False object moving on body</td>
</tr>
<tr>
<td>Nose</td>
<td>Olfactory receptor cells</td>
<td>• Gas molecules</td>
<td>Chemical</td>
<td>• Aroma</td>
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<td></td>
<td></td>
<td></td>
<td>• Stimulant</td>
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<td></td>
<td></td>
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<td>• Mood affectant</td>
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<tr>
<td>Tongue</td>
<td>Taste buds</td>
<td>• Contact with the tongue</td>
<td>Molecular interaction</td>
<td>• Taste</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(bitter, sweet, sour, saline)</td>
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<tr>
<td>External Stimulus</td>
<td>Sensor</td>
<td>Phenomenon</td>
<td>Adverse Sensation</td>
<td>Potential Safety Hazard</td>
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<tr>
<td>----------------------------</td>
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<td>-------------------------------</td>
</tr>
<tr>
<td>Linear Acceleration/ Tilt</td>
<td>Otolith</td>
<td>2-D vs 3-D</td>
<td>Multiple Equivalent States</td>
<td>Over/under Correct Climb Angle</td>
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<td>Rotational Deceleration</td>
<td>Semicircular Canals</td>
<td>Inertia</td>
<td>Counter-Revolution</td>
<td>Overcorrect</td>
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<td>Sound</td>
<td>Middle Ear</td>
<td>Unequal Masking</td>
<td>False Direction of Sound</td>
<td>Misinterpret Source Location</td>
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<tr>
<td>Sound</td>
<td>Middle Ear</td>
<td>Masking</td>
<td>Noise</td>
<td>Miscommunication</td>
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<tr>
<td>Out-of-Plane Rotation</td>
<td>• Otolith</td>
<td>Coriolis</td>
<td>False Rotation</td>
<td>Miscorrect</td>
</tr>
<tr>
<td></td>
<td>• Canals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrational/ Mechanical Pulses</td>
<td>Cutaneous</td>
<td>Simulation</td>
<td>Object Moving on Body</td>
<td>Distraction</td>
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## AFTEREFFECTS

<table>
<thead>
<tr>
<th>External Stimulus</th>
<th>Sensor</th>
<th>Phenomenon</th>
<th>Adverse Sensation</th>
<th>Potential Safety Hazard</th>
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<tr>
<td>Bright Burst of Light (white/color)</td>
<td>Retina</td>
<td>Bleaching</td>
<td>• Negative Images</td>
<td>Color Codes Misread</td>
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<td></td>
<td></td>
<td></td>
<td>• Erroneous Color</td>
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<tr>
<td>Intense Burst of Noise (white/color)</td>
<td>Middle Ear</td>
<td>Unequal Masking</td>
<td>False Direction of Sound</td>
<td>Misinterpret Source Location</td>
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<tr>
<td>Intense Burst of Noise</td>
<td>Middle Ear</td>
<td>Masking</td>
<td>&quot;Ringing&quot;</td>
<td>Miscommunication</td>
</tr>
<tr>
<td>Rotational Oscillation</td>
<td>Semicircular Canals</td>
<td>Inertia</td>
<td>Rotation</td>
<td>Turn Rate Error</td>
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<td>External Stimulus</td>
<td>Sensor</td>
<td>Phenomenon</td>
<td>Adverse Sensation</td>
<td>Potential Safety Hazard</td>
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</tr>
<tr>
<td>Bright Burst of Light (white/color)</td>
<td>Retina</td>
<td>Bleaching</td>
<td>Diminished Image</td>
<td>• Temporary Blindness</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Slower Reaction Time</td>
</tr>
<tr>
<td>Intense Light (white/color)</td>
<td>Iris/Retina</td>
<td>Greater Threshold Level</td>
<td></td>
<td>• &quot;Blinded&quot; to low I signals</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Colors Misread</td>
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<tr>
<td>Low Light Level</td>
<td>Iris</td>
<td>Lens Effect</td>
<td>Poor Resolution</td>
<td>Difficult to:</td>
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<td></td>
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<td></td>
<td>• Identify Distant Objects</td>
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<tr>
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<td></td>
<td></td>
<td>• Resolve Multiple Objects</td>
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<tr>
<td>Low Light Level</td>
<td>Iris/Retina</td>
<td>Pulfrich Effect</td>
<td>Retarded Signal Transmission</td>
<td>Slower Reaction Time</td>
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<tr>
<td>Peripheral Light Source</td>
<td>Retina</td>
<td>Blind Spot (monocular)</td>
<td>No Reception</td>
<td>Object &quot;Vanished&quot;</td>
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<tr>
<td>Out-of-Plane Rotation</td>
<td>Otolith/Canals</td>
<td>Coriolis</td>
<td>False Rotation</td>
<td>Nausea</td>
</tr>
<tr>
<td>Noise</td>
<td>Middle Ear</td>
<td>Masking</td>
<td>Greater Threshold Level</td>
<td>• Deaf to low I Sound</td>
</tr>
<tr>
<td>Environment (T, p, ...)</td>
<td></td>
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<td>• Miscommunication</td>
</tr>
</tbody>
</table>


