Signal Detection Theory (SDT)
Principles in Aircraft Mishap Investigation

Application in Analysis of Causal Factors in a USMC Night Bombing Practice Mission Mishap

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• David Gillis has no financial conflict of interest to declare.

• This presentation does not contain off label drug recommendations or discussions.
Target marked with 2
smudge pots, 5’ apart

Night, air-to-ground weapons delivery

30° dive angle
350 KIAS
The mishap occurred during a night practice air-to-ground weapons (bomb) delivery, conducted at the Delamere bombing range, near Darwin, in Australia’s Northern Territory on August 20, 1988.

We will be exploring Signal Detection Theory science in the context of a US Marine Corps F-18C Hornet Controlled Flight into Terrain (CFIT) fatal mishap.

This is a re-visiting and extending of a presentation first given in 1999 at the Naval Aerospace Medicine Institute quarterly staff conference at Pensacola Naval Air Station.

The circumstances of this mishap have generated heightened interest, the extent of which I only recently learned, while preparing this presentation.
Salient aspects of this mishap include missed communication at many levels. Signals of significant risks of unanticipated outcomes parade throughout the unfortunate history of this preventable death and loss of an aircraft. It is my hope we can add other pieces to the picture that we puzzle over even now.

The concept of signal detection theory permeates from start to finish, book-ended by violent losses of consciousness, and linked throughout by information losses, rusty procedural skills and, in the end, life itself.

After acknowledging a number of prior presentations (none of which I have seen), we begin with an overview of the mishap’s climatic events, then return to earlier events which set the stage for disaster, events which were the handmaidens of death, though frequently not noticed or understood, but with a continued presence and effects.
Naval Safety Center

Thanks to:

• LT Alisa J. Blitz-Seibert, MC, USN (FS)
  – AA Mishap Case #3 identified root mishap causal factors

• CAPTs Nick Davenport and Lee Mandel, NAVSAFECEN

• LCDR Ed Park, RAM Class 1999

• LCDR Jay McMahon, RAM Class 2000

• LT Jose Troche, RAM Class 2000
  – Mishap Case #1 presented at AsMA Grand Rounds, May 1999
August 1998

- Summary: Aircraft impacted the ground during night air-to-ground weapons delivery
- Mission: Air-to-Ground
- Environment: Night, NVD’s not used.
- Evolution: 30-degree dive, A/G weapons
- Souls on Board: One
Investigation

• Aircraft at impact
  – Crater 170’ due west of target
  – 60° nose down (vs. 30°)
  – 550 kts (vs. 350 kts)
  – Left wing down 30° (vs. level)
  – Not maneuvering
  – Low AOA
  – Heading 328° true (vs. 360° planned)
• MW states MP rolled in from ~6500’ AGL vs. 8000’;
  0.9-1.3nm inside the 2.4 nm radius

Privileged Information: This is part of a limited use Naval Aircraft Mishap Investigation. Limited distribution and special handling required IAW OPNAVINST 3750.6
Background of the Marine Aviator

◦ A USMC Naval Aviator and Weapons and Tactics Instructor (WTI)
◦ Graduated Naval Postgraduate School Aviation Safety Officer Course with honors.
◦ Advanced rapidly to Flight Leader after success as Wingman, then Section Leader, and Division Leader in flight
◦ Reputation as “master and teacher of others in the USMC” Temporarily left the squadron to attend Amphibious Warfare School, with agreement to return to the squadron upon completion of the year-long course
◦ Upon completion, during a 2-week leave period, the pilot was “T-boned” while backing out of a parking space in Georgetown, rendered unconscious and hospitalized for several days. Assigned limited duty for 3 weeks to recuperate
Background of the Marine Aviator

° When tested 3 weeks later for traumatic brain injury (TBI) impairment at the Walter Reed Army Medical Center (WRAMC), he was significantly impaired compared to normal. He was given three months for recovery and he then tested within normal limits.

° Received 10 days of refresher training in the Fleet Replacement Squadron (FRS) – which consisted primarily of a transcontinental cross-country flight and a NATOPS (Naval Aviation Training and Operational Procedures Standardization) exam, which he passed.

° A medical recommendation from WRAMC that the pilot would require 12-18 months of duty before a combat deployment seems to have been lost in communication to the Squadron or to Naval Aerospace Medical Institute (NAMI).