## SENSORY CONFLICT

<table>
<thead>
<tr>
<th>External Stimulus</th>
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<th>Phenomenon</th>
<th>Adverse Sensation</th>
<th>Potential Safety Hazard</th>
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</thead>
<tbody>
<tr>
<td>Linear Acceleration/ Tilt</td>
<td>• Otolith</td>
<td>Vision vs</td>
<td>Opposing Sensations (weighted by environment)</td>
<td>Accepted Wrong Cue</td>
</tr>
<tr>
<td></td>
<td>• Retina</td>
<td>Inner Ear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Noise</td>
<td>• Middle Ear</td>
<td>Vision vs</td>
<td>Opposing Sensations (weighted by environment)</td>
<td>Accepted Wrong Cue</td>
</tr>
<tr>
<td>• Object Emitting Sound</td>
<td>• Retina</td>
<td>Middle Ear</td>
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<td>Out-of-Plane Rotation</td>
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<td>• Canals</td>
<td>Inner Ear</td>
<td></td>
<td>• Nausea</td>
</tr>
<tr>
<td></td>
<td>• Retina</td>
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</tbody>
</table>
LIFE IN THE AIR IS NOT THE SAME AS LIFE ON THE GROUND

**ON THE GROUND**
While we are in contact with the earth, the pull of gravity squeezes the pressure sensors in various portions of the body, thus telling us in which direction the earth lies.

**IN FLIGHT**
While in flight centrifugal forces combine with the pull of gravity, resulting in G-forces which make the cent-of-the-pants sense completely unreliable as an attitude indicator.
SD ILLUSIONS

- Giant-Hand Illusion
- Graveyard Spin
- Postroll Illusion
- The Leans
- Gravitoinertial Effect
OUTLINE

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• **Motion Perception Cues**
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MOTION PERCEPTION CUES

- Visual
- Vestibular (inner ear)
- Tactile (pressure)
- Proprioception
  (muscle, tendon, joint)
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INNER EAR MECHANISM

VESTIBULAR SYSTEM

• Somatogyral
  Semicircular Canals
  – sense rotational acceleration

• Somatogravic
  Otolith
  – sense linear acceleration
VESTIBULAR SYSTEM

• Utricular Otolith
  ~ linear acceleration

• Saccular Otolith
  ~ acoustic/vibration

• Semicircular Canals
  ~ rotational acceleration
VESTIBULAR SYSTEM
VESTIBULAR SYSTEM
SEMICIRCULAR CANALS
ORTIENTATION OF SEMICIRCULAR CANALS
SEMICIRCULAR CANAL

- Semicircular Canal
- Ampulla of a Semicircular Canal
- Cupula
- Endolymph Fluid
- Filaments of Hair Cells
- Hair Cells
- Vestibular Nerve
ROTATION OF SEMICIRCULAR CANAL
SD ILLUSIONS DUE TO SEMICIRCULAR CANALS

Graveyard Spin
SD ILLUSIONS DUE TO SEMICIRCULAR CANALS

Postroll Illusion

Actual bank after cessation of roll

Perceived bank after cessation of roll
SD ILLUSIONS DUE TO SEMICIRCULAR CANALS AND OTOLITH

The Leans

- **Actual**: Pilot allows wing to drop at a sub-threshold rate.
- **Perceived**: Pilot detects attitude error from instruments and returns to wings level at a supra-threshold rate. Pilot aligns head and trunk with perceived vertical and leans to right.
OTOLITH: 2 degrees-of-freedom
REAL WORLD: 3 degrees-of-freedom

EQUIPERCEPTION
G-Excess Illusion

ACCELERATE DURING CLIMB

ACCELERATE DURING LEVEL FLIGHT

Equipereception Maneuvers
Spatial Disorientation - Physiology of Flight
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MOTION PERCEPTION MODEL

ASSUMPTIONS

• Cyclopean Model

• Actual Perception ~ 1G Perception
Acceleration & Pitch:

\[ F_x = -F \cos \alpha - W \sin(\theta_a + \alpha) \]

Pitch Only:

\[ F_x = -W \sin(\theta_p + \alpha) \]

Perceived Pitch:

\[ \therefore \theta_p = \sin^{-1}[n \cos \alpha + \sin(\theta_a + \alpha)] - \alpha \]
VALIDITY OF SD MODEL
FLIGHT DYNAMICS
OTOLITH FORCE COMPONENTS

Aircraft State:

- \( \theta \) ~ Pitch
- \( \Phi \) ~ Roll
- \( p, q, r \) ~ Pitch, Roll, Yaw Velocities
- \( a \) ~ Aircraft Acceleration
- \( R \) ~ Head Location Relative to A/C CG
- \( \alpha \) ~ Otolith Angle

\[
\begin{align*}
f_x &= -\left[ \cos \alpha \sin \theta + \sin \alpha \cos \theta \cos \phi \right] \\
&\quad - \left[ a_x \cos \alpha - a_z \sin \alpha \right] \\
&\quad - \left[ (qR_z - rR_y) \cos \alpha - (pR_y - qR_x) \sin \alpha \right] \\
&\quad - \left[ \left\{ p(qR_y + rR_z) - R_x (q^2 + r^2) \right\} \cos \alpha - \left\{ r(pR_x + qR_y) - R_z (p^2 + q^2) \right\} \sin \alpha \right]
\end{align*}
\]

\[
\begin{align*}
f_y &= \cos \theta \sin \phi - a_y - \left[ \dot{r}R_x - \dot{p}R_z \right] - \left[ q(pR_x + rR_z) - R_y (p^2 + r^2) \right]
\end{align*}
\]
EQUIPERCEPTION MANEUVERS
CLIMB/DIVE/ACCELERATION

\[ f_x = -\sin (\alpha + \delta + \gamma) - a_{xa} \cos (\alpha + \delta) \]
\[ f_y = 0 \]

\[ \sin (\alpha + \delta + \gamma) + n \cos (\alpha + \delta) = \text{constant} \]
EQUIPERCEPTION NOMOGRAM
EFFECT OF ACCELERATION ON PERCEIVED PITCH

Effect of Acceleration

- Actual forces exerted on pilot during forward acceleration.
- Perceived acceleration

Effect of Deceleration

- Actual forces exerted on pilot during forward deceleration.
- Perceived deceleration

The resultant force is perceived by pilot as the force of gravity thereby causing a false sensation of pitch-up.

\[ Fa = \text{force due to forward acceleration (inertia)} \]
\[ Fg = \text{force due to gravity} \]
\[ Fr = \text{resultant force} \]
\[ Fd = \text{force due to deceleration (inertia)} \]
SPATIAL DISORIENTATION
~ COORDINATED TURN ~

Diagram showing forces and angles in a coordinated turn.
POTENTIAL ACCIDENT
JFK Jr’s MISTAKE WASN’T AS SIMPLE AS ‘POOR JUDGMENT’

“I think most pilots can piece together the series of factors involved in the JFK Jr. accident and identify a case of spatial disorientation. … therefore culminating with the spiral and lack of recovery.”

- Jennifer Melvin
  Aviation Safety, November 1999
POTENTIAL ACCIDENT/INCIDENT DUE TO SPATIAL DISORIENTATION

<table>
<thead>
<tr>
<th>MANEUVER</th>
<th>EQUIVALENT PERCEPT</th>
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</thead>
<tbody>
<tr>
<td>Takeoff</td>
<td>12° pitch up, constant speed</td>
</tr>
<tr>
<td>0.2 G acceleration</td>
<td></td>
</tr>
<tr>
<td>Landing</td>
<td>6° pitch down, constant speed</td>
</tr>
<tr>
<td>0.1 G deceleration</td>
<td></td>
</tr>
<tr>
<td>Climb</td>
<td>¼ G acceleration, level flight</td>
</tr>
<tr>
<td>16°, constant speed</td>
<td>13° dive at ½ G acceleration</td>
</tr>
<tr>
<td>Coordinated Turn</td>
<td>5° pitch up</td>
</tr>
<tr>
<td>30° bank</td>
<td></td>
</tr>
<tr>
<td>Pullout</td>
<td>11° pitch up</td>
</tr>
<tr>
<td>½ G</td>
<td></td>
</tr>
</tbody>
</table>
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SD ACCIDENT PREVENTION

• Identify critical SD maneuvers.