° The Squadron Flight Surgeon issued an Up Chit after a telephone consultation with a NAMI neurologist. NAMI came away from the conversation expecting an on site evaluation.
Temporary squadron deployment to Australia for air-to-ground weapons delivery training

° The mishap pilot returned to his squadron, which was deployed in Japan. No F/A-18C Hornet simulators were available in Japan.

° Squadron temporarily deployed to Australia to conduct weapons and tactics training at Delamere bombing range in the Northern Territory, near Darwin. Daylight bombing and strafing practice preceded the night practice bombing mission during the deployment.

° The mishap pilot was uncomfortable with daytime bombing and violated the “don’t go below altitude” several times during weapon delivery.
Mission Brief and Departure Relevant Information

Interview of the mishap wing pilot was notable. He recalled the pilot mentioned several times that he did not feel ready for a night practice bombing mission and expressed anxiety regarding the flight. He stated he had not performed a practice night bombing flight in approximately two years!

When the mishap pilot departed the brief and went to his aircraft he inadvertently left his flight chart in the briefing room. During the section takeoff, the mishap wing pilot noted the lead aircraft had a strobe light, but navigation lights had not been turned on. He notified the mishap pilot of this and navigation lights were turned on.

The mishap pilot’s F-18C center instrument display had been griped for an inoperative dimming rheostat. Because of high cockpit and canopy glare that main instrument display was turned off. Squadron policy did not consider that discrepancy a downing condition for night flight! This required alternating ‘pageing’ of instrument and weapons procedures onto the left cockpit display.
Approach to Bombing Target

- 180°
- "8,500' assigned"
- "5,500' actual"
- "Overshot entry point, steep banked reversal"
- "3500' Pickle – (Barometric)"
- "2500' Floor – (Radar altimeter)"
- Altitude (ft)

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Gillingham illusion results in an unrecognized curved approach to the smudgepot target, creating a visual illusion as a result of the left turn. Pilot pushes over to keep visual target on his nose, and has no information as to location of the horizon or altitude.
The Gillingham Illusion

Research has shown there are three distinct types of SD-unrecognized, recognized and incapacitating. Each type impacts the pilot in a different way, and each should be thoroughly understood by the pilot before experiencing them in flight: Post-Roll Illusion (Type I), the Graveyard Spin Illusion (Type II), and the Giant Hand Illusion (Type III) is presented.


Subjects experienced a consistent tendency to increase bank angle after given control of the aircraft immediately following the roll maneuver, while thinking they were maintaining a constant bank angle. In some cases, the pilots rolled the aircraft completely inverted. When pilots rely on their perception of bank, following a roll, they will inadvertently increase their bank in the direction of the previous roll.
With regards to the EGPWS signal, the MP may or may not have recognized the essential stimulus, which was the Baro-altimiter signal of 3500 ft. He may have failed to set the alert altitude, or the disabled display may be the villan. With regards to the visual signal for ordinance release and pull-up, it was essentially absent, the smudge pot target presenting only a point source light suitable only for homing, which appears to be what the MP was attempting to execute.

Given the existing 4% illumination conditions this mishap was predictable. Careening towards the ground in a dive progressing to 60 degrees, a bank progressing towards 90 degrees and a speed approaching 550 knots from an altitude of 5,500 ft. likely exceeded the MP pilots temporal limits for processing critical information.

This particular training mission should undergo such analysis in the mission planning stage and in the pre-flight stage, incorporating the temporary and local meteorological, illumination, and aircraft functional status critical to the safe conduct of the mission.
The mishap pilot was not provided with the requisite flow of flight information in a timely manner nor in a recognizable manner considering the flight environment and the potential critically short time of the run-in phase unless the mission was flown with little to no deviation from perfectly.

Information flow and clarity was never adequate for the actual circumstances of flight during this bombing practice phase of flight. The critical sensory limits, analysis, and decision making and execute times were exceeded given the 5,500 ft altitude at initiation of the run-in, further aggravated by the overshoot and maneuvers to salvage the run-in.

This common knowledge appears to have been lost among the squadron command, the operations officer, the NATOPS officer and the flight surgeon, who were not sufficiently engaged in the training process to recognize the danger and intervene to assure adequate safety.
Loss of Enhanced Ground Proximity Warning System Function

The likelihood of a vestibular illusion was augmented by the prolonged circling in a 30 degree bank. The short duration, but steeply banked turn to correct the over run of the run-in course error may have been accompanied by a push over to initiate the planned 30 degree dive angle.

The early stages of a Gillinham illusion would confuse the visual sighting picture of the dimly illuminated smudge pots.