• Constrain flight maneuvers to avoid potentially hazardous SD maneuvers.

• Override misperception orientation.
Potentially Hazardous Dive Maneuver

- Pitch angle limit from dive dynamics
  \[ \theta_p < \theta_{\text{Limit}} \]

- Bank angle limit
  \[ \phi < \cos^{-1} \left[ \frac{\sin \alpha}{\sin(\theta_{\text{Limit}} + \alpha)} \right] \]
## Critical SD Maneuvers

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>G-Excess Illusion</th>
<th>Elevator Illusion</th>
<th>Potential Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level Flight Accel/Decel</td>
<td>X</td>
<td></td>
<td>Collision Into Terrain</td>
</tr>
<tr>
<td>Climb to Avoid Obstacle While Accelerating</td>
<td>X</td>
<td></td>
<td>Obstacle Collision</td>
</tr>
<tr>
<td>Descent to Altitude While Accelerating</td>
<td>X</td>
<td></td>
<td>Collision Into Terrain</td>
</tr>
<tr>
<td>Pullout from Dive</td>
<td></td>
<td>X</td>
<td>Collision Into Terrain</td>
</tr>
<tr>
<td>Coordinated Turn</td>
<td></td>
<td>X</td>
<td>Graveyard Spiral</td>
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</table>
TRAINING TO AVOID & OVERCOME SD ACCIDENTS

• Training with spatial disorientation.

• Flight path planning.

• Induced cues.
TRAINING WITH SPATIAL DISORIENTATION

“Just experiencing the symptoms in a controlled environment will place most aviators in a position of realizing they aren’t perfect and that it can happen to them.”

- Classroom
- Simulator
- In-Flight
CLASSROOM TRAINING FOR SD

- Understanding SD
- Barany chair
SIMULATOR TRAINING FOR SD
IN-FLIGHT TRAINING FOR SD

• Student pilot is instructed to close his/her eyes.
• Instructor maneuvers to simulate:
  - Pitch Misperception
  - Elevator Illusion
  - False Climb in a Turn
  - Diving During Turn Recovery
  - Leans
  - Postroll Effect
  - ...Other
## SD TRAINING EFFECTIVENESS

<table>
<thead>
<tr>
<th>Type of instruction(^a)</th>
<th>Number of responses</th>
<th>Median rating(^b)</th>
</tr>
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<tbody>
<tr>
<td>Classroom instruction</td>
<td>43</td>
<td>7.0</td>
</tr>
<tr>
<td>Discussion of SD accidents/incidents</td>
<td>33</td>
<td>7.0</td>
</tr>
<tr>
<td>Barany chair</td>
<td>33</td>
<td>8.0</td>
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<tr>
<td>Other SD demonstration devices</td>
<td>16</td>
<td>10.0</td>
</tr>
<tr>
<td>Recovery from unusual attitudes in an aircraft</td>
<td>31</td>
<td>10.0</td>
</tr>
<tr>
<td>Recovery from unusual attitudes in a flight simulator</td>
<td>33</td>
<td>10.0</td>
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<tr>
<td>SD demonstration sortie(^c)</td>
<td>45</td>
<td>13.0</td>
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OUTLINE

- Background
- Objectives
- General Disorienting Effects
- Motion Perception Cues
- Inner Ear Mechanism
- Motion Perception Model
- SD Accident Prevention
- Conclusions
SD MODEL CAN BE USED TO:

- Develop algorithms for flight trainers.
- Develop special purpose trainers for critical maneuvers.
- Advise commercial airlines of potentially hazardous flight maneuvers.
- Develop guidelines for cockpits and instruments.
- Apprise insurance companies of SD risks.
SAFE FLYING