Thinking he was wings level, while actually banked left wing down would cause the visual effect of the smudge pot image tending to move beneath the nose, prompting an increasing dive angle and increasing bank to maintain the anticipated visual relationship of the smudge pot to the nose of the aircraft. Absent any visual clues to the real horizon or altitude, the mishap pilot was a set up for a fatal vestibular illusion.
Loss of Enhanced Ground Proximity Warning System Function

Given the abnormal attitude of the aircraft at this point, the EGPWS recognizes the radar altimeter cannot provide a valid Doppler radar altitude and enters a 28 second functional pause.

It is unclear whether the mishap pilot recognized any alerting signal of this pause or whether, if recognized, his 550 kn airspeed, 60 degree dive angle, confusing sensory inputs and unexpectedly short time interval until CFIT prevented diagnosis and response in time to avoid a CFIT. He was dealing with only a few seconds at this point.
Hypothesis re mishap F/A-18C: pilot expected EGPWS alert for ordinance release and pull and thus selected his visual bomb run cues as the center of his attention.

The chosen focus of attention may be subject to distractors interfering with the intended monitoring of the selected signals to be the focus of attention. This can occur when two or more tasks require simultaneous monitoring.

The MP pilot does not appear to have appreciated he needed to attend to his altitude, suggesting he did not sample his altimeter and that his visual attention was focused on the smudge pot target, which rendered no horizon or altitude information to the pilot.
The Role of Signal Detection Theory

Missed Signals leading to CFIT

**FIGURE 2.2** The change in the evidence variable X caused by a weak and a strong signal. Notice that with the weak signal, there can sometimes be less evidence when the signal is present (point B) than when the signal is absent (point A).
Wickens, Chapter 2: Signal Detection and Absolute Judgment, 1987

**FIGURE 2.3** Hypothetical distributions underlying signal detection theory: (a) high sensitivity; (b) low sensitivity.
Payoffs

- Payoffs influence a person’s placement of $X_c$ so as to maximize potential gain and/or minimize potential loss associated with responses. This is represented by the following equation:

$$\beta_{opt} = \frac{P(N)}{P(S)} \times \frac{V(CR) + C(FA)}{V(H) + C(M)}$$

Characteristically, the adjustment of Beta in response to observed losses and gains is less than optimal.
Signal Detection Theory

• “Will the security guard monitoring a bank of television pictures detect the abnormal movement on one of them?”
• Will the radiologist detect the abnormal x-ray as he scans it?”
• Will the pilot detect the set of cues for pull up from the dive?
Signal Detection Theory

- **Signal**
  - 1. Detect concealed weapon by airport security
  - 2. Detect contact on radar scope
  - 3. Recognize tumor on chest X-ray
  - 4. Recognize cue set for pull up from ordnance delivery run

- **Noise**
  - 1. All non-weapon items on the passenger and bags
  - 2. Screen highlights not representing aircraft
  - 3. Normal structures and organs displayed in the X-ray
  - 4. Failure to recognize cue set for pull up from ordnance delivery run
Signal Detection Theory

• We use a 2 X 2 matrix for analysis:
• Four classes of joint events:
  – hits-a signal exists and is detected
  – misses- a signal exists and is not detected
  – false alarm-no signal exists, but thought to be detected
  – correct rejection-no signal and none detected
Two States of the World and Four Outcomes of SDT

When to initiate pull-up?

<table>
<thead>
<tr>
<th>Pilot Response</th>
<th>Cues Present</th>
<th>Cues Absent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>False Alarm</td>
<td>Correct Rejection</td>
</tr>
<tr>
<td>No</td>
<td>Miss</td>
<td></td>
</tr>
</tbody>
</table>
Four Outcomes of SDT

- Cue set for initiation of dive pull up exists and is recognized
- Cue set for dive pull up exists and is not recognized
- Mis-perception of pull up cue set and premature pull up (abort)
- Cue set not present, recognized not to be present
- Hit: Pull Up
- Miss: CFIT
- False alarm: Miss target
- Correct Rejection: Continue Run In
## Four Outcomes of SDT

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<tbody>
<tr>
<td>Yes</td>
<td>Pull Up</td>
<td>Early Pull Up</td>
</tr>
<tr>
<td>No</td>
<td>CFCR</td>
<td>Continue Run In</td>
</tr>
</tbody>
</table>
Yes, Houston, We Have a Signal! Good S/N ratio, strong, kurtotic signal, low noise, low probability of CFIT or early (inaccurate) release

$X_c$ is pilot’s Response Criterion

$\leftarrow------\text{Noise}------\rightarrow$  $\leftarrow------\text{Signal}------\rightarrow$

Probablity

$$
\begin{align*}
\text{CFIT} & \quad X_c \\
\text{Run} & \quad \text{In} \\
\text{Pull} & \quad \text{Up} \\
\text{Abort} & \\
\text{Neuronal Activity} & 
\end{align*}
$$

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However, you don’t need a computer to generate your curves – you can hand draw your conceptualized normal distributions that represent the two world states under consideration at the moment. There is math and graphing software to generate the numbers and draw the graphs.

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Night S/N with Radar Altimeter and GPWS

At night, with reduced visual signals, the Xc is shifted left to improve detection of the remaining cue set. This generates a larger Abort probability, reducing night bombing accuracy.

Neuronal Activity

\[ \text{Noise} \rightarrow \text{Signal} \]

CFIT

Run

\[ \text{XC} \]

Abort

Pull

Up
Night S/N with Radar Altimeter and GPWS
Pilot adjusts his $X_c$ to reduce aborts, with minimal effect on CFIT risk, anticipates strong signal

Neuronal Activity

<table>
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<td>Run In</td>
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<td>Abort</td>
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<td>Neuronal Activity</td>
<td></td>
</tr>
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</table>
Night S/N without Radar Altimeter and with GPWS Lapsed Signal reduced or absent and less sensitivity. If lapse not detected, $X_c$ suggests miss to be expected.

Neuronal Activity

Probability

Run
In

CFIT

Pull Up

Abort

Neuronal Activity

$X_c$
Night S/N without Radar Altimeter and EGPWS
Signal reduced and less sensitivity: corrected. Run-in aborted.

The relationship of signal detection theory and epidemiology is clearly evident in this ROC graph.

Figure 2. Predictive values for all-cause and cardiovascular mortalities, and hard events in receiver operating characteristic analysis. The red line indicates cardiac death, the blue line indicates all-cause death, and the black line indicates hard events. AUC, area under the curve.
Receiver-Operator Characteristics Curves (ROC Curves)

- $d' = 1$ (lots of overlap)
- $d' = 3$ (not much overlap)

ROC curves

Hits vs. False alarms
FIGURE 2.5 The ROC (receiver operating characteristic) curve. For the three boxes on the left, sensitivity is high, and the criterion is shifted from a low to a high value. These are mapped to their respective positions on the ROC curve. On the right, the box showing one point of lower sensitivity is similarly mapped to its position in ROC space.
Thank you

Questions?
Wickens, Chapter 2: Signal Detection and Absolute Judgment, 1987

**FIGURE 2.2** The change in the evidence variable $x$ caused by a weak and a strong signal. Notice that with the weak signal, there can sometimes be less evidence when the signal is present (point $B$) than when the signal is absent (point $A$).
Wickens, Chapter 2: Signal Detection and Absolute Judgment, 1987

![Diagram of Signal Detection and Absolute Judgment](image)

**FIGURE 2.3** Hypothetical distributions underlying signal detection theory: (a) high sensitivity; (b) low sensitivity.
Payoffs

- Payoffs influence a person’s placement of $X_c$ so as to maximize potential gain and/or minimize potential loss associated with responses. This is represented by the following equation:

$$
\beta_{opt} = \frac{P(N)}{P(S)} \times \frac{V(CR) + C(FA)}{V(H) + C(M)}
$$

Characteristically, the adjustment of Beta in response to observed losses and gains is less than optimal.
Calculation of signal detection theory measures

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Signal detection theory (SDT) may be applied to any area of psychology in which two different types of stimuli must be discriminated. We describe several of these areas and the advantages that can be realized through the application of SDT. Three of the most popular tasks used to study discriminability are then discussed, together with the measures that SDT prescribes for quantifying performance in these tasks. Mathematical formulae for the measures are presented, as are methods for calculating the measures with lookup tables, computer software specifically developed for SDT applications, and general purpose computer software (including spreadsheets and statistical analysis software).

The relationship of signal detection theory and epidemiology is clearly evident in this ROC graph.

**Figure 2.** Predictive values for all-cause and cardiovascular mortalities, and hard events in receiver operating characteristic analysis. The red line indicates cardiac death, the blue line indicates all-cause death, and the black line indicates hard events. AUC, area under the curve.
Receiver operating characteristic
From Wikipedia, the free encyclopedia
http://en.wikipedia.org/wiki/Receiver_operating_characteristic
Receiver operating characteristic, From Wikipedia, the free encyclopedia http://en.wikipedia.org/wiki/Receiver_operating_characteristic
There was no augmented feedback to identify the multiple errors, beginning with the inadvertent altitude loss while orbiting, overrunning the run-in heading, the unrecognized progressive bank during run-in, the progressive increase in dive angle and airspeed, the progressive increase in bank angle, and the lapse phase of the EGPWS and looming CFIT. Off-target feedback in these critical parameters could have been life-saving. The several seconds remaining prior to CFIT are insufficient time for recognition, diagnosis, decision making, response and recovery.

Segmented training would have improved the orbiting phase of the night bombing practice and reduced the likelihood of carry-over of orbiting attitude loss in further complicating the bombing run-in phase of training.

The two year or more absence from operational flying likely took its toll on procedural tasks, particularly under the high stress, black hole environment.

The t-bone auto impact injury may have resulted in some mild, residual compromise of working memory, complicated by the remoteness of the relevant training for night bombing.
Thank you

Questions?
• Could meeting bombing accuracy be temporarily more important than safety, considering pressure to perform?

• Given the black night with no visible horizon clues, EGPWS signal was the only potentially reliable clue-- when it paused its operation MP was left with only a point source of light with no horizon or height reference in his peripheral vision -- and was likely unaware he no longer had a functioning EGPWS signal

• In this mishap the MP had not only experienced a serious TBI, but had a prolonged absence from night flights such as the mishap flight. His squadron was deployed to Japan, with no F-18C simulars available and scheduled for a night bombing exercise in a visual black hole with a non-functioning for night flight center MFD and a poorly marked visual target for such conditions. He likely had no such flight in at least two years!

• It seems likely the MP was not adequately familiar with the flight parameters that would induce the 28 second functional lapse in the EGPWS nor how such lapse would be announced in the cockpit.
Post-Roll Effect (Gillingham Illusion)

Following sustained roll rates of three different magnitudes (four if you consider the null condition as a roll rate), the subject was tasked to maintain the last perceived bank angle. The rates of roll tested were at 10 degrees/sec, 20 degrees/sec, and 30 degrees/sec. There was found a significant difference between the null roll condition and the three different roll rate responses. It was also found that each roll condition, upon stopping, generated a roll sensation contrary to the direction of the initial roll. For example, if the direction of roll was clockwise, then the sensation perceived by the pilot was counterclockwise, and generated stick inputs that resulted in a clockwise aircraft movement.
SDT

The MP had recent training in daytime bombing practice, characterized by serious deficiencies, including violating the "don't go below" altitude after ordinance release. His daytime performance in bombing was neither error-free or at an automated level.

Daylight bombing practice was insufficient in this case, and nighttime practice was non-existent for at least two years! "We do this all the time," says the squadron Co! Not!

The MP had inadequate opportunity to develop the prerequisite long term memory and automation necessary to successfully and safely execute night bombing practice in the environmental circumstances into which he was thrust. His preflight anxiety was entirely justified by the risk to which he was being exposed!

The MP was faced with conflicting demands, decision making with uncertainties that could not be resolved within the critical time available. Task conflicts and no recent practice, presented in a most challenging black hole scenario and a high anxiety state which properly reflected the danger of his circumstances all conspired to further constrain the MP probability of success.
Constraints not adequately considered that led to this CFIT mishap include:

1) no recent training or practice in the procedures,

2) acceptance for night flight of a serious instrumentation deficiency in the aircraft

3) failure to identify the severely constrained visual environment of this night mission and the local environment in which it was to be conducted,

4) the increased risk of vestibular illusions in the restricted visual environment of the mission,

5) review of the limitations of bank and dive angle of the critical EGPWS altitude functions

6) lack of clear, continuous display and look-ahead warning of altitude, attitude and airspeed factors during the bombing run-in phase of flight.
The MP was not optimally sampling his cockpit and external environment in order to successfully maximize on-target release of his ordinance while minimizing the likelihood of a controlled flight into terrain, given the black hole visual environment and his lack of recent exposure to the required procedural performance.

Lacking recent experience, the MP may have had inadequate information for forming an accurate mental model for the bombing run in phase of flight. Nor would such a model likely have included the various visual and vestibular illusions that may have occurred.

The F/A18-C MP had NO redundancy of the critical information of attitude, altitude or spatial position with regards to height above the ground or proximity to his target.
• Could meeting bombing accuracy be temporarily more important than safety, considering pressure to perform?

